An Intertidal Monitoring Program for Mobil, Port Stanvac (Sth Australia): Anthropogenic Versus Natural Disturbance.

Leanne M. Piller, B.Sc. (Hons)
Department of Zoology
The University of Adelaide

Submitted in fulfillment of the requirements
for the degree of Masters of Science

THE UNIVERSITY OF ADELAIDE
Faculty of Science

- December 1998 -

Table of Contents

Chapter 1: General Introduction

Chapter 2 Designing a Biomonitoring Program for the Rocky Intertidal Region: A Review

Chapter 3: Pilot Study Investigation of Rocky Intertidal Areas in Gulf St Vincent

Chapter 4: Monitoring of GSV Study Sites for Spatial and Temporal Trends

Chapter 5: Modelling of an Oil Spill at Port Stanvac

Chapter 6: Selection of a Bioindicator

Chapter 7: The impact of Trampling on Rocky Intertidal Animals

Chapter 8: Recommended Ongoing Monitoring Design for Mobil, Port Stanvac

Appendices

Masters Thesis Abstract

"An Intertidal Monitoring Program for Mobil, Port Stanvac (South Australia): Anthropogenic Versus Natural Disturbance".

A problem associated with operation of Mobil's Port Stanvac Oil Refinery, situated in Gulf St Vincent (GSV), South Australia, is the accidental release of oil into the marine environment. If this occurs, the adjacent rocky coastline is likely to be impacted. A challenge in this situation is to partition the variation associated with an oil spill from that arising naturally or from other human induced disturbances (such as recreational pressure). This thesis focuses on the development and implementation of a monitoring program for Mobil, Port Stanvac.

The thesis includes a number of phases. Initially a pilot study and a literature review were completed; the latter to outline pertinent characteristics of GSV, review the impacts of oil and identify appropriate monitoring designs and biomonitoring techniques. A preliminary study focused on temporal and spatial patterns in the intertidal assemblage in GSV. This was followed by computer modelling of the fate of oil spilt from the Port Stanvac refinery and an investigation of the effectiveness of *Bembicium nanum* as a bioindicator animal. It was likely that trampling could be a confounding influence at study sites and the impact of this perturbation was experimentally investigated. Finally, the outcomes of these phases were used as a basis for designing and initiating an ongoing monitoring program.

Pilot Study

The mid-eulittoral section of a number of sites within GSV were sub-divided into two 'zones' ('upper' and 'lower') and sampled for dominant intertidal biota. These were identified and counted and those physical parameters likely to influence distribution and abundance were concurrently measured. Various census methods were also trialed. The pilot study identified nine sites for further monitoring and indicated the most efficient sampling methods to be used for the remainder of the study.

Literature Review and Selection of a Monitoring Design

The literature review established that although confounding factors (e.g. dredging, stormwater outfalls, the Christies Beach wastewater outfall and recreational shore use) were operating in GSV their impact on the selected study sites was likely to be minimal.

A "Beyond-BACI" monitoring design (see Underwood 1992[1]) using a population level focus and an appropriate bioindicator was used during preliminary monitoring so that if a perturbation intervened its effect could be assessed statistically. The spatial scale of relevance to a 'moderate' operational oil spill was at the level of the 'reef' (or equivalent region on the rocky shore) and the temporal scales of interest were weeks (designated 'Times') and seasons (designated 'Periods'). The two errors (α and β) which can arise during a statistical analysis were considered equally undesirable and were set *a priori* to 0.05.

---

[1] Underwood, A.J. (1992) Beyond BACI: The detection of environmental impacts on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* **161**, 145-178.

Preliminary Study

Selected sites were monitored for 15 months (commencing in February/March 1995) using sampling protocols identified as optimal in the pilot study. Owing to a paucity of intertidal macroflora the study concentrated on the spatial and temporal patterns of the intertidal animal assemblage, an approach which was necessary as no *a priori* indicator species had been identified.

Preliminary sampling highlighted enormous spatial and temporal variability in the intertidal assemblage. This variability obscured identifiable seasonal trends apart from increased variability in winter and spring. Despite differences in assemblage structure most sites were dominated by the small gastropod *B. nanum*.

Two disturbances intervened during the preliminary study; northward sand drift, which resulted in severe decimation of assemblages at one site, and a ruptured refinery effluent pipe. A "Beyond-BACI" assessment of the effects of these perturbations on the abundance of *B. nanum* detected a significant effect at the longest temporal scale of 'Before-After' in the case of the sand perturbation only. However, the analytical power to detect impacts at the temporal scales of 'Times' and 'Periods' was lower than desired due to the early intervention of the two perturbations and confounding effects caused by storm mobilisation of substrata at a number of 'control' sites.

<u>B. nanum</u> - a useful Bioindicator

The abundance of *B. nanum* and its usefulness in investigating the 'unplanned' perturbations during the preliminary study suggested it may be a useful bioindicator for the monitoring program. Its sensitivity to fresh Arabian light crude oil and Mobil petroleum was therefore assessed experimentally. No mortality resulted when *B. nanum* individuals were exposed to small doses of either type of oil for a short time. However, significant behavioural changes (including loss of adherence) were noted and this could potentially manifest as a population level response to oiling. Therefore, *B. nanum* was recommended as the bioindicator of choice for inclusion in the monitoring program.

Modelling of Oil Transport

To optimise site choice for the monitoring program likely oil spill grounding sites needed to be predicted. This was done using the 'FLOWM' Model of Dr. J. Bye (Flinders University) to produce computer simulations of oil transport under various tidal and seasonal conditions. The model parameters were validated and refined on the basis of an oil spill at the refinery in September 1996. Seasonal simulations revealed some trends but considerable variation in the location and extent of oiling depending on the timing of oil release and prevalent wind, wave and tidal conditions. Therefore, the maximum possible number (and spread) of study sites for inclusion in ongoing monitoring was advocated.

Confounding Factors

Trampling was identified as the primary disturbance associated with recreational shore use. To quantify this a number of trampling experiments were conducted targeting gastropods in the 'bare' substrata characteristic of the majority of the GSV sites. These animals were not sensitive to trampling at low intensities, implying that the trampling levels associated with monitoring were not likely to significantly impact on assemblages at study sites. However, under heavy 'weekend' and moderate 'school-holiday' trampling regimes reduced abundances of small *B. nanum* were seen.

Ongoing Monitoring

The results from the previous phases led to recommendations for an ongoing monitoring program using a "Beyond-BACI" design and incorporating two temporal scales of sampling in the 'upper' zone at eight 'stable' sites in GSV. The abundance of *B. nanum* in each of four size classes was the biological variable of interest and it is recommended that this is assessed in conjunction with substrata composition and the degree of oiling prevalent at selected study sites.

The oil induced effect size to be detected by the monitoring program is a 50% greater change in the abundance of *B. nanum* (excluding very small settlers) than occurs (on average) in the set of 'control' sites. One sampling run was completed prior to the project being handed over to Mobil.

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university and, to the best of my knowledge and belief, it contains no material previously published or written by another person except where due reference or acknowledgment is made.

I give my consent to this thesis being made available for photocopying and loan.

Signed: Date: 17/3/99

Acknowledgments

I would like to dedicate this thesis to my husband Trevor Shirlock and our twins; Amy and Chelsea. The girls slowed me in the writing-up of this project when they were still *in utero* but that was nothing compared to the distraction they became (although a welcome one) once they were born. The only way I was able to finally finish this thesis was by calling in the cavalry (e.g. my parents, husband and parents-in-law) for some pretty intensive stints of babysitting.

There were many people who facilitated completion of this thesis. Firstly, I would like to thank my supervisors, Assoc. Prof. A. Butler, Prof. R. Baudinette and lastly (but by no means least) Dr F. Sheldon. Fran has been a great source of encouragement especially during the tedious 'writing-up' phase of this project and I can not thank her enough. I would also like to thank Brenton Stead, John Bloomfield and Michael Cove who were my Mobil contacts. Thanks also to Dr Bye for allowing me to use his 'FLOWM' Model. He is truly a gentleman and spent numerous hours explaining the model, adjusting some of its parameters and solving problems which arose as we adapted it to suit an oil spill situation at Port Stanvac. I would also like to thank Dr A. J. Underwood, Dr K. Walker, W. March, J. Carey, P. Petrusevics and P. Pfennig for their expert help and advice and the National Tidal Facility (Flinders University) for supplying relevant data. Wendy March, in particular, has been a great source of inspiration. In addition, the "Flinders Ranges Group"; Dr Andrew Boulton, Sandra Grinter, Sam Wade and Peter Schultz have been great mates and have always offered me encouragement and a kick when necessary. I wish Sandra and Sam luck with completion of their respective projects and must add that we had all better write up journal papers soon or Uncle Andrew won't be happy! In addition, I would like to thank Andrew Boulton and Marg Davies for teaching me a lot during 'honours'. They gave me a good research grounding on which to base this and future research work.

Field work involves field assistants and I am very grateful to the many hours put in by Brian Piller and Michael Maros who were diligent assistants. Yvette Piller and Trevor Shirlock were also valuable field workers. The Zoology Department at The University of Adelaide has been a great place to work both during my honours year and then while completing my Masters Thesis. In actual fact I think it must have been too great and the people much too nice as I seemed to have difficulty finishing up my work and finally saying goodbye. I would like to thank all past and present members of the Zoology Department, but particularly Dr M. Davies, Dr S. Barker, Brydie Hill, Colin Bailey, Steve Walker, Steve Milne, Emma Cronin, Melissa Bradbury, Sue Graham, Marielle Janssen, Tara Ingerson, Craig Styan, Jo Strzelecki, Nupur Goundar, Gail Edwards, Denae Wade, Piers Brissenden, Phil Kempster, Dr R. Seymour, Adrienne Burns, Stuart Blanch, Jim Puckridge, James Wallman, David Williams, Dr D. Paton and Assoc. Prof. M. Geddes for making my time in this place stimulating and enjoyable.

This project was supported by APA and CEED scholarships and I would like to thank CEED project managers who assisted with provision and management of the latter scholarship and Mobil for supplying the funding.

List of Figures

Figures Description Page

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

List of Tables

Chapter 5

Chapter 6

Chapter 7

Chapter 8

List of Plates

Plates Description Page

Chapter 3

Chapter 4

Chapter 5

Chapter 8

List of Appendices

Chapter 1 General Introduction

This thesis concerns the development of a monitoring program for Mobil's Port Stanvac Oil Refinery. In designing an effective monitoring program it is necessary to understand the pollutant or activity that is to be detected and the likely effects it may have on the area and biota it contacts.

Mobil operates a coastal oil refinery within Gulf St Vincent (GSV). A potential hazard of their operation is the accidental release of crude or refined oil into the marine environment. In the event of an operational oil spill it is likely that the rocky intertidal area which dominates much of the immediate coast will be affected. Therefore, the monitoring program will focus on the rocky intertidal zone, in particular its structure and ecology and how it is likely to be changed by an oil spill.

1.1 Monitoring to Detect an Environmental Impact

In this era of technology and urbanisation, environmental disturbance by humans is increasing. Freshwater and marine communities are especially susceptible to human induced perturbation and are frequently exposed to a range of activities which can modify underlying biological patterns and processes (Keough and Mapstone 1995). The risk of increased environmental disturbance has been tracked by a growing public awareness of the problem (Fairweather 1993). Many countries have introduced legislation requiring the implementation of monitoring programs to detect environmental change, a trend which has stimulated the development of suitable monitoring techniques (Millard *et al.* 1985, Glasby 1997). However, the design of programs to detect environmental disturbances has not matched the increasing demand for their use (Underwood 1989 & 1991a). An interesting development in monitoring programs (see Chapter 2) is the shift in emphasis from disturbance induced change at the level of the organism to population level (Emlen 1989) and assemblage level (e.g. Warwick and Clarke 1993) effects.

Anthropogenic activities which result in environmental disturbances can be defined as any human related processes which place stress on a system (Underwood 1989).

These activities fall into a number of categories including planned developments, services required by the public, such as treatment and release of sewage, recreational activities, such as trampling on a rocky shore, or exploitative activities, such as fishing (Fairweather 1990, Keough and Mapstone 1995). An additional category is reserved for random or accidental events, such as oil spills, which are difficult to monitor due to their unpredictable nature (Michener 1997). However, despite this difficulty, a way of rapidly, reliably, and cost-effectively monitoring and detecting the ecological impacts of human activities on natural populations is needed (Underwood 1992, Osenberg and Schmitt 1996, Michener 1997).

In order to assess how an environmental disturbance has impacted a system it is necessary to compare the perturbed and unperturbed states and to have an understanding of the intrinsic patterns and processes underpinning natural systems (Karr 1987). Techniques which allow such comparisons include measuring the physico-chemical composition of discharges, investigating biochemical, cellular and physiological responses in organisms, and implementing field based sampling programs focusing on biological monitoring at the population or assemblage level (Keough and Mapstone 1995, Osenberg and Schmitt 1996).

Biological monitoring is used in the belief that sampling the biota provides information on the condition of the ecosystem under examination (Herricks and Cairns 1982, Underwood 1995a). The collection of appropriate field data is the best way to provide evidence about a disturbance and assess whether an impact has occurred (Keough and Mapstone 1995, Underwood 1995a & b). However, it is only by focusing on how an activity affects biota at population or higher levels that the ecological implications of a perturbed habitat can be interpreted in a meaningful way (Underwood 1995a).

Monitoring programs can be tailored to serve a variety of purposes. They can provide a tool for assessing the condition of the environment or promoting its conservation, prevent environmental damage by providing feedback which enables management to avert deleterious change, and can play a role in assigning responsibility for damage (Constable 1991, Peterson 1993). However, regardless of the use which is to be made of results from a monitoring program, its primary function must be to detect the impact it was designed to detect (Lewis 1978, Underwood 1991a). This central need has fuelled the refining of monitoring designs from those outlined by Green (1979) through to the complex Beyond-BACI designs advocated by Underwood (1991a, 1992 & 1993a). These designs all place a heavy emphasis on the importance of formal statistical methodology as opposed to 'descriptive' monitoring techniques (Stewart-Oaten 1996).

1.1.1 Scope and Objectives of Monitoring

A monitoring program must be able to yield clear evidence about the magnitude and existence of 'real' environmental impacts. This requires an understanding of what variations, e.g. in population parameters, would be expected under perturbed and unperturbed conditions, and under the influence of 'trivial' and 'important' perturbations (Stewart-Oaten 1996). The response variables chosen for this task should ideally be easy to measure and sensitive to the impact but relatively stable in the unimpacted state (Keough and Mapstone 1995).

Variability and Temporal and Spatial Scales

An inherent characteristic of natural systems is their stochastic nature (Osenberg and Schmitt 1996, Roberts *et al.* 1998). This variability is independent of a perturbation although it may be exacerbated by such an event. A system with high intrinsic variability can generate a 'noisy' signal which may obscure trends associated with a disturbance (Underwood 1993a), or even exaggerate the 'true' impact related change (Hilborn and Stearns 1982). This occurs because in any natural system multiple, unsuspected factors can be modifying patterns and processes. The greater the natural variability the more difficult it becomes to separate impact induced change from the background fluctuations, and the more costly and extensive the monitoring design needs to be to achieve this separation (Keough and Mapstone 1995).

Variability in a system operates over a range of spatial and temporal scales (Thrush *et al.* 1996). It can also manifest as a time and space interaction which results in alterations in the time course of abundances of populations in different locations (Underwood 1992). A poorly designed monitoring program is one which ignores a high level of background variation, is too sensitive to a biologically insignificant impact, or is not sensitive enough to detect a biologically important event (Keough and Mapstone 1995). To be effective a monitoring program needs to be fine-tuned so that its ability to detect a change (its power), is balanced against the size of the impact to be detected (the effect size). These considerations also need to be weighed against the costs of running the monitoring program.

A well designed monitoring program needs to focus at temporal and spatial scales which are relevant to a particular perturbation. This can only be achieved if the temporal and spatial scales over which a perturbation is likely to operate are predicted and then related to underlying processes which may be affected by the perturbation (Karr 1987, Underwood 1991a, 1992, 1993a & 1994a). Only when this has been achieved can variations and patterns seen in monitoring data which are coincident with a perturbation be partitioned from the background variability (Andrew and Mapstone 1987).

Clearly, the major focus of a monitoring program should be the functional scale at which a particular organism (or assemblage) is likely to respond to its environment (Andrew and Mapstone 1987, Young 1990). However, the source of observed variation in sampling programs is often linked to processes operating at several scales (Underwood and Kennelly 1990, Karlson and Hurd 1993). This means that the spatial and temporal scales utilised in the sampling schedule can affect the results and how they are interpreted (Millard *et al.* 1985, Young 1990, Ward and Jacoby 1992, Thrush *et al.* 1996). This problem can be addressed by optimising a monitoring program to incorporate a range of temporal and spatial scales. Underwood has succeeded in this undertaking in his asymmetrical, repeated measures (Beyond-BACI) monitoring designs which have established a statistically rigorous way of monitoring and testing for disturbance induced effects at least under certain circumstances.

In order to identify the appropriate functional and therefore spatial and temporal scales over which a perturbation is likely to be felt, computer modelling can be utilised. Processes like physical transport (of contaminants and larvae) and life history parameters of indicator populations (such as longevity, age structure, rates of reproduction and mortality) can be modelled and used to identify the scales of importance for a particular animal or community and contaminant (Walters 1993).

1.1.2 The Importance of Baseline Studies

An environmental impact, for the purpose of this project, can be viewed as a change in the environment over a given period of time as a result of direct or indirect human activity (Keough and Mapstone 1995). To be able to detect an environmental change the baseline condition of the area of interest needs to be established and used as a yard-stick against which anthropogenic changes can be assessed in context (Ward and Jacoby 1992, Jan *et al.* 1994). However, since the underlying ecological processes in a community are often slow and complex, a long-term data set is recommended. This is particularly necessary when monitoring rocky shores where 10 years of data may be needed before trends can be identified against the high inherent background variability (Jan *et al.* 1994). A shorter sampling time may not only fail to show clear patterns but may also give misleading results (Southward 1991). Baseline data can be used to assess variation at a range of scales and can be useful in optimising the sampling design of a monitoring program, for example by aiding in selection of the number of locations and replicates needed given the 'natural' variability of the system (Underwood and Kennelly 1990).

It is important that clear decision criteria are defined well before a monitoring program is implemented. For example, the magnitude and direction of change that is expected in association with a particular perturbation should be discussed at an early stage (Keough and Mapstone 1995). The level of change that is to be tolerated also needs to be defined *a priori*. Only then can the observed change be compared to the baseline data. This avoids a biased monitoring program and prevents a *post hoc* subjective allocation of effect size.

1.1.3 The Relationship Between Cause and Effect

Many monitoring programs which have successfully detected an 'effect' in response to a particular activity fail to clearly establish a link between the perturbation and the observed change (Underwood and Peterson 1988, Underwood 1991a, Beyers 1998). Another problem is the focus of monitoring programs on changes (in particular decreases) in the average abundance of organisms. A decline in population abundance can occur in response to an impact. However, it is also possible that a disturbance of 'intermediate' magnitude can trigger an increase in diversity and possibly increased abundance of certain opportunistic species (Connell 1978, Sousa 1979a & b, Underwood 1995a & b). Therefore, any change (either increase or decrease) in population means that correlates with a perturbation must be considered as an environmental impact (Underwood 1991a).

In addition to abundance changes disturbances may result in altered variability within a natural system. For example, Warwick and Clarke (1993) detected increased variability in meiobenthos experimentally exposed to organic enrichment and concluded that this can be a characteristic of stressed assemblages. Increased variability may be attributed to changes in the population structure of individual species or may occur when a stressed assemblage is replaced by a new suite of organisms (Chapman *et al.* 1995). Altered temporal variability in a perturbed natural system can arise as changes in the frequency or timing of major population parameters, such as recruitment of juveniles into a coastal population (Underwood and Denley 1984, Underwood and Fairweather 1989), trigger a reactive response which results in changes in the rate or magnitude of fluctuations in organism abundance around the 'long-run' averages (Underwood 1991a). Monitoring procedures which focus on altered abundances alone may fail to detect such an impact.

1.1.4 Summary

In summary, it is known that the intertidal area is particularly susceptible to anthropogenic perturbation but its inherent stochasticity makes identification of changes specific to a particular disturbance difficult to quantify (Jan *et al.* 1994). Variation in intertidal assemblages can manifest as spatial patchiness and fluctuations in species abundance over time in response to such processes as unpredictable recruitment. Disturbance induced fluctuations may manifest in a susceptible population as increased temporal variance or alterations in the time courses of organisms, as well as being reflected by simple changes in the average abundances of a stressed population (Underwood 1991a).

A monitoring program capable of detecting anthropogenic change against a 'noisy' background requires a clear link between the sampling variable and the disturbance, a long-term data set and a design which is able to partition the variation of interest (whether it manifests as an altered variance or a change in the abundance of a target species) from natural variation (see Chapter 2).

1.2 Background to the Project

To design an effective monitoring program for Mobil's Port Stanvac Oil Refinery it was necessary to consider the dynamics and general characteristics of GSV. The physical oceanography, coastal topography and the main coastal substrata types required consideration to place the project within a broad context before a finer focus could be achieved. A review of information relating to the study area in GSV, oceanographic characteristics (such as wind and tidal action) and the type of coastline which dominates GSV in the vicinity of the refinery was used as background information for this project (Appendix A). The location of the refinery within GSV, a brief history of refinery operation, disturbances which have occurred in the region and previous studies of local biota were also of relevance to this project and have been reviewed in Appendix A. An overview of the information contained in Appendix A will now be given.

GSV is a shallow marine basin which forms an *inverse estuary* with limited water exchange with the open ocean (Appendix A: Fig. A.1). Adelaide is situated on the eastern side of the Gulf and impacts on the coast through such activities as effluent discharges and recreational use of the shore. GSV has a large spring to neap tidal range and characteristically has higher mean sea levels in winter than in summer (Womersley and Edmonds 1958).

Wind is known to influence tidal range and is the main determinant of general water circulation (Bye 1976). Since oil is a surface born contaminant, wind direction and strength are expected to have an important role in its transport. In GSV the wind tends to be mainly south to south-east in summer and south-west to north in winter (Petrusevics 1990). Mathematical models have been used to simulate tidal elevations and currents and predict circulation patterns in water bodies (including GSV) under varied tidal and wind conditions (see Appendix A: Fig. A.2). The modelling work of Marcus Grzechnik (Adelaide University) specifically addressed the transport of oil in GSV but was not at a useable stage when a monitoring design was being formulated. However, the 'FLOWM' Model of Dr John Bye (Flinders University) was adjusted to enable predictions of the passage and ultimate destination of oil spilt in the Gulf (see Chapter 5).

Oil spilt at Port Stanvac is likely to ground along the eastern coast of GSV. To the north of the coast the shore tends to be relatively sheltered but south of Port Stanvac the steeper coastal gradient typically results in higher energy exposure and stronger current velocities, particularly in winter (Womersley and Clarke 1979, Coast Protection Board 1984). However, the breakwater and reef at Port Stanvac and offshore reefs at Port Noarlunga decrease the incident wave energy experienced by these regions which will in turn affect the transport of oil to the shore and its persistence on the shore. This illustrates the importance of considering coastal topography in predicting oil transport and ultimately the fate of grounded oil.

The coastline in the vicinity of the Port Stanvac Oil Refinery is characterised by rocky headlands interspersed by irregular wave cut platforms and sandy beaches (Womersley and Clarke 1979). Another feature of the coast is the presence of boulder and cobble littoral deposits at the bases of many of the cliffs (Shepherd and Sprigg 1976). Both mobile rocky substrata (such as boulder and cobble) and the more stable substrata afforded by bedrock reefs and platforms found intertidally house a range of animals and plants which are most at risk of damage should an oil spill occur near Port Stanvac.

The Port Stanvac Oil Refinery receives crude oil for refinement and exports refined oil and other products (such as lubricants). The primary points where oil can be spilled are the 'Deep Ocean Point' (or crude marine berth), the 'Wharf Point' and the pipeline that leads into the refinery (Appendix A: Fig. A.3). A procedural oil spill did occur from the 'Deep Ocean Point' on the 23rd of September 1996. This event was used as a 'modelling pilot study' to validate the 'oil transport modelling' component of this project and to investigate oil induced changes in the intertidal assemblage (refer to Appendices A & B and Chapters 4, 5 & 6).

A number of factors other than an oil spill potentially impact the eastern side of GSV in the vicinity of Port Stanvac (Appendix A: Fig. A.4). These include natural northward sand drift in winter and spring, sewage discharge from Christies Beach, the Mitsubishi stormwater discharge and the addition of pollutants from Christies Creek and the Onkaparinga River (Appendix A: Table A.1). Within the refinery localised sand dredging (Appendix A: Fig. A.5) and refinery effluent discharge may also result in coastal impacts.

A few studies have been conducted in GSV which proved useful as background information for this project. Perhaps the most relevant of these were the surveys conducted in 1979, 1980 and part of 1981 by Womersley. Womersley (1988) recorded the intertidal biota present in the region and attempted to establish their abundance and seasonal patterns over the period of the study. Biota abundance tended to fluctuate markedly on a seasonal basis but extreme variability in organism abundance between years was also found. This work highlighted the need for a long term data-set to establish trends against the large background variability characteristic of the intertidal region generally.

1.3 Thesis Plan and Aims

1.3.1 Significance

This project will provide Mobil with a method of independently assessing the effects of an operational oil spill using an appropriate monitoring program and indicator species. Mobil is aware that an oil spill is a potential hazard associated with the operation of their Port Stanvac plant and is prepared to take responsibility for this as indicated by their support of this research. Since not all changes following an oil spill would be attributable to the spill, this project allows the statistical separation of effects 'due' to the spill from incidental or 'noise' related changes.

In the event of an oil spill occurring, the monitoring program will allow Mobil to have an objective discussion with relevant environmental bodies. It will also enable them to mount a defence in response to any charges that are laid and minimise the cost impact of such charges. Mobil has a desire to have an environmental conscience and to consider the environmental consequences of their activities. These needs will be met by an ongoing biological monitoring program. Mobil ultimately aims to use the monitoring program to help meet Australian environmental standards in their operations and practices.

This project also provides a means of monitoring coastal recovery following an oil spill and of assessing any subsequent clean-up operations that are implemented. Additionally, in its pre-impact stages the project will allow assessment of effects on intertidal biota related to the private ownership of the refinery site. Any trends which appear to be associated with this private ownership (such as a lifting of trampling and collection pressure on susceptible biota) can then be tested experimentally.

1.3.2 Aims

The project aimed to establish the existing condition of the intertidal area at Port Stanvac. This baseline could then be used as a starting point for designing an ongoing monitoring program using suitable bioindicators. The monitoring program needs to partition variation due to the other pollution sources mentioned from those statistically attributable to an oil spill. To achieve this it was necessary to investigate the temporal and spatial trends seen at various sites within GSV. In addition, the project aimed to investigate the effects of recreational shore use. This component of the project focused on the impact of trampling (in particular) and collection pressure on some of the more common intertidal animals. Two experiments were specifically designed to investigate the effects of trampling. In optimising the design of the planned monitoring program another aim was to identify suitable control and impact sites within GSV. This could only be achieved by using a computer model to predict the most likely sites of oil spillage and grounding.

Specifically, this thesis addressed the following questions:

1. What type of monitoring design recommended in the literature could be adapted to test for an intertidal oil spill impact?
2. What was the baseline (existing) condition of the intertidal region at Port Stanvac and other regions along the eastern coast of GSV?
3. What was the most appropriate bioindicator (or bioindicators) to use in monitoring for an oil spill impact and what other parameters should be assessed concurrently?
4. What spatial and temporal trends were exhibited by biota in coastal areas of GSV?
5. What influence does pollution, such as Mobil's dredging spoil, the Mitsubishi storm water outflow and the Christies Beach wastewater discharge, have on the coastal region and particularly the selected bioindicator?
6. What was the effect of recreational use of coastal regions on intertidal assemblages and the selected bioindicator?
7. What recommendations, taking into account the information generated by questions 1-6, can be made to Mobil concerning all aspects of the monitoring design?

1.3.3 Project Overview

The project was conducted in six phases as outlined below.

Phase 1: Pilot Study

- Rocky intertidal sites within GSV were visited.
- Sites were assessed on the basis of their assemblages, topography and accessibility for suitability as monitoring sites.
- Data sheets and a photographic key of relevant animals and plants were compiled.
- Potential sampling strategies were assessed.

Phase 2: Preliminary Study

- Optimal sampling strategies from phase 1 were adopted for use in a longer-term preliminary study.
- A monitoring program was selected to track temporal and spatial changes in the intertidal assemblage at selected sites over a period of approximately 15 months. The design was chosen on the basis of a literature review of monitoring techniques.
- The monitoring design and sampling strategies were chosen to be such that if a disturbance intervened a test of the monitoring design, and the impact, could be made.
- This phase also allowed investigation of the potential influence of confounding factors which may confuse changes associated with an oil spill.
- The recreational use of study sites was monitored during the preliminary study.

Phase 3: Modelling of an Oil Spill at Port Stanvac

- This involved using models developed by Dr J. Bye (Flinders University) to attempt to predict the most likely grounding sites of oil spilt near Port Stanvac.
- Predicted seasonal grounding sites were examined assuming oil was released from the 'Deep Ocean Point' or the 'Wharf Point' (see Appendix A: Fig. A.3) at various times within a simulated tidal cycle.

Phase 4: Choice of Bioindicators

- The suitability of potential indicator (animal) species were examined with particular reference to their abundance, spatial distribution and behaviour (e.g. preference for the 'top' and 'undersurface' of mobile substrata).
- The species which met the main bioindicator criteria was then tested experimentally for a 'cause-and-effect' relationship with Arabian light crude oil and Mobil refined product (petroleum). Exposure to these two forms of oil was of short duration and only acute (immediate) effects were investigated.

Phase 5: The Effect of Trampling on Intertidal Animals

- The impacts of acute trampling on susceptible animals were examined using multivariate and univariate analyses.
- Two acute trampling experiments were performed, the first simulating the type of foot traffic that might be encountered on a busy shore over a weekend, and the second simulating the type of disturbance that might occur over a two-week school holiday period.

Phase 6: Recommendations and Implementation of the Ongoing Monitoring Program

- The outcomes of the previous phases were combined to enable recommendations for the ongoing monitoring program to be made.
- Study sites were redefined where necessary and the first run of the ongoing sampling schedule was implemented.
- The data obtained were examined so that final adjustments to the monitoring design could be made.

1.3.4 Thesis Plan

The overall structure of the thesis and its development is shown in Fig. 1.1. The thesis builds on a general introduction to monitoring and examination of characteristics of GSV (Chapter 1 & Appendix A), with a literature review of monitoring designs (Chapter 2). In addition, general reviews on the character of the intertidal zone, activities which impact on this region (including trampling and collection), oil and its behaviour when spilt and the effects of oil on intertidal biota were undertaken (Chapter 2). Bioindicator species and the use of bioindicators were also reviewed as background material to assist in designing a suitable monitoring program for Mobil, Port Stanvac (Chapter 2).

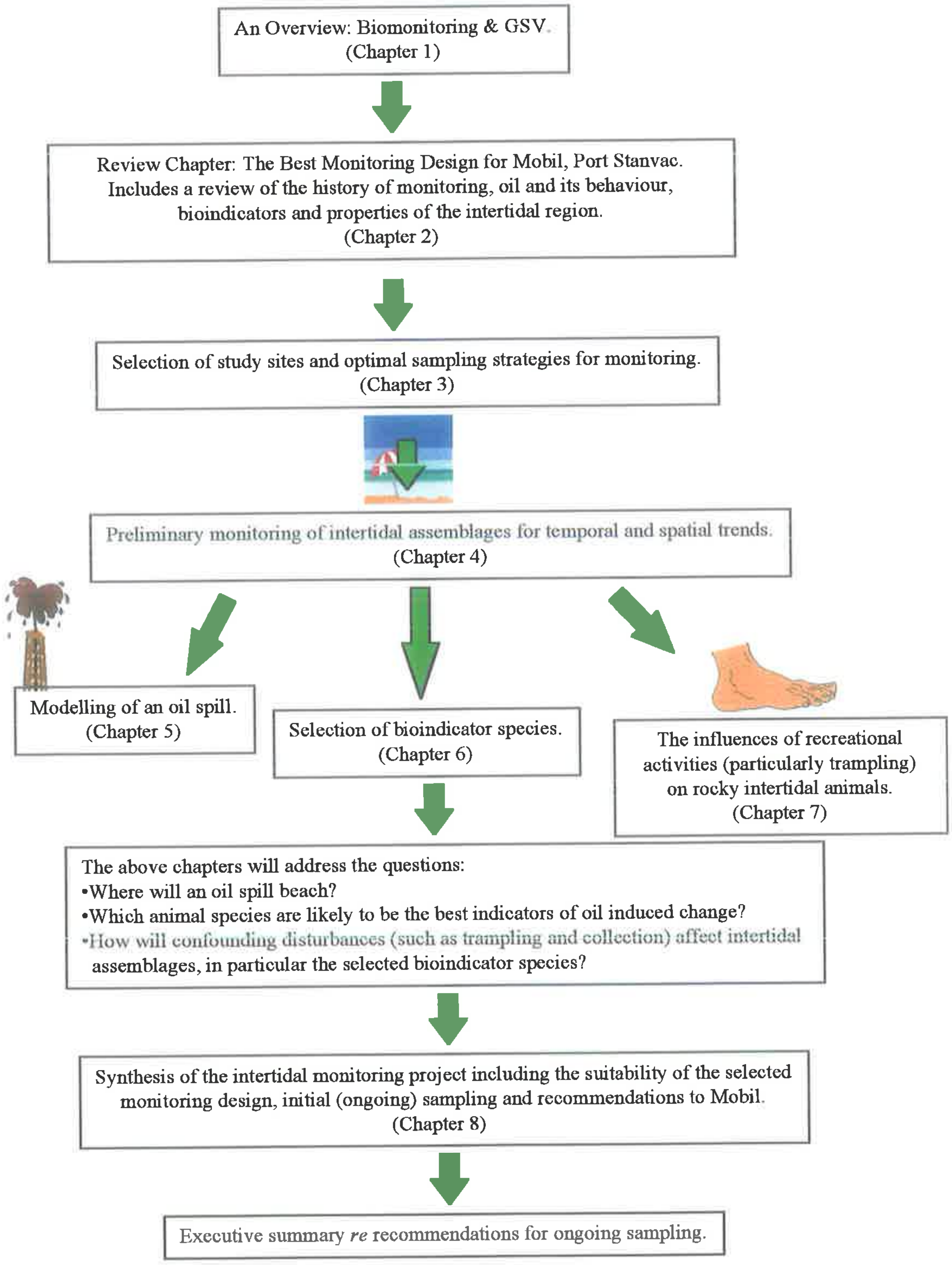
The suitability of specific study sites and identification of appropriate sampling protocols forms Phase 1 of this project and was investigated in Chapter 3. Chapters 1-3 were then used to generate a tailored monitoring program and optimal sampling protocols for use in a 15 month preliminary assessment of spatial and temporal trends (focusing on animal assemblages) at study sites within GSV (Phase 2, Chapter 4). The preliminary investigation allowed some quantification of confounding factors which were operating in GSV. Recreational use of the study sites was also addressed during preliminary monitoring (Chapters 4 & 7).

It was apparent that three separate lines of investigation needed to be followed in this thesis in order to select the most appropriate monitoring design to suit Mobil's needs. The first involved determination of where spilt oil was likely to ground, the second involved the selection of a suitable indicator species to detect an oil impact, and the final line of investigation involved assessment of how recreational site use (in particular trampling) was likely to affect intertidal assemblages and the selected bioindicator.

The first line of investigation was undertaken in phase 3 of the project which used computer modelling to predict the most likely sites where oil spilt from the refinery would ground (Chapter 5). The oil spill which occurred on the 23rd of September was used to validate the model and was also discussed in terms of its biological consequences (Chapter 6). Following validation of the 'FLOWM' Model, seasonal modelling was performed to predict the likely seasonal grounding sites of oil along eastern GSV. This was intended to maximise the likelihood of inclusion of an 'impact' site in the suite of selected sites for ongoing monitoring (Chapter 5).

The suitability of different intertidal animals as oil spill bioindicators was investigated in Chapter 6. This chapter includes two experiments addressing the susceptibility of the most 'appropriate' bioindicator to acute crude oil and petroleum exposure (Phase 4). Trampling and other recreational activities were identified as perturbations which could potentially confound a monitoring program and these required further investigation (Phase 5). Recreational site use was censused and two trampling experiments were completed (Chapter 7).

The outcomes of Chapters 1-7 were synthesised to enable final recommendations for an ongoing monitoring program for Mobil, Port Stanvac (Phase 6, Chapter 8). The initial sampling results and the suitability of the selected monitoring design for detecting an operational oil spill in the region are discussed in Chapter 8.



An Overview: Biomonitoring & GSV.
(Chapter 1)

Review Chapter: The Best Monitoring Design for Mobil, Port Stanvac. Includes a review of the history of monitoring, oil and its behaviour, bioindicators and properties of the intertidal region.
(Chapter 2)

Selection of study sites and optimal sampling strategies for monitoring.
(Chapter 3)

Preliminary monitoring of intertidal assemblages for temporal and spatial trends.
(Chapter 4)

Modelling of an oil spill.
(Chapter 5)

Selection of bioindicator species.
(Chapter 6)

The influences of recreational activities (particularly trampling) on rocky intertidal animals.
(Chapter 7)

The above chapters will address the questions:
- Where will an oil spill beach?
- Which animal species are likely to be the best indicators of oil induced change?
- How will confounding disturbances (such as trampling and collection) affect intertidal assemblages, in particular the selected bioindicator species?

Synthesis of the intertidal monitoring project including the suitability of the selected monitoring design, initial (ongoing) sampling and recommendations to Mobil.
(Chapter 8)

Executive summary *re* recommendations for ongoing sampling.

Fig. 1.1 A flow chart showing the stages involved in developing a suitable monitoring program for Mobil, Port Stanvac and how they relate to the chapters in this thesis.

Chapter 2.
Designing a Biomonitoring Program for the Rocky Intertidal Region: A Review

2.1 Introduction and Aims

The rocky intertidal zone is the area of the coast which is dominated by rock substratum, and extends from above the mean high tide level, where it is covered by seawater only during extremely high tides or receives water as splash only, to below mean low tide level, where it is emergent between waves or during very low tides (Womersley and Thomas 1976). It is an extreme and dynamic place, characterised by temporal (e.g. tidal fluctuations) and spatial (physical habitat) variability. The distribution of biota inhabiting this variable environment tends to be physically defined by their tolerance to the range of conditions they experience on the shore and the adaptive mechanisms (such as clamping shut during air exposure, aggregating in crevices or under rocks to avoid desiccation, and strategies to maintain their position when exposed to heavy wave action) they utilise to cope with the conditions. The range of adaptive strategies adopted by biota to face the extreme conditions superimposes further layers of diversity and heterogeneity on the area.

The rocky intertidal zone is also a region of concentrated human disturbance due to the tendency of humans to live around the coast, particularly in Australia. Isolating the impact of human disturbances (such as trampling, sewage discharges and collection of intertidal animals) from the background variability of the rocky intertidal zone can be an extremely difficult and challenging task (Keough and Quinn 1998). One particular human disturbance affecting the rocky intertidal zone is localised oil spills from refineries, which can result in a variety of effects on coastal areas and their biota.

In the event of an oil spill occurring from the Port Stanvac Oil Refinery it is likely that the rocky intertidal zone and its biota will be perturbed. As mentioned previously, it can be difficult to isolate variation associated with a particular perturbation from inherent variability, and even more difficult to isolate the impact of this one event from other human impacts operating locally. This is particularly so with the Port Stanvac Oil Refinery, situated in Gulf St Vincent (GSV), where numerous confounding disturbances (both natural and anthropogenic) are operating (Appendix A). One way of detecting an impact in the event of an oil spill is to establish an ongoing monitoring program.

With respect to designing a monitoring program for the Port Stanvac Oil Refinery, the aims of this chapter were to:

- Review the characteristics of the rocky intertidal zone.
- Examine natural disturbance in the rocky intertidal zone.
- Examine human impacts, particularly those pertaining to an oil perturbation, in the rocky intertidal zone.
- Review aspects of oil as a pollutant.
- Review monitoring programs and techniques that may be suitable for oil spill monitoring and adapted to enable assessment of oil impacts in the rocky intertidal zone in and around Port Stanvac.

Tailoring a monitoring program to suit the specific requirements of the refinery requires an understanding of the area which is likely to be impacted (the rocky intertidal zone), and the mechanism of transport and characteristics of oil and its likely effects on biota and habitat; all within the context of existing methods of monitoring. Specific characteristics of GSV in the vicinity of Port Stanvac have been considered previously (Chapter 1 & Appendix A) but relevant generalised characteristics of the rocky intertidal region will be dealt with in this chapter. In addition, existing monitoring designs and the importance and use of bioindicators in monitoring will be considered. This information will provide background material for later chapters and will assist in the *a priori* selection of the monitoring design that would appear to best fit the needs of Mobil.

2.2 The Rocky Intertidal Region: A General Review

The rocky intertidal region around Port Stanvac is at risk of oil contamination and is the focus of the planned monitoring program (see Chapter 1). Therefore, it was necessary to review features of this region that could be of relevance (see Appendix C). An overview of some of the more pertinent intertidal characteristics will now be given.

2.2.1 Habitat Variability and Intertidal Zonation

The intertidal region is an extreme and dynamic habitat largely influenced by the action of tides and waves (Carefoot and Simpson 1977, Menge and Farrell 1989, Underwood 1994a, Underwood and Chapman 1995). These physical factors create temporal variability over a range of scales (hours, days, months and seasons) and this variability may be modified spatially on local (micro and meso) and regional scales (Black 1979, Underwood and Chapman 1995).

A number of vertical zones, defined primarily by the duration and extent of water coverage they experience during the tidal cycle, can be identified within the rocky intertidal region. For the purposes of this project I have used the classification system of Womersley and Thomas (1976) which recognizes four main zones; supralittoral, eulittoral, sublittoral and the sublittoral fringe. The eulittoral zone can sometimes be further divided into three distinct sub-zones; the upper eulittoral, the mid-eulittoral and the lower eulittoral. A description of intertidal zonation (including dominant biota) can be found in Womersley and Thomas (1976) and Appendix C.

A range of hard substrata types occur intertidally including; boulders (which are often interspersed with cobble, pebble or sand), reefs and rocky extensions of land-masses (Jan *et al.* 1994, Underwood and Chapman 1995). Additional physical variability in rocky areas can occur in response to the geological composition and the susceptibility to erosion of the rock (Underwood and Chapman 1995). The type of substrata found in the rocky intertidal region (e.g. stable reef-rock or mobile boulders) will interplay with such factors as shore exposure, ambient weather conditions and rock microtopography to determine the composition of assemblages colonising an area and their stability. However, biotic factors and disturbance are also important determinants of intertidal assemblage composition and structure.

The relative importance of biotic *versus* abiotic factors as they interact at a range of temporal and spatial scales can vary both within and between intertidal sites (Stephenson and Stephenson 1949, Dakin 1950, Womersley and Edmonds 1958, Lewis 1964, Stephenson and Stephenson 1972, Morton and Miller 1973, Underwood 1973, Emson and Faller-Fritsch 1976, Carefoot and Simpson 1977, Underwood 1978a & b & 1979, Underwood and Denley 1984, Underwood and Chapman 1989, Russell 1991, Jan *et al.* 1994, Schoch and Dethier 1996). For example, in a stable intertidal region factors such as competition and grazing (Sousa 1979a & b, Lieberman *et al.* 1984, McGuiness 1987a & b) are likely to be more important in structuring the assemblage than disturbance (Underwood and Chapman 1995).

2.2.2 The Importance of Planktonic Dispersal and Disturbance

Planktonic Dispersal

Important factors affecting the distribution patterns and composition of the intertidal assemblage and having major effects on adult population dynamics are planktonic dispersal, settlement and recruitment (Gaines and Roughgarden 1985, Butler 1987, Possingham and Roughgarden 1990, Gaines and Bertress 1992, Underwood 1994b, Richards *et al.* 1995, Underwood and Chapman 1995). A planktonic stage is a common lifecycle strategy used by intertidal animals. At large scales planktonic transport and dispersal is a passive process primarily influenced by ocean currents, tidal activity, wind and waves (Gaines and Roughgarden 1985, Underwood and Fairweather 1989, Underwood and Chapman 1995), but at smaller spatial scales active site selection responses can occur (see Underwood 1994b). Planktonic dispersal is both spatially and temporally variable and unpredictable and the numbers of new recruits arriving at a site are not influenced by conspecific adults or juveniles already present, nor by competition, predation or physical disturbance on the shore (Underwood and Fairweather 1989, Underwood 1994b, Underwood and Chapman 1995).

The importance of disturbance and recruitment limitation and their interaction as factors structuring intertidal assemblages have been demonstrated in a number of studies (Dayton 1971, Peterson 1979, Sousa 1979a & b, Paine 1984, Sousa 1984a, Gaines and Roughgarden 1985, Sutherland 1987).

Disturbance

Disturbance in the intertidal region can be of natural (e.g. violent destructive storm action) or anthropogenic origin (see Blake 1979, Ghazanshahi *et al.* 1983, Connell and Keough 1985, Sousa 1985, Durán *et al.* 1987, Liddle and Kay 1987, Castilla and Bustamante 1989, Underwood and Kennelly 1990, Fairweather 1991a & b, Kingsford *et al.* 1991, Keough *et al.* 1993, Underwood 1993b, Grigg 1994, Kaly and Jones 1994, Wynberg and Branch 1994, Underwood 1995a & b). Many anthropogenic activities thought to be acting in the vicinity of Port Stanvac and potentially influencing the distribution patterns of intertidal plants and animals have been considered previously (Appendix A). However, recreational activities occurring in the intertidal region, especially human predation (or collection pressure) and trampling required further consideration (Appendix C) due to their potential to confound an ongoing monitoring program.

Human predation (particularly the collection of molluscs) has been shown to critically influence intertidal communities (e.g. Ghazanshahi *et al.* 1983, Moreno *et al.* 1984, Castilla and Durán 1985, Hockey and Bosman 1986, Moreno *et al.* 1986, Olivia and Castilla 1986, Hockey *et al.* 1988, Durán and Castilla 1989, Wynberg and Branch 1997). Recreational trampling on rocky shores can also alter intertidal communities (Suchanek 1978, Beauchamp and Gowing 1982, Ghazanshahi *et al.* 1983, Cole *et al.* 1990, Kingsford *et al.* 1991, Povey and Keough 1991, Brosnan and Crumrine 1994, Wynberg and Branch 1997). However, the effects of trampling can be modified by factors including intertidal position, morphology of the species and microtopographical features of the substrata (Anderson *et al.* 1981, Beauchamp and Gowing 1982, Kay and Liddle 1989, Liddle 1991, Brosnan and Crumrine 1994).

Succession can be an important process in intertidal communities which are exposed to frequent, patchy, natural disturbance at a range of spatial and temporal scales by maintaining species diversity and providing colonisation opportunities for new recruits (see Connell and Slayter 1977, Sousa 1984b, Begon *et al.* 1986, Farrell 1991). A range of biotic and abiotic factors (see Appendix C & Underwood 1981a & b, Jara and Moreno 1984, Farrell 1991, Underwood and Chapman 1995) can influence successional changes in an intertidal community.

2.2.3 Overview of Processes

The observed biotic patterns on rocky intertidal shores represent the interactions of a number of processes. Chance elements such as recruitment, resource partitioning and disturbance shape intertidal assemblages in combination with predation, grazing, competition, and physical stresses, such as wave and tidal action and associated challenges. Studies of intertidal communities have generated hypotheses that identify natural disturbance (Connell 1978, Connell and Keough 1985), food web regulation, competition for space (Paine 1984), recruitment limitation (Gaines and Roughgarden 1985, Sutherland 1987), or a combination of these factors, as being of prime importance in structuring these communities. Although these factors may be of major importance to the co-existence of organisms they may act differentially in time and space, and their relative importance in shaping community structure and its complexity will similarly fluctuate temporally and spatially.

2.3 Disturbance and Environmental Monitoring

2.3.1 Environmental Disturbance

Disturbances can range in magnitude from subtle, localised events to massive destructive events that trigger large scale environmental change (Skilleter 1995). When occurring in natural systems, disturbance provides opportunities for new organisms to become established as space is cleared or predators are removed (Dayton 1971, Sousa 1984a). The release of 'free' space is particularly important in sessile communities (Denley and Underwood 1979). Chance events such as storms, unseasonable hot weather, or the movement of boulders (McGuiness 1987a & b) can all act to open up intertidal space without otherwise altering the system (Skilleter 1995). Natural disturbance tends to operate patchily so that mosaics of disturbed areas occur on shores interspersed by non-disturbed areas (Dethier 1984, Skilleter 1995). This situation promotes maintenance of diversity by affording refuge space to different species (Dethier 1984). However, certain anthropogenic disturbances, such as an oil spill, may occur on a larger scale and alter the substratum in such a way that it becomes unsuitable for colonisation by a particular species.

There have been many debates over the definition of a disturbance (Skilleter 1995). In this thesis, a disturbance is considered to be an environmental fluctuation or perturbation that can, but does not always, result in a biological change (Underwood 1989). If a biological change does occur, it can manifest in a range of ways such as altered species abundance, altered diversity or species dominance, or some other change to assemblage structure (Skilleter 1995). The only disturbance which is of interest and potentially detectable in a monitoring program is one that results in stress (defined as a biological change in a population in response to a particular trigger) in the target population. It is difficult to identify and monitor stresses in natural populations due to their inherent natural variability in time and space. However, it is important to differentiate between disturbances that trigger a response in the target population and those that do not initiate a response (Underwood 1989).

Underwood (1989) identified several types of disturbance; ‘Type I’, ‘Type II’ and ‘Catastrophic’, which are defined by the effects they elicit in a target population (Fig. 2.1). A ‘Type I’ disturbance does not result in a detectable response in the population, while a ‘Type II’ disturbance results in changes that may be temporary, long-term or permanent. The remaining disturbance category is ‘Catastrophic’; where the population and its habitat is totally destroyed (Underwood 1989). A small localised oil spill is most likely to be either a ‘Type I’ or a ‘Type II’ pulse disturbance (of short duration relative to the longevity of the target population). In the case of an oil spill at Port Stanvac, a perturbed section of the rocky shore is likely to eventually recover due to the self cleansing action and low oil retention rates characteristic of rocky shores.

Disturbances can also be defined by the duration for which they influence a population. On this basis they fall into two categories; pulse and press (refer to Bender *et al.* 1984, Underwood 1989, Grigg 1994) (Fig. 2.2). Disturbances that elicit effects on a target population may cause these changes directly or indirectly. For example, a direct response in a target population of molluscs impacted by oil would be mortality as coated animals were physically smothered. The triggered changes may also be an indirect response to a disturbance that alters the availability of resources (food, substrata or space) or physically changes the environment (Skilleter 1995).

'Type I' Disturbance

'Type II' Disturbance

Fig. 2.1 Comparison of disturbance types by the effects they induce. A 'Type I' disturbance does not trigger a detectable response in Population I, but a 'Type II' disturbance manifests as a reduced abundance in Population II. Changes associated with a 'Type II' disturbance can range from short term to permanent responses. Disturbance responses seen in target populations can be species specific, with the same disturbance constituting a 'Type I' disturbance relative to one species and a 'Type II' disturbance relative to another. The arrows shown in the graphs represent the onset of the disturbance (After Skilleter 1995).

Fig. 2.2 Comparison of pulse (short duration) *versus* press (extended duration) disturbances. The population subjected to a pulse disturbance has rapidly returned to its pre-disturbance abundance, while the press disturbance results in a persistently depressed post-impact abundance. The arrows represent the onset of the disturbance and their width represents the duration of the event (After Underwood 1989).

2.3.2 The Intensity, Timing and Frequency of Disturbance

Disturbances can differ in their intensity, timing and frequency, which (in turn) can affect the stress response in the target population and its ability to recover. One way in which a disturbance can elicit stress responses and influence recovery of an impacted area is by triggering alterations in the time course and progression of successional mechanisms (Sousa 1984a & b, Underwood 1989). The successional stage of an assemblage and the age and physiological state of its component biota can also influence the susceptibility of organisms to perturbation and their ability to recover from such an event (Skilleter 1995).

The intensity of a disturbance can result in differential effects on a perturbed area. As an example, massive storm waves represent an intense event capable of removing entire plants from their attachment area, whereas a less intense episode may only remove portions of fronds (Kennelly 1987). A more intense event is likely to induce greater successional change and be matched by a longer recovery time than would occur in response to a less intense stimulus (Underwood 1989).

The seasonal timing of a disturbance can also be an important determinant of the response and recovery made by an impacted population (Jara and Moreno 1984, Kennelly 1987, Skilleter 1995). The study by Kennelly (1987) found that manual removal of the kelp overstorey in winter (when kelp recruitment was intense), resulted in simultaneous colonisation of the bare space by kelp, filamentous algae and turf algae, with the kelp rapidly dominating to form a canopy. The same manipulation at any other time of the year resulted in initial increases in microalgal and invertebrate cover, and eventual dominance by turf algae. This example illustrates that the most likely organisms to opportunistically colonise vacated space are those which have larvae or propagules in the water close to the affected area at the time of the disturbance. These opportunists may be species with an extended breeding period or they may be organisms whose recruitment time fortuitously coincides with the disturbance (Skilleter 1995).

The frequency of the disturbance can also affect how rapidly a population recovers, with some (stable) populations able to quickly return to their pre-impact abundance following frequent disturbances (Underwood 1989). A stable population is one that is able to return to its pre-impact condition before the next disturbance intervenes. The more frequent the disturbance the less time is available for the population to recover and the more likely it is to be driven to local extinction (Underwood 1989).

2.3.3 Recovery Following Disturbance

The presence of the planktonic larval stages of many intertidal organisms are important in the recovery of a perturbed intertidal area (Sousa 1984b, Skilleter 1995). If local extinction of a particular species occurs in response to a disturbance, new recruits can arrive from the plankton to recolonise the disturbed habitat if its condition allows (Kennelly 1987). In the case of larger, more generalised disturbances, populations may take much longer to return to pre-disturbance levels, or may never regain their pre-impact condition. The latter scenario means an entirely different biological structure will exist at the disturbed site (Skilleter 1995).

Underwood (1989) identified three features displayed by populations that affect their ability to recover from a perturbation (Fig. 2.3). The first of these is ‘inertia’, which equates to the response generated by a disturbance of a specified intensity, frequency and type (Selye 1973). The ‘inertia’ of a population can be gauged objectively by identifying the maximum size and type of perturbation that does not cause a response. Two other population attributes are ‘stability’ and ‘resilience’, and these determine whether the population will recover (e.g. return to its pre-impact abundance) following a disturbance (Underwood 1989). The rate of recovery is specifically defined in reference to the magnitude of a disturbance, and is termed the ‘stability’ of the population. The ‘resilience’ of a population is a measure of its ability to recover from different magnitudes of disturbance (Underwood 1989). The larger the magnitude of the disturbance that a population can recover from, the more ‘resilient’ it is said to be.

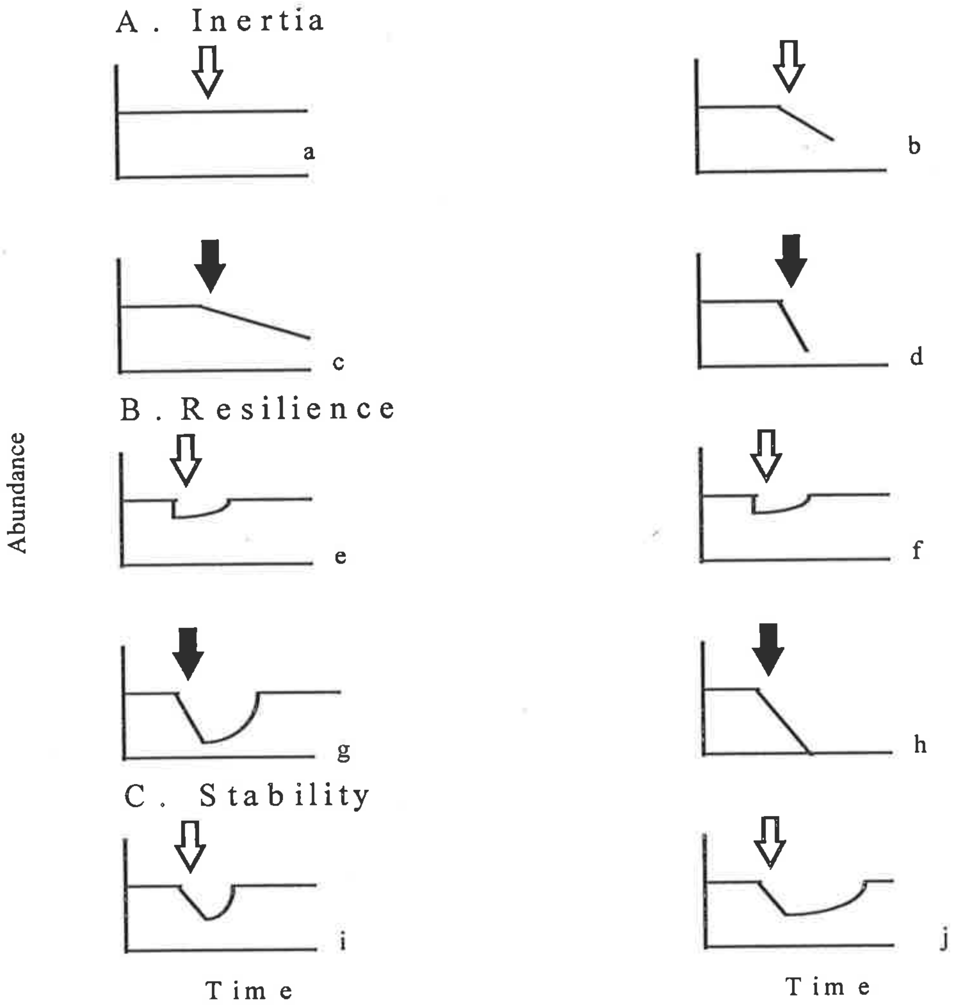


Fig. 2.3 Characteristics of stressed populations are shown as hypothetical fluctuations in local population abundance. Filled arrows represent a large acute perturbation and unfilled arrows a smaller magnitude acute event. **A. Inertia:** the population shown in a) & c) is more <u>inert</u> than the population shown in b) & d). The population in a) does not respond to the small perturbation that causes a stress response in population b). Both populations are affected by the larger perturbation, with the population on the right (d) being more severely and rapidly affected by the perturbation that the population on the left (c). **B. Resilience:** the population shown in e) & g) is more <u>resilient</u> than that shown in f) & h), with both populations recovering from a small perturbation, but only the population on the left (g) recovering from a larger perturbation that drives the population on the right (h) to extinction. **C. Stability:** the population on the left (i) is more stable than that on the right (j), as indicated by its rapid recovery (After Underwood 1989).

2.3.4 Disturbance Size: Important *versus* Trivial Impacts

Determining the importance of a disturbance can be subjectively affected by ecological and economic considerations. This bias needs to be addressed in the design of monitoring programs which should be sensitive to important impacts (as defined *a priori*) ideally on biological and economic grounds, but not oversensitive to smaller 'trivial' responses (Keough and Mapstone 1995). The ability of a population to recover from a certain magnitude disturbance within a realistic time frame should be factored into the determination of important versus trivial impacts (see Underwood 1992). This is a particularly important issue in the present study and I will return to it in Chapter 8.

2.3.5 An Oil Disturbance

Oil is the disturbance that is of interest to this project and the planned monitoring program at Port Stanvac. The physical and chemical nature of oil, its behaviour in the pelagic state and its fate when spilt at sea have been reviewed (see Appendix D). However, the fate of oil when it reaches the shore are of most relevance to this project and will be discussed in this section.

The Fate of Oil on the Shore

Climate and weather affect the condition of pelagic and beached oil, with wind and temperature interacting to influence evaporation of its volatile constituents, while wind and waves can affect emulsion formation (Baker 1983). The viscosity of stranded oil is affected by temperature, and both temperature and exposure to sunlight affect degradation rates (Baker 1983 & 1991). The timing of an oil spill in reference to seasonal and tidal factors can determine where oil beaches and influence how rapidly and effectively it is naturally removed from a beach. For example, the increased energy level of winter seas will tend to promote removal of beached oil (natural 'self-cleaning') by facilitating its degradation and redistribution, while dodge tides will have the opposite effect (Baker 1991, Hayes *et al.* 1993).

Once oil beaches its fate is determined primarily by shore energy, the dominant substratum type (Gundlach *et al.* 1978, McLauren 1985, Tsouk *et al.* 1985, Baker 1991, Garrity and Levings 1993), shore geomorphology and exposure (Owens and Rashid 1976, Owens and Robilliard 1981, Tsouk *et al.* 1985, Hayes *et al.* 1993, Sauer *et al.* 1998) and a number of physical processes, including sediment transport and weathering (Antia 1993, Hayes *et al.* 1993). Its final fate is either penetration into the substrata or persistence on the surface. The depth of oil burial within sediment is related to the viscosity and degree of weathering of the oil (see Appendix D), the wave energy of the shore, the shore sediment type, and the pore size and spaces (including biota burrows and plant root pathways) present in the sediment (Gundlach *et al.* 1978, Baker 1991, Essaid *et al.* 1993, Garrity and Levings 1993). If large volumes of oil are persistent on shores, penetration into sediments may be enhanced and oil masses are more likely to incorporate stones and gravel and harden to form relatively persistent asphalt pavements (Baker 1991).

In general, a rocky, high energy shore will tend to be less impacted and recover faster from an oil spill than most other shores. This is because rock does not absorb the oil, leaving it to be removed by the mechanical action of waves. However, coarse sand beaches with high incident wave energy, record the deepest oil burial (Gundlach *et al.* 1978). Sheltered shores will tend to retain oil due to the diminished wave action they experience and the generally greater algal or mangrove cover they support (Owens and Rashid 1976, Baker 1991, Garrity and Levings 1993, Hayes *et al.* 1993). Oil that is buried in sediments will generally be slow to weather, resulting in a prolonged life and increasing its toxicity to the environment (Gundlach *et al.* 1978, Nounou 1980, Baker 1991, Essaid *et al.* 1993, Sauer *et al.* 1998). Oil spilt near coastal areas tends to eventually accumulate intertidally, often at high levels and in shallow subtidal regions, resulting in most risk to biota in these areas (Rutzler and Sterrer 1970, Nelson-Smith 1973a & b, Chasse 1978, Clark 1982, Baker 1991, Farmer and Li 1994).

2.4 The Effects of Oil on Intertidal Organisms

Toxic chemicals found in anthropogenically altered environments, such as hydrocarbons in a marine system, are termed xenobiotics (Moore 1985). These chemicals can be available for uptake by organisms (Nelson-Smith 1973b, Baker 1991, James and Kleinow 1994, Overton *et al.* 1994). The mechanism and routes via which animals or plants are exposed to xenobiotics depend on the characteristics of the xenobiotic and the lifestyle of the organisms it contacts.

The chemical concentrations of xenobiotics in environmental samples are not accurate predictors of biological and ecological effects. This is because the prevailing environmental conditions can affect the percentage of the chemical that is biologically available (Maslins 1989, Burton and Scott 1992). The bioavailability of toxicants and how readily they are metabolised is more important than their chemical concentration and low level toxicant exposure can still have adverse effects on animals which bioaccumulate them (Burns and Smith 1980, Buhler and Williams 1988, Klungsøyr *et al.* 1988, Maslins 1989, Burns 1993).

Oil is a complex pollutant (see Appendix D) and the impact it has on intertidal animals can be highly variable depending on the characteristics of the animal involved, the duration and route of exposure, and the oil type, volume and condition (e.g. degree of weathering) (Nelson-Smith 1973a & b, Tatem *et al.* 1978, Blackman and Law 1981, Vargo 1981, McGuiness 1990, Chang 1991, Maher and Aislabie 1992, Burns 1993, Gary and Handwerk 1994, Overton *et al.* 1994).

Generally, refined products will produce more toxic effects than crude oil; with relative toxicity being directly correlated to the proportion of aromatic hydrocarbons in the oil (Nelson-Smith 1973b, Neff *et al.* 1976, Clark 1982 & 1989, Pople *et al.* 1990, Overton *et al.* 1994). However, this is balanced by the high volatility of many refined products, such as gasoline, which promotes rapid weathering and dispersal (see Appendix D & Widbom and Oviatt 1994). Therefore, spilt petrol is expected to have little impact on intertidal animals unless it beaches very rapidly (Clark 1989).

The most acutely toxic and abundant components of fresh oil are the monoaromatic (benzene) and diaromatic (naphthalene) components (Stromgren 1987, Clark 1989, Overton *et al.* 1994, see Appendix D). When oil is recently spilt these compounds are likely to induce toxic changes in organisms (Ewa-Oboho and Abby-Kalio 1994, Overton *et al.* 1994). As the oil weathers it becomes less acutely toxic but still contains the high molecular weight polycyclic aromatic hydrocarbons (PAH's), many of which are mutagens or potential carcinogens (Stromgren 1987, Chang 1991, Maher and Aislabie 1992, Gary and Handwerk 1994, Overton *et al.* 1994). As weathering occurs these compounds may become enriched in the residual bulk oil (Stromgren 1987, Baker 1991, Overton *et al.* 1994).

Intertidal invertebrate communities are particularly vulnerable to the floating component of oil (especially 'mousse') which can coat and suffocate them, while the heavier components of oil can harm subtidal assemblages (Suchanek 1993). Heavy mortality across a range of invertebrate groups has been reported as a consequence of coating with fresh crude oil, which may prevent or inhibit respiration (Baker 1991). Similar effects have been reported with intertidal plants and newly settled spores. Oil adherence may also impede the mobility of (non-sessile) animals or cause them to become dislodged and carried away by wave or current action to less favourable positions (Suchanek 1993).

Oil pollution can impact on individual organisms by inducing death or causing sublethal physiological, cytotoxic or cytogenic effects (Hose *et al.* 1983, Stiles 1992, Sami *et al.* 1992, Suchanek 1993). At the population level, effects range from altered abundance, a shift in age composition, altered genetic variability, reduced recruitment, and modified competitive and predator/prey interactions (Suchanek 1993, Jan *et al.* 1994). Alterations in individual and population parameters as a consequence of oil exposure may also manifest as community level changes (Warwick 1986, 1988a & b, Warwick *et al.* 1990a & b, Suchanek 1993).

2.4.1 Mechanisms of Oil Exposure

The mode of feeding, the zone in which an animal lives, and tidal and other environmental factors can influence the degree of contact with oil and therefore its impact (Nounou 1980, Vargo 1981, Clark 1982, Wardrop 1983, Overton *et al.* 1994, Glegg and Rowland 1996). For example, air or water temperatures may affect the activity of invertebrates and hence their exposure to oil (Wardrop 1983). Also, the bioavailability of hydrocarbons, the sensitivity of the organism and their ability to bioaccumulate (or conversely metabolise oil) can affect the toxic responses of a given species (Wardrop 1983, Overton *et al.* 1994). Oil can also cause changes (e.g. to the substratum or epilithon) which make conditions unfavourable for settlement and colonisation, thus inducing secondary effects to the species of interest (Watt *et al.* 1993, Christie and Berge 1995).

Pelagic animals are able to move through contaminated areas and in some instances avoid prolonged exposure to oil, but benthic animals on or near the seabed, and sessile or mobile invertebrates on intertidal shores are less able to avoid contamination (Nelson-Smith 1973b, Laubier 1980, Sastry and Miller 1981, Baker 1983, Wardrop 1983, Davies *et al.* 1993, Glegg and Rowland 1996). Hydrocarbons dissolved or dispersed in the water can gain entry to an animals body via the gills, skin or gastrointestinal tract (James and Kleinow 1994, Overton *et al.* 1994). However, the presence of mucus, cuticles or shells may act as a physical barrier to oil entry (Wardrop 1983, Baker 1991). The gills of invertebrates are particularly vulnerable to aromatics, which can irritate their surfaces and stimulate massive mucus secretion, while surfactants in the oil cause erosion of gill and gut tissue (Nelson-Smith 1973b, Nounou 1980, Guzmán *et al.* 1991, Suchanek 1993). Such effects can cause significant problems with osmotic regulation and respiratory exchange (Guzmán *et al.* 1991).

Hydrocarbons present in the sediment may be absorbed by direct dermal contact and ingestion. Filter feeders and deposit feeders are also likely to directly ingest and accumulate dispersed or sedimented oil (Baker 1983). Oil accumulation by mussels in a range of locations has been well documented (Laubier 1980, Floc'h and Diouris

1980, Rowland and Volkman 1982, Burns 1993). Oil which has become incorporated into the tissues of plants and low trophic organisms, or which externally coats such prey items, may be ingested and absorbed via the gastrointestinal tract by predatory organisms higher in the food chain (Nelson-Smith 1973b, Shaw and Wiggs 1980, James and Kleinow 1994).

A number of studies of marine invertebrates have shown that accumulation of hydrocarbons is non-selective and depends mainly on the levels of the pollutant in the environment (Laubier 1980, Carls 1987). Many animals select food particles for ingestion on the basis of particle size and have no mechanism to reject particles according to taste or consistency (Nelson-Smith 1973b). Even if a particle-discriminatory ability does exist, it may be inactivated by oil-induced narcotic effects (Overton *et al.* 1994).

Hydrocarbon accumulation sites in tissues differ between species, but ingested hydrocarbons tend to become fixed in tissues with a high fat content, including the liver, pancreas and gonads of marine invertebrates (Laubier 1980, Nounou 1980). Hydrocarbons can also accumulate in lipoproteins such as plasma, cutaneous and nervous tissue. By affecting cellular mechanisms, oil exposure can cause tissue necrosis and tumours in susceptible animals (Nounou 1980, Overton *et al.* 1994). Bioaccumulation of potentially carcinogenic hydrocarbons can occur in the tissues of animals and then be passed higher up the food chain (Laubier 1980, Nounou 1980, Overton *et al.* 1994).

Hydrocarbon sensitivity varies between species and within a species according to life stage and general health (Smith *et al.* 1987, Stacey and Marcotte 1987, Overton *et al.* 1994, Cripps and Priddle 1995, Thomas and Budiantara 1995). A number of organisms, including crabs (Jackson *et al.* 1981), amphipods (Sanders *et al.* 1980), and some molluscs (Phillips 1980, Swaileh *et al.* 1994) can show a seasonal variability in oil sensitivity.

Generally, larval and juvenile invertebrate lifestages are more susceptible to oil exposure than more mature life stages (Baker 1983 & 1991, Jan *et al.* 1994, Widbom and Oviatt 1994). Bioassays focusing on the toxicity of the soluble fractions of oil have found that adult invertebrates can sustain lethal effects from exposure to water soluble oil fractions in the 1-100 ppm range (Hyland and Schneider 1976), while smaller, more sensitive larvae and juveniles can suffer mortality at concentrations of 0.1-1 ppm (Suchanek 1993). Sublethal responses to the soluble fraction of oil have been reported in adult marine invertebrates at concentrations of 10-100 ppb (Hyland and Schneider 1976), while larvae have shown sublethal responses at concentrations as low as 1-10 ppb (Nounou 1980). The most common processes altered by sublethal exposure to oil include reproduction, growth, respiration, excretion, chemoreception, feeding, movement, stimulus response and susceptibility to disease (Hyland and Schneider 1976, GESAMP 1977, Sanders *et al.* 1980, Farke *et al.* 1985, Overton *et al.* 1994).

2.4.2 Invertebrates and Oil

Invertebrates are very diverse in structure and function and this is matched by a similarly wide range of responses to oil pollution (den Hartog and Jacobs 1980, McGuiness 1990, Peterson 1993, Suchanek 1993). They tend to be important members of intertidal systems and many are vulnerable to oil exposure, as either an acute or chronic stressor (Suchanek 1993). Shore invertebrates tend to be highly susceptible to oil due to their restricted mobility and the tendency of oil to float on the water surface which maximises pollutant contact (Nounou 1980, Clark 1982, Wardrop 1983, Garrity and Levings 1993, Suchanek 1993).

As a slick, oil can physically suffocate intertidal animals and it can also induce direct toxic effects (Nelson-Smith 1973b, Nounou 1980, Clark 1982, Watt *et al.* 1993). Crude oil in the form of a 'mousse' is potentially very damaging to shoreline invertebrates (Suchanek 1993), and can kill most organisms which it heavily coats (Baker 1991, Watt *et al.* 1993). Heavy oils and 'mousse' emulsions clog or blanket surfaces and fine structures, inhibiting respiration, movement, feeding and digestion (Nelson-Smith 1973b, Nounou 1980, Garrity and Levings 1993, Suchanek 1993). Small mobile invertebrates may be dislodged (as oil adheres to their shells) and carried away by waves or currents, potentially to less suitable habitats (Denny *et al.* 1985, Suchanek 1993, Trussell *et al.* 1993).

Molluscs, crustaceans, worms, and echinoderms can suffer high mortalities if coated with fresh crude oil (Nelson-Smith 1973b, Baker 1983 & 1991). Exposure to fresh oil can also result in behavioural changes that can ultimately affect survivorship (Levell 1976). Narcotic effects including detachment or retraction into their shell (Blackman *et al.* 1973) and cessation of swimming (Brodersen 1987) have been reported in molluscs and crustacean larvae respectively when exposed to fresh crude oil. However, crude oil is generally less toxic to invertebrates when it is weathered (Wardrop 1983, but see Bender *et al.* 1980, Clark and Ward 1994).

In addition to effects on the immediate health of organisms, spilt oil can alter the structure of assemblages by changing natural patterns and processes, such as succession (Smith and Hackney 1989, Shaw 1992). Both acute catastrophic oiling and chronic oil pollution are characterised by increased mortality and decreased community diversity, in association with dominance by a few resistant species (Clark 1982). This situation is followed by extreme fluctuations in populations of opportunistic fauna. Over time, the population oscillations slowly dampen and diversity returns to its pre-oiled levels (Clark 1982).

Some studies suggest otherwise, but it would appear that most invertebrate communities subject to major oil spills do not recover quickly (e.g. within a few years) (Koreas and Burns 1977, Clark 1982, Baker 1983, Elmgren *et al.* 1983, Suchanek 1993). Population and community structure is typically altered for 2-15 years by large oil spills, with the actual recovery time depending on the type of community impacted, its successional state, the severity of the disturbance, the characteristics of the oil, and the nature of the habitat prior to oiling (Blackman and Law 1981, Clark 1982, Baker 1983, Shaw 1992, Teal *et al.* 1992).

2.4.3 Intertidal Flora and Oil

Oil can cause mortality or affect the growth of a range of plants including seagrasses, mangroves (Spooner 1970, Wardrop 1983 & 1987, Baker 1991, Grant *et al.* 1993, Duke *et al.* 1997), saltmarsh flora (Cowell 1969, Baker 1991), macroalgae (Floc'h and Diouris 1980, Baker 1991, Vantamelen *et al.* 1997), lichen and epilithon. It is important to consider the effects of oil on epilithon, lichen and macroalgae as they are a major component of the intertidal food chain and may also provide habitat and shelter for some intertidal invertebrates in GSV.

Oil can damage flora in a variety of ways. It may act as a physical barrier and prevent gas exchange, coat the plant and cause mechanical breakage and tissue damage, induce toxic effects, affect soil or sediment properties, or the ability of other plants to grow and compete (Floc'h and Diouris 1980, Baker 1983, Antrim *et al.* 1995). A number of hydrocarbons can enter the leaves and stems of plants, and are thought to interfere with the structure of intercellular membranes and regulation of essential metabolic processes (Nelson-Smith 1973a).

Intertidal areas, even if completely denuded of plant life, can rapidly recover as new spores recruit into the area but community composition may change dramatically (Baker 1991). For example, ephemeral algal blooms have been observed on rocky sections of the shore that had been cleared of plant life by a severe oil spill in Panama (Jackson *et al.* 1989). Indirect floral changes can also occur when oil eliminates or reduces the density of grazers, allowing invasion and proliferation of opportunistic algal species; a situation which can persist for several years (Avolizi and Nuwayhid 1974, Chasse 1978, Floc'h and Diouris 1980, Clark 1982, Baker 1983).

Macroalgae including *Fucus gardneri* (De Vogelaere and Foster 1994, Stekoll and Deysher 1996) and the sensitive brown alga *Laminaria ochroleuca* (Floc'h and Diouris 1980) have been reported to suffer severe damage, including tissue necrosis, and overweighting and subsequent loss in response to oiling. Oil induced effects can also flow on to the next generation. This was seen in the 1989 *Exxon Valdez* oil spill (Miller 1990), where damage to adult *Fucus gardneri* resulted in loss of new zygotes and created unfavourable conditions for the subsequent growth of juvenile thalli (Brawley and Johnson 1991, Stekoll and Deysher 1996, Vantamelen 1997).

Algae and lichen in rock pools or present high in the intertidal region are particularly susceptible to oil-induced effects, and smothering of these organisms in large volume oil spills has been reported (Chasse 1978, Baker 1983). Epilithon is particularly prone to oil damage. This is because of the high oil contact rates the epilithon experiences as some oil particles become attached to the substrata and a proportion remain suspended in the water column (Baker 1983). Blue-green algae (a component of some epilithon films) have been reported to be severely damaged by oiling (Krupp and Jones 1993).

2.5 Bioindicators and Oil

2.5.1 Selection of Biological Variables

Laboratory studies are useful to establish links between a toxicant and the performance or 'health' of an individual, but it is more difficult to assess ecological change at higher biological levels (Maltby and Calow 1989, Cairns *et al.* 1993). This is because populations, communities and ecosystems are influenced by stochastic processes such as planktonic dispersal, recruitment variability and immigration (McGuiness 1990, Fairweather 1991b, Clark and Ward 1994, Christie and Berge 1995).

2.5.1.1 Biological Levels of Pollution Induced Change

The starting point for environmental stress responses is at the biochemical and physiological level of the organism (Moore 1985, Giesy *et al.* 1988, Johnson *et al.* 1993). Changes at these levels are capable of providing an early and sensitive indication of detrimental effects occurring in response to environmental stress (Giesy *et al.* 1988, Giesy and Graney 1989), while changes at higher biological levels impact on the sustainability of the target population and the larger community (Warwick *et al.* 1990b, Cairns *et al.* 1993). A broad understanding of the different biological levels that can be altered by exposure to a pollutant is necessary when designing a monitoring program.

Organism Level Indicators

Pollution effects at the level of the individual, which result in sublethal changes in health and/or performance, fall into a number of sub-categories (Moore 1985). The most obvious effects on the individual are acute changes, typically mortality, but cellular, sub-cellular, physiological and pathological changes can also occur (Giesy *et al.* 1988, Giesy and Graney 1989). Bioaccumulation of pollutants is another response that is indicative of exposure of the individual to pollutants.

i) Cellular and Sub-Cellular Responses

Cellular and sub-cellular responses are biochemical alterations, including chemical imbalances and abnormal or excessive biochemical functioning, which are triggered in central metabolic organs by pollutant exposure (Moore 1985, Sindermann 1988, Celander *et al.* 1995, Keough and Mapstone 1995). These changes may be effective acute predictors of chronic effects at higher levels of organisation because changes must occur at lower levels before they can manifest as higher level changes (Moore 1985, McKee and Knowles 1986, Regoli 1992). However, it is important when using sub-organism indicators that they are related in a meaningful way to ecologically pertinent endpoints for the individual and the population (Graney and Giesy 1986, Keough and Mapstone 1995).

ii) Physiological Responses

Physiological changes in response to toxicant exposure can be used as a way of quantifying that exposure. These include alterations in feeding and burrowing rates, the valve movement response in mussels (Abel 1976, Nounou 1980, Olla *et al.* 1983, Kramer *et al.* 1989, Coles *et al.* 1994), respiration and oxygen consumption, excretion and nitrogen balance, growth, fecundity, osmotic and ionic regulation and haematology (Avolizi and Nuwayhid 1974, Widdows 1985, Sindermann 1988). Physiological responses can quantify an organisms condition (e.g. oxygen : nitrogen ratio), its performance (using rate variables such as growth) and its growth efficiency, at an early stage of sublethal pollutant exposure and change (Olla *et al.* 1983, Widdows 1985). However, to be a useful indicator of biological change the physiological variable used should be responsive to environmental stress over a range of scales from sublethal to lethal (Widdows 1985).

A difficulty associated with using physiological indicators is the extreme range of responses that can be triggered by a host of highly variable intrinsic and extrinsic factors (Sindermann 1988). This response variability can be standardised by adopting an adjusted physiological measure, such as the 'scope for growth' measurement which quantifies the instantaneous growth rate of an animal (Sindermann 1988). Widdows (1985) and Widdows *et al.* (1990) found links between the 'scope for growth' and concentrations of hydrocarbons and metals in bivalves.

iii) Pathological Responses

Pathological indications of pollutant exposure include inflammation, necrosis, neoplasms, skeletal abnormalities, lowered disease resistance and increased disease incidence (Maslins *et al.* 1983, Browder 1988, Sindermann 1988, Sidall *et al.* 1993). Pathological indicators can provide the first obvious signs of extreme environmental contamination (Keough and Mapstone 1995), but are often non-specific to the stressor (Sindermann 1988). Another difficulty is that it is often uncertain how changes at the level of the individual will affect the population (Keough and Mapstone 1995).

iv) Bioaccumulation

The degree of pollutant bioaccumulation can also be used as a measure of pollutant exposure. Marine molluscs have been widely used for this purpose due to their ability to accumulate and concentrate organic and metal pollutants (Burns and Smith 1980, Farrington *et al.* 1983, Akberali and Trueman 1985, Goldberg 1986, Pereira *et al.* 1992, Burns 1993, Davies *et al.* 1993). Filter feeding bivalves have been particularly useful in quantifying the spatial and temporal extent of pollutants in aquatic systems e.g. "Mussel Watch" (Farrington and Tripp 1993). Bivalves make good bioindicators because they are sedentary, can bioaccumulate toxins, tend to be cosmopolitan with relatively stable and extensive local populations, are able to integrate biologically available toxicants over time, and can be readily manipulated experimentally (Farrington *et al.* 1983). Problems associated with the use of bioaccumulators are that many can survive under quite high pollutant loads (Farrington *et al.* 1983) and that definitive links have yet to be established between toxicants in the field and the health of the animal or population (Keough and Mapstone 1995).

v) Other Responses

Many contaminants are mutagens, teratogens and carcinogens capable of inducing genetic responses in organisms and affecting reproduction, fertilisation, and patterns of larval settlement (Sindermann 1988, Keough and Mapstone 1995). For example, reduced competence of planktonic invertebrate larvae will affect settlement or post-settlement survival of the individual and impact on the population structure of adults (Keough and Mapstone 1995). Chromosomal anomalies induced by contaminant exposure have been seen in eggs, embryos and the larval stages of shellfish (Nounou 1980). Such effects may result in direct increases in mortality, or the genetic change may act indirectly to impact on future lifestages and populations (Sindermann 1988).

Population Level Indicators

The most common methods used to quantify population level pollutant effects have relied on static population measures such as; the presence/absence of a species, altered abundance, or altered population structure (Suchanek 1993, Keough and Mapstone 1995). Detecting ecological change at the population level means that exposure to a pollutant or some other perturbation has resulted in the accumulation of sufficient changes in individuals to be detectable as 'important' population level changes (Underwood 1992). The real difficulty lies in establishing the link between changes in the individual and changes in the population, the latter being complex (particularly if the species has a planktonic life stage) and hard to simulate realistically in the laboratory (Keough and Mapstone 1995).

Community Level Indicators

Most community level studies investigating pollutant effects and disturbance responses have focused on benthic faunal communities (Burd *et al.* 1990, Keough and Mapstone 1995). Such studies have been extensively discussed in the scientific literature (Elmgren *et al.* 1983, Warwick 1986, Gray *et al.* 1988, Help *et al.* 1988, Warwick 1988b, Warwick *et al.* 1988, Gray 1989, Gray *et al.* 1990, Warwick *et al.* 1990b, Warwick and Clarke 1991).

Community level biomonitoring is labour intensive and expensive due to the expertise and time required to census organisms (Keough and Mapstone 1995). It is also difficult to link responses to stressors (which are often complex and poorly understood) to the observed community change. The great complexity seen in a community also makes it virtually impossible to realistically establish the system in the laboratory in order to investigate toxicant induced changes under controlled conditions.

The advantage of a community approach for biological studies is that, unlike lower levels of biological organization, the sampled assemblage structure reflects the integrated and assimilated conditions over a period of time (Karr 1987, Dostine *et al.* 1993, Warwick 1993). By focusing on the community, a broad selection of responses to toxicant exposure is offered (Gray *et al.* 1990). This can be an advantage where there is no *a priori* basis for selecting an indicator species (Dostine *et al.* 1993), or where the perturbation is accidental and therefore not readily predictable (Warwick 1993).

Community changes seen with stress responses include a reduction in species diversity, a change in size structure to smaller species, and dominance by opportunistic species (Levings *et al.* 1983, Schindler 1987). Community responses to stressors have been reviewed by Gray (1989) who sees such classical changes as occurring late in the sequence of change (Gray *et al.* 1990).

2.5.1.2 Single Species and Multiple Species Toxicity Testing

Toxicity testing ultimately aims to monitor or predict the effects of single compounds, elements or mixtures of compounds on the health of individual organisms, populations, communities or ecosystems (Soule 1988, Giesy and Graney 1989). This is done by introducing a pollutant into biological systems of varying complexity (Maltby and Calow 1989). Such environmental bioassays play an important role in assessing the actual or potential impacts of anthropogenic agents on natural environments (Calow 1989, Giesy and Graney 1989).

The focus of toxicity testing has tended to be on short-term acute responses rather than on chronic long-term effects, which are frequently inferred from acute studies (Giesy and Graney 1989). However, a pollutant may have a different mode of toxic action in chronic and acute exposures making the latter inference undesirable. A useful discussion of acute, chronic and sublethal laboratory toxicant testing is given by Rippon and Chapman (1993), while Mackay *et al.* (1989) reviews the use of bioassays to detect chronic sublethal effects on biota.

Single species bioassays have been the primary source of data used to evaluate the relative sensitivities of organisms to chemicals or effluents (Cairns and Niederlehner 1987). Death is often the biological response measure used in bioassays, with the most common test being determination of the lethal dose (or concentration) of the pollutant (the LD_{50} or LC_{50}) which will kill 50% of the test population over a given period of exposure (Nounou 1980, Keough and Mapstone 1995). Despite the focus on single species bioassays, it is also important to aim some toxicity tests at the community level (Buikema *et al.* 1982, Cairns 1983, Rippon and Chapman 1993), where pollutants are likely to differentially affect organisms which are interacting in a complex way and which have varied food, habitat and reproductive requirements (Sprague 1971, Connell 1974, Cairns 1983, Perry and Troelstrup 1988, Soule 1988, Underwood and Peterson 1988, Warwick *et al.* 1988, Rippon and Chapman 1993).

2.5.2 Selection of a Bioindicator

The rocky intertidal zone is the area most likely to be impacted by an oil spill from the Port Stanvac Oil Refinery, and epilithon and invertebrates are most at risk of sustaining damage. The major oil types handled by the refinery are petroleum and Arabian light crude oil (Appendix D). A petroleum oil spill is likely to rapidly weather and lose its volatile constituents, while Arabian light crude oil is expected to weather more slowly and possible form a 'mousse' and be more damaging as a smothering agent than as a toxic agent.

Epilithon and its constituent species have frequently been used to monitor pollution in streams (Yasuno and Whitton 1986). A review of the usefulness of algae in freshwater monitoring can be found in McCormick and Cairns (1994). However, due to sampling difficulties and lack of extensive studies on intertidal epilithon (see McLulich 1986, Hill and Hawkins 1990) similar monitoring has not occurred in marine systems, and this material was not considered further in the design of a monitoring program for Mobil, Port Stanvac. Lichen is the dominant plant in the supralittoral zone at some GSV sites but again was not suitable for consideration as a bioindicator material due to difficulties associated with its sampling and quantification.

Intertidal invertebrates are likely to be impacted by an oil spill and are relatively easy to monitor and census (Jan *et al.* 1994). It was expected that one or more of the intertidal invertebrates seen in GSV (Chapter 1 & Appendix C) would be suitable bioindicators of oil pollution. Gastropod and bivalve molluscs were generally an obvious component of the intertidal fauna and were expected to be the best source of bioindicators for monitoring oil-related change. See Chapter 6 for an investigation of the suitability of different GSV species for use as bioindicators.

2.6 Development of Environmental Monitoring Designs

A major challenge in detecting an environmental impact is to differentiate the effect of interest from natural temporal and spatial variation ('noise'), and to distinguish between 'trivial' and 'important' impacts (Osenberg *et al.* 1994, Keough and Mapstone 1995). Therefore, it is necessary to choose an appropriate variable to monitor and to have an awareness of the natural variation seen in that variable over a range of temporal and spatial scales under 'normal' and perturbed conditions.

The need for effective monitoring programs has led to a review of existing monitoring designs, and recently some quite complex and statistically rigorous designs have been advocated and extensively discussed in the literature (including Stewart-Oaten *et al.* 1986, Underwood 1991a, 1992 & 1993a, Green 1993, Underwood 1994a & 1995a). Analysis of variance (ANOVA) is commonly used to analyse data generated from many of the (univariate) monitoring designs aiming to detect anthropogenic change. This is a statistical technique used to partition the variation associated with various factors (explicitly identified by the investigator in the design of the study) and to assess their relative magnitudes against the 'noise' in the data set (Zar 1984, Millard *et al.* 1985).

2.6.1 Statistical Power, Acceptable Error Rates and Effect Size

A number of factors need to be considered when designing a monitoring program. These include the size of the impact to be detected, the power of a program to detect this impact, and the error risks associated with determining whether or not an impact has occurred (Underwood 1997). These considerations will be discussed briefly in the following paragraphs.

A statistical investigation of a perturbation begins with a null hypothesis (a statement of no change). This basically states that a perturbation has not produced an alteration in an assessed parameter. The null hypothesis is paired with an alternative hypothesis which states that an impact of a specific magnitude has occurred (and produced an alteration in the assessed parameter). A statistical test is then used to give a probability of obtaining the data if the null hypothesis were true. If that likelihood is low, then a *decision* is made to reject the null hypothesis and to accept the specified alternative hypothesis (Strong 1980, Toft and Shea 1983, Fairweather 1991a, Mapstone 1995).

There are four possible outcomes of a statistical test, two 'true' outcomes and two erroneous results (Table 2.1). The 'true' statistical outcomes are acceptance of a true null hypothesis and rejection of a false null hypothesis. However, an analysis may also result in retention of a false null hypothesis (a 'Type II' error) or rejection of a true null hypothesis (a 'Type II' error) (Mapstone 1995). These two errors have their own costs, and the consequences of each need to be considered to ensure that the risks of both are kept to an acceptable level (Bernstein and Zalinski 1983, Rotenberry and Wiens 1985, Andrew and Mapstone 1987, Fairweather 1991a, Mapstone 1995, Keough and Mapstone 1997). Traditionally, scientific studies arbitrarily set the 'Type I' error rate (α) at 0.05, but often give little consideration to 'Type II' errors (β) and the power ($1-\beta$) of the analysis (Toft and Shea 1983, Andrew and Mapstone 1987, Peterman 1990a & b, Fairweather 1991a, Keough and Mapstone 1997). Mapstone (1995) reviewed a number of unpublished environmental impact reports and found many where the null hypothesis of no impact was not rejected, but only a few where the 'Type II' error was less than 0.4 for impacts ranging from 80-100% in the measured variables.

Prior to beginning a monitoring program it is necessary to specify the magnitude and form of the maximum environmental impact e.g. the effect size (ES), which would be 'acceptable' (Cohen 1988, Mapstone 1995). The ES can be defined as the difference between the null hypothesis and the alternative hypothesis (Winer 1971, Cohen 1988). As the effect size is increased, the ability, or power, of a monitoring program to detect the effect also increases (Mapstone 1995). It is difficult to determine how large an effect is to be expected as a consequence of exposure to a perturbation unless relevant theoretical considerations that are independent of the hypothesis being tested exist (Rotenberry and Wiens 1985). In the absence of such considerations it is advisable to use experimental methods to select a biologically or economically meaningful ES (Mapstone 1995).

The power (P) of a statistical test is related to β, and is essentially the probability that the null hypothesis will be rejected when it is false and the specified alternative hypothesis is true (Bernstein and Zalinski 1983, Toft and Shea 1983, Gerrodette 1987, Peterman 1990a & b). Loosely, the statistical power of a monitoring program is a measure of the likelihood that an impact would be detected when one really does exist (Keough and Mapstone 1995). An *a priori* determination of the power of a planned monitoring program can be used to avoid wasting time, effort and resources, and to optimise a design (e.g. selecting the number of replicates). In contrast, an *a posteriori* power assessment can be used to interpret results when a null hypothesis is retained (Cohen 1973, Peterman and Routledge 1983, Toft and Shea 1983, Gerrodette 1987, Peterman 1989 & 1990 a & b, Taylor and Gerrodette 1993).

Table 2.1 The four outcomes (1-4) of a statistical analysis designed to test a null hypothesis. The probability of each outcome is presented in parentheses (adapted from Toft and Shea 1983).

	Decision Made	
Actual situation	Null hypothesis retained	Null hypothesis rejected
Null hypothesis true	1. Correct ($1-\alpha$)	2. Type I error (α)
Null hypothesis false	3. Type II error (β)	4. Correct ($1-\beta$)*

* ($1-\beta$) = power of the analysis

2.6.2 A Review of Techniques Used in Environmental Monitoring

2.6.2.1 The Basic Design

The earliest monitoring designs used a paired set of sites consisting of a single 'control' and a single 'impact' site, monitored a single time following an impact. This design is not able to differentiate between an impact and natural spatial variation, lacks 'true' replication (see Hurlbert 1984), and violates many of the criteria discussed by Green (1979). The use of multiple 'controls' and a single 'impact' location or multiple 'control' and multiple 'impact' sites sampled once following an impact improves on the previous monitoring design, but still does not provide a way to measure change (Keough and Mapstone 1995). It is also possible that the control and impact groups were different purely by chance before the impact intervened. The only case where this basic design is justifiable is when pre-impact data is not available and a *post hoc* assessment of impact is needed. In such a situation the minimal requirements would be multiple 'control' sites (the number being determined by weighing the costs and benefits associated with maximising this variable) and a single 'impact' site (Stewart-Oaten *et al.* 1986, Keough and Mapstone 1995, Underwood 1995a).

2.6.2.2 The BACI and BACIP Designs

Spatial variation is a natural phenomenon in systems (Eberhardt 1978) and could result in differences between separate sites (designated 'control' and 'impact') after an activity commenced even if the activity failed to have a major impact (Keough and Mapstone 1995). This necessitated the development of the **B**efore **A**fter **C**ontrol **I**mpact (BACI) design which was intended for environmental impact studies and is able to control for pre-impact site differences (Green 1979, Humphrey *et al.* 1995). In its most basic form, this design consists of two treatment groups; designated 'control' and 'impact', which are sampled once prior to and once following a perturbation. The basic BACI design has been criticised by many environmental biologists for its lack of temporal and spatial replication which prevents a valid test of the interaction between 'before-after' and 'control-impact' treatments (Bernstein and Zalinski 1983, Hurlbert 1984, Stewart-Oaten *et al.* 1986, Eberhardt and Thomas 1991). However, Green stated that this design met only the minimal requirements of monitoring and did, in fact, recommend spatial and temporal replication where possible (Green 1979 & 1993). The BACI design can also be extended to community-level data (see Faith *et al.* 1991).

Bernstein and Zalinski (1983) and Stewart-Oaten *et al.* (1986) both advocated using temporal sampling to overcome some of the deficiencies in the more basic BACI design. One 'control' (C) and one 'impact' site (I) are sampled simultaneously a number of times 'before' and 'after' the perturbation (see Peterson 1993). Since the design uses paired 'control' (which could be a single site or the mean of a set of sites) and 'impact' locations it became known as the **B**efore **A**fter **C**ontrol **I**mpact **P**aired (BACIP) design (Keough and Mapstone 1995). The analysis used with this design statistically contrasts the means of C-I differences between the 'before' and 'after' time periods to assess if they change coincidentally with the commencement of the perturbation (Stewart-Oaten *et al.* 1986). Importantly, Stewart-Oaten *et al.* (1986) recommended using infrequent, randomised sampling times to achieve sampling independence and to avoid coinciding with regular cyclic processes that might be occurring in the system. This version of the BACI design became popular in environmental monitoring studies (Green 1993) and recognised that it was unlikely that a population would be stable through time even in the absence of a disturbance. It should be noted that subsampling in a BACIP monitoring program does not increase the degrees of freedom of the main test or directly influence the power of the analysis (Hurlbert 1984, Zar 1984). However, it does provide a more accurate and less biased estimate of the mean at a particular time (Keough and Mapstone 1995).

The major problem with a BACIP approach to environmental monitoring is its inability to determine whether a statistical 'site-time' interaction is due to 'treatment' or 'site' effects (Keough and Mapstone 1995). This is a serious problem as marine organisms, in particular, often show asynchronous population fluctuations (Underwood 1991a) which may be an essential mechanism in population and community dynamics (Butler and Chesson 1990). This can only be overcome by the use of multiple 'control' sites and, if possible, more than one 'impact' site (Green 1993). Another deficiency with the BACIP design is its failure to deal with a change at the 'impact' location which is unrelated, but coincident with a perturbation, and restricted to that site (Keough and Mapstone 1995).

ANOVA and Serial Correlation

The analysis of variance (ANOVA) used with these monitoring designs assumes that deviations of the observations from their true means (errors) are uncorrelated in time and space (Zar 1984, Millard *et al.* 1985). However, patterns in nature, and observations in monitoring, often show temporal and spatial correlation (see Millard *et al.* 1985). It has also been shown that spatially or temporally correlated data can significantly affect the outcome of ANOVA tests (Millard *et al.* 1985).

To avoid serial correlation, where samples are not independent within and between different temporal treatments (Green 1993), it is necessary to choose a sampling interval that is long enough for some turnover of individuals or species, through migration, mortality or recruitment (Underwood 1993a). This can be achieved by considering the organism being sampled and its longevity when allocating sampling times. For very long-lived organisms the most appropriate sampling period may be intervals of greater than a year which would make it unlikely that short term effects will be detected or that the program will be long enough to collect a reasonable time series data set. Alternatively, for short-lived or highly mobile organisms counts taken at short intervals may show little serial correlation (Underwood 1992, Keough and Mapstone 1995, Underwood 1995a). The initial choice of sampling times can be reassessed after several sampling occasions, usually towards the end of the pre-impact period, for example with a Durbin-Watson test. If serial correlation is present it can be treated by eliminating some time intervals from the data set, and persisting with the adjusted time intervals in the post-impact monitoring period (Keough and Mapstone 1995), or by using an analysis which incorporates serial correlation.

Trends in C-I differences before or after the perturbation will invalidate the statistical analysis used in temporally replicated BACI designs, and may not be detected until late in the monitoring program. Appropriate data transformations may remove such trends but introduce new problems such as loss of important biological information, or an increase in variance and consequent loss of statistical power, possibly leading to abandonment of the analysis (Zar 1984, Keough and Mapstone 1995). It is possible in such a situation to analyse the trends themselves by considering the samples through time as two ordered series rather than as random from the 'before' and 'after' periods. If this is done, orthogonal polynomials can be used to resolve the actual trends through time (Keough and Mapstone 1995).

2.6.2.3 MBACI

MBACI is the design recommended by (Keough and Mapstone 1995). It uses multiple 'control' and (if possible) multiple 'impact' locations and is analogous to the Beyond-BACI design discussed extensively by Underwood (1991a, 1992 & 1993a, 1994a & 1995a), except that it focuses on a single designated spatial and temporal scale.

2.6.2.4 Beyond-BACI

The BACIP design can be improved by the use of multiple 'control' locations sampled multiple times 'before' and 'after' an impact occurs. This combines the temporal replication found in the BACIP design with greater spatial replication in the form of multiple 'control' locations (Underwood 1991a, 1992 & 1993a). Underwood (1993a) advocates the use of multiple, randomly-chosen 'control' locations selected from a set of appropriate locations e.g. rocky shores with a similar suite of organisms. Practical problems associated with this monitoring design include locating suitable control sites and the increased expense and sampling effort needed compared with more basic designs (Keough and Mapstone 1995).

Beyond-BACI and Temporal and Spatial Considerations

Underwood states that the focus of monitoring techniques on detecting changes in the average values of an assessed parameter may be poor practice as it ignores impacts that result in altered variance (Underwood 1991a, 1992, 1993a & 1994a). This deficiency is addressed with a Beyond-BACI design which basically uses a repeated measures ANOVA, incorporating various factors (including two or more 'time' and 'spatial' scales) and allowing a complex partitioning of variance (Underwood 1993a). To accommodate different temporal scales of interest, sampling effort is allocated to an appropriately short sampling interval (Times) which is nested within a longer sampling interval (Periods). Sampling then consists of a series of 'Before' and 'After' Periods divided into distinct intervals with a series of randomly assigned Times nested within each (Underwood 1993a). Similarly, if more than one spatial scale is of interest, sampling effort can be partitioned to incorporate them (see Underwood 1992). The specific use of a Beyond-BACI design, with reference to temporal scale considerations, will be discussed further in Chapters 4 & 8.

To maximise the efficiency of a Beyond-BACI design it is advisable to determine the expected response prior to monitoring and allocate sampling effort accordingly. For example, it is known that pulse disturbances operate over a shorter time scale than press disturbances, and recovery from the former is generally more rapid. Therefore, responses to a pulse event are expected to be seen as changes in variance over short time scales and would be best detected with a design using many intervals (Periods) and few times within intervals (Times). The reverse is true for detection of a press effect or a slower pulse event (Keough and Mapstone 1995).

The temporal sampling used in a Beyond-BACI design regards time as the variable of interest which, as previously mentioned in relation to the BACIP design, can result in serial correlation and violate one of the underlying assumptions of ANOVA (Zar 1984). This problem can be overcome in some instances by using randomising sampling times (Stewart-Oaten *et al.* 1986). However, selecting truly random sampling times can be difficult and it is also important to take account of seasonal patterns in a population. Therefore, Stewart-Oaten *et al.* (1986) advocates the use of appropriate fixed sampling intervals, and treatment of the sampling times as a 'fixed' effect (see Zar 1984). Again, a consideration of the scale of the study is necessary, as randomisation of sampling through time within seasons, as long as serial correlation is avoided, could be appropriate (Stewart-Oaten *et al.* 1986).

Underwood's suite of Beyond-BACI monitoring designs gives consideration to spatial as well as temporal scales. It is possible that a perturbation may have an impact that is of interest at more than one spatial scale, depending largely on the character of the disturbance (Keough and Mapstone 1995). For instance, if oil grounds on a rocky reef, changes within small sections of the reef, as well as effects to the entire reef, are likely to be of interest. Localised changes within the reef could be tolerated but major changes at the larger spatial scale could be considered ecologically unacceptable. This illustrates the need for an *a priori* consideration of the aims of a monitoring program and a knowledge of the disturbance and the effects it is expected to elicit. Only then can the temporal and spatial scales that are relevant to the disturbance be incorporated into the monitoring design.

Keough and Mapstone (1995) believe that the MBACI design has advantages over the Beyond-BACI design of Underwood (in that they save effort and resources). The MBACI design may indeed be appropriate to detect a range of impacts and should be used preferentially when it is suited to the disturbance being monitored. However, the Beyond-BACI design allows partitioning of variance over a range of important scales and can allow detection of complex 'mixes' of disturbance (such as combination pulse and press events). Choice of the most appropriate design for a monitoring program should be based on the type and magnitude of disturbance that is likely to occur, and the persistence and amount of change that is predicted over different spatial and temporal scales. These considerations then need to be balanced against power and resource concerns.

2.6.2.5 Response Surface and Grid Sampling Models

Response surface and grid sampling models primarily deal with the distribution and spread of effects associated with a perturbation, and are not designed to test hypotheses about this distribution. These techniques tend to be used in situations where a perturbation is known to be present, such as a continuous sewage outfall, and are useful in compliance monitoring (Keough and Mapstone 1995). They involve establishment of a sequence of sites over a gridded area in which the primary discharge point is centrally located. The parameter of interest, such as effluent dilution, is then sampled across sites (Keough and Mapstone 1995). The collected data is then fitted to a response surface and a three-dimensional plot generated. This and a similar technique known as indirect gradient analysis (refer to Whittaker 1967, Minchin 1987 & Ellis and Schneider 1997), could not be adapted to Mobil's requirements and will not be discussed further.

2.6.2.6 Summary Statistics

Summary statistics, such as species richness and diversity, can be useful measures in environmental monitoring. Summary techniques represent community structure as a single value (which can then be subjected to univariate analysis techniques) (Sundberg 1983). However, using species diversity and similar measures results in a loss of information on species function (Karr 1987). A criticism of diversity indices is their lack of robustness in response to seasonal and other temporal factors, as well as pollution and anthropogenic disturbance (Sundberg 1983).

Derived Indices of Environmental Pollution

Derived indices of environmental quality compiled, for example, by using the total number of aquatic invertebrate taxa and the total number of such taxa intolerant to a particular pollutant, can be useful in monitoring for pollution effects (Lenat 1993, Lang and Reymond 1995). Another approach involves using ecologically similar groups (guilds), such as particular functional feeding groups, to detect environmental change. Use of this technique is illustrated by Schlosser (1982), who detected a decline in invertivore and invertivore-piscivore fish in response to anthropogenic alteration of a headwater stream.

2.6.2.7 Dominance Curves

This technique superimposes separate *k*-dominance curves for abundance and biomass to produce abundance-biomass-comparison curves (ABC). Species are ranked on the *x*-axis, on a logarithmic scale, in order of importance for both biomass and abundance, and this is graphed against the cumulative percentage dominance on the *y*-axis (Clarke and Warwick 1994a). There are three possible curves produced by this technique (Fig. 2.4) which correspond to unpolluted, moderately polluted and severely polluted conditions (Warwick 1986).

It is hypothesised that disturbed benthos will be represented by a macrofaunal abundance curve that is above the biomass curve (Warwick 1986). This trend occurs as one or a few large species, each represented by a small number of individuals, will coexist with the numerical dominants which will tend to be a small species with a typically high level of stochasticity (Clarke and Warwick 1994a). The distribution of biomass will show strong dominance, while the distribution of individuals among species will be more even, and hence will lie below the biomass curve. When a perturbation constitutes a moderate disturbance, the large competitive dominants are eliminated, reducing the mismatch between the numerical and biomass dominants so that the biomass and abundance curves are fairly close and may overlap and cross. As the level of perturbation increases the communities become dominated by one or a few small species resulting in an abundance curve that overlies the biomass curve for its entire length (Clarke and Warwick 1994a).

Dominance curves have been useful in describing the responses of benthic macrofauna and meiofauna to perturbation (Warwick *et al.* 1990a & b). Their advantage is that 'controls' are not needed as the abundance and biomass curves are, in effect, acting as internal references to each other. However, it is advisable to use external reference samples as a further check of the results, and to include adequate replication (Clarke and Warwick 1994a). This technique goes further than univariate statistics and is able to extract information on the dominance pattern without reducing community data to a single summary statistic (Clarke 1990).

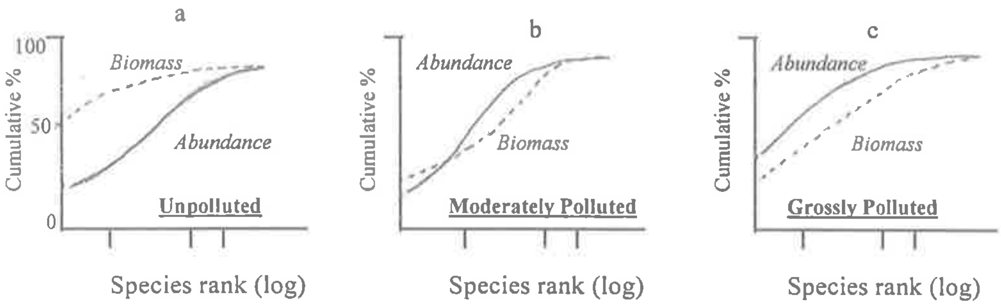


Fig. 2.4. Hypothetical *k*-dominance, or abundance/biomass comparison (ABC) curves, representing unpolluted, moderately polluted and severely polluted (or otherwise disturbed) macrobenthic communities. When conditions are stable and disturbance is infrequent the biomass curve lies above the abundance curve (a). Under moderately polluted conditions the abundance curve is close to the biomass curve (b), and under heavily perturbed conditions the abundance curve lies above the biomass curve for its entire length (c) (After Warwick 1986).

2.6.2.8 Multivariate Techniques

The monitoring designs discussed to this point have generally relied on a single variable that is assumed to be representative of environmental change (Sundberg 1983, Keough and Mapstone 1995). However, the real world consists of complex, interactive, dynamic systems in which multiple physical and biological processes co-vary in time and space (Huston 1985). Understanding the dynamics of any complex interactive system, whether in an impacted or unimpacted condition, is likely to be better elucidated at a community level (Powell 1989, Jan *et al.* 1994, Keough and Mapstone 1995). The community level is the common focus for many environmental studies and is believed to reflect the integration of conditions over a period of time (Warwick 1993).

Various multivariate techniques have been extensively discussed in the scientific literature (e.g. Gauch and Whittaker 1981, Minchin 1987, Clarke and Green 1988, James and McCulloch 1990, Clarke 1993, Palmer 1993, Warwick 1993). Such techniques were developed as a way to describe and analyse complex ecological data sets, and are now widely used to address a range of questions and problems including environmental monitoring. They are able to reduce the complexity of a huge data set, comprised for example of a 'sites x species' matrix, to a manageable level while preserving species-specific information (James and McCulloch 1990, Cobelas *et al.* 1995). In manipulating the data in this manner it is possible to suggest ecological explanations for observed patterns.

Multivariate techniques are generally sensitive to changes in community patterns arising as a result of pollution and disturbance (Sundberg 1983, Warwick *et al.* 1990a & b, Warwick 1993). As previously mentioned, they have the disadvantage of being labour intensive and expensive (Warwick 1993). However, it is possible to use higher taxonomic levels, such as family, to show patterns associated with a perturbation, and save processing time and money (Warwick 1988a & b). A brief description of the most common multivariate techniques used in pollution studies and biological monitoring will now be given.

Clustering

Multivariate methods were first developed for use in terrestrial plant communities, and were then used to describe patterns in marine soft sediment benthic communities (Keough and Mapstone 1995). The simplest and most commonly used of these early techniques involved clustering to group samples that displayed the greatest similarity in their attributes in a branching structure (James and McCulloch 1990). A popular technique of this type is Agglomerative Hierarchical Cluster Analysis. This begins by forming a pairwise similarity matrix among objects (e.g. individuals, sites, populations, taxa). The two most similar objects are then placed into a group and the similarities of that group to all other groups are calculated. Repeatedly the two closest groups are compared until a single group remains (James and McCulloch 1990). The resultant hierarchical 'tree' is able to show patterns but has the disadvantage of lacking robustness if different algorithms are applied to the data. For this reason the Bray-Curtis index is often used as it tends to give fairly consistent results (Faith *et al.* 1987).

Principle Components Ordination and Canonical Correspondence Analysis

Ordination methods such as Principle Components Analysis (PCA) and Canonical Correspondence Analysis (CCA or CANOCO), with its variant, detrended correspondence analysis, are useful techniques for handling multivariate data sets. PCA has enjoyed wide usage in ecology and systematics. This technique is again able to reduce the complexity of a large data set to a manageable size, which is done by producing a smaller number of abstract variables, termed principle components, which are linear combinations of the original variables (Keough and Mapstone 1995). Each of the principle components successively generated are uncorrelated with previous ones, and the aim of the analysis is to identify groups of similar variables "by using the cross-correlated counts of species (numbers and abundance) and positioning the groups on the derived axes" (Keough and Mapstone 1995, pg 37). Identification of a perturbation-induced change with this technique would occur if the 'control' sites grouped out separately to the 'impact' sites. Problems associated with clustering techniques include sensitivity to outlying data and the abstract nature of the derived axes, both of which make interpretation of the results difficult (James and McCulloch 1990).

Correspondence analysis composes a two-way contingency table of counts of objects and their attributes (Keough and Mapstone 1995). Scores are then calculated for each of the row and column categories in the table and eigenvectors generated to illustrate the way in which the rows and columns deviate from what would be expected with independence (Hill 1973). The extraction of continuous axes of variation from species occurrence or abundance data is then used to apply identified environmental gradients (indirect gradient analysis) (ter Braak 1996). This is achieved by relating the pattern of variation seen in community composition (usually well represented by the first few ordination axes) to the environmental variables (Gauch 1982). Canonical correspondence analysis (CCA) extends on this by using known environmental variables to select the ordination axes (ter Braak 1996). In the situation where species display bell-shaped, or unimodal, responses to environmental gradients a detrended approach (detrended canonical correspondence analysis) is more appropriate, yielding an ordination plot that shows the relative positions of species and sites, with vectors representing environmental variables (ter Braak 1989 & 1996). The technique allows the approximation of the centres of species distribution along each of the environmental variables and improves the power to detect the effects of interest (ter Braak 1989 & 1996). Applied examples of the effective use of gradient analysis are given in ter Braak (1989).

Multidimensional Scaling

Multi-dimensional scaling (MDS) has been widely used in recent environmental studies, including investigation of pollution effects (Faith *et al.* 1991, Clarke 1993, Clarke and Warwick 1994a & b). MDS simplifies a complex community data set into points scattered in multidimensional space so that ecological patterns can be seen and interpreted (Kenkel and Orloci 1986, Clarke and Warwick 1994b, Keough and Mapstone 1995). MDS is preferred to some other multivariate methods as it is less affected by the underlying relationships between species or samples, in particular distribution of species abundances (but see Clarke 1993).

Non-metric MDS (using transformations, standardisations and similarity coefficients suitable to the hypothesis being tested) has been effective as an ordination technique

(Clarke 1993). Hybrid multidimensional scaling (HMDS), which combines metric and non-metric criteria, is described in Faith *et al.* (1987), along with the importance of the choice of a dissimilarity measure in ecological ordination techniques. The main problem inherent in the use of MDS and other multivariate methods is that although patterns may be seen in the data, interpretation of their importance tends to be qualitative and subjective (James and McCulloch 1990).

Despite recent advances in multivariate techniques it is still not possible to relate the distance between points on an MDS plot to the size of the impact in a statistically meaningful and consistent way (Keough and Mapstone 1995). Therefore, MDS is most useful in environmental monitoring as a support to other techniques, when a pre-impact data set is absent, or when the expected response to a perturbation is not known and cannot be used to select a suitable univariate indicator (Keough and Mapstone 1995).

MANOVA and Discriminant Analyses

Multivariate **An**alysis **o**f **V**ariance (MANOVA) and the related discriminant function analysis are useful in situations where a range of variables have been gathered for the same sample set and there is more than one dependant variable (Wilkinson 1990, Keough and Mapstone 1995). These techniques are similar to ANOVA in concept and can be used to handle complex monitoring designs.

MANOVA can be more useful than ANOVA in that changes in a suite of organisms can be tested, rather than relying on a single univariate measure (Keough and Mapstone 1995). However, MANOVA assumes that the variables being analysed are independent, an assumption that may be violated in many situations and which needs to be assessed before an analysis proceeds. This is a major difficulty, but these techniques can still serve as a useful analysis tool if the appropriate care is taken (Day and Quinn 1989, Tabachnik and Fidell 1989).

2.6.2.9 Staircase Design

This technique was designed for fishing and fisheries management and is used to monitor effects occurring under different impact regimes (Walters *et al.* 1988, Keough and Mapstone 1995). The basic methodology involves adjusting the intensity of the impact, such as fishing effort, and measuring the responses in target species (Walters *et al.* 1988). In this way it is possible to identify the point where the impact has no serious effect on the target population. This method of impact assessment would not be useful in detecting oil spill effects at Port Stanvac.

2.7 Best Monitoring Design for Port Stanvac

In the event of an operational oil spill occurring at Port Stanvac, it is likely that the rocky intertidal area that dominates much of the coastline adjacent to the oil refinery will be impacted (see Chapter 1). Therefore, the rocky intertidal area, particularly the mid-eulittoral zone, is the focus of a monitoring program. As well as being identified as one of the habitats likely to be impacted by an oil spill, the rocky intertidal area is relatively easy to access and its biota are able to be censused non-destructively. These are important considerations when planning an ongoing monitoring program.

A web of interactive factors, both biotic and abiotic, determines the biological consequences of an oil spill. These include the type and amount of oil and its condition (e.g. degree of weathering), physical environmental factors (e.g. substrata type and prevailing weather conditions) and prior exposure of the area to oil. The presence of other pollutants, the 'self-cleaning' ability of any contaminated coastal sites, the rapidity of any manual spill cleanup and the nature of biota are also important in determining the biological consequences of an oil spill (Loya & Rinkevich 1980, Baker 1991, Suchanek 1993). The complexity of these factors and the way in which they interact, together with the difficulty in determining likely oil grounding sites (see Chapter 5), means that it is not possible to specifically and accurately predict all possible scenarios associated with an operational oil spill at the refinery. Therefore, it is important to establish a generalised monitoring program which is sensitive to a range of effects in response to an unknown volume spill of either crude oil or refined product at an unpredictable stage of weathering, which may ground at a number of different coastal sites in GSV.

Intertidal biota are likely to be affected by the floating component of the oil as it is carried ashore, and may suffer direct toxic effects or physical effects such as smothering. Oil is unlikely to be retained in rocky areas although it may accumulate in sand between rocks and may be trapped in small amounts in rock crevices and between areas of upthrust rock. Long term oil retention on GSV rocky shores is not expected. This, coupled with the relative longevity of most intertidal animals (see Quinn *et al.* 1992), and the likelihood that oil release will be rapidly detected and managed by refinery personnel, means it is likely that an operational oil spill will act as a pulse disturbance in the area and that recovery will be rapid.

The literature review of environmental monitoring techniques (Section 2.6) suggested using a Beyond-BACI approach to monitoring for an oil spill at Port Stanvac. This improves on other BACI techniques in that it is able to assess perturbation-induced variance on a range of temporal (and spatial) scales. As an oil spill is likely to occur as a rapid pulse disturbance, it should be most readily detected using a design with many intervals or 'Periods', in which a few shorter sampling intervals ('Times') are nested (Keough and Mapstone 1995). Preliminary monitoring will focus on two different 'zones' within each designated site, although the primary spatial scale of interest is at the level of the entire reef, or equivalent areas of the shore (see Chapter 4). The two temporal scales of interest are expected to be 'weeks' and 'seasons', and this will be discussed in Chapter 4.

Utilising a Beyond-BACI design in preliminary monitoring allows a test for significant perturbation effects should an intervening impact occur. Since the two errors (α & β) which can arise during statistical testing are considered equally undesirable they have both been set to 0.05 (see Mapstone 1995). Therefore, the desired power of statistical testing to determine if an impact has occurred will be 95%. The effect size to be determined is not known and requires further investigation once the most appropriate environmental variable has been selected.

Intertidal fauna were considered more appropriate bioindicators than intertidal floral elements due to the difficulty in sampling the latter (Jan *et al.* 1994) and their relatively poor representation in the mid-eulittoral zone at eastern GSV sites (Womersley and Thomas 1976, Womersley 1988). A literature review considering the general effects of oil on intertidal biota found in GSV (section 2.4) could not identify a suitable *a priori* bioindicator animal, although gastropods, which display a range of responses to oiling, dominated the targeted intertidal zone (Womersley and Thomas 1976, Womersley 1988). However, consideration of the various biological levels that can be used to determine pollutant-induced effects, suggested a population approach for monitoring in GSV (section 2.5.1.1). The lack of an identified *a priori* bioindicator animal meant that a suite of animals needed to be studied (in conjunction with relevant physical site characteristics) to determine spatial and temporal trends during the pilot study (Chapter 3) and preliminary monitoring (Chapter 4) phases of this project. Such a broad community approach was necessary until a bioindicator species could be selected (Chapter 6), and until spatial and temporal trends in intertidal assemblages had been examined (Chapter 4).

The variability reported in intertidal biota in the vicinity of Port Stanvac (Womersley 1988) meant that long term monitoring was necessary to partition variation associated with an oil spill from natural variation ('noise') (Underwood 1991a, 1992, 1993a & 1994a). A long-term program is also important to differentiate between 'trivial' and 'important' impacts (Osenberg *et al.* 1994, Keough and Mapstone 1995). A knowledge of natural variation in GSV could only be achieved by selecting appropriate biological variables and examining their fluctuations under perturbed and unperturbed conditions over a number of temporal and spatial scales. Therefore, a preliminary study of GSV and its biota in the vicinity of Port Stanvac was needed (Chapters 3 & 4).

A Beyond-BACI design requires selection of a number of 'control' and at least a single 'impact' site (section 2.6.2.4). However, the difficulty in accurately predicting potential 'impact' sites within GSV (due to seasonal and shorter term variations in tide, wind strength and direction, and wave conditions and therefore oil transport) meant that a range of sites were required for preliminary monitoring. This approach maximises the likelihood of at least one of the monitored sites being perturbed.

Chapter 3. Pilot Study Investigation of Rocky Intertidal Areas in Gulf St Vincent

3.1 Introduction

In order to optimise resources for the monitoring program it was necessary to establish the most appropriate sampling protocols (Hewitt *et al.* 1993) and to investigate the amount of temporal and spatial variation in various intertidal animal and plant assemblages in Gulf St Vincent (GSV). In addition, the Beyond-BACI design advocated *a priori* for preliminary and ongoing monitoring (see Chapter 2), required choice of a number of spatially separate 'control' sites, which should ideally be randomly chosen from a large number of suitable sites, and be representative of the 'impact' site(s) (e.g. similar in substrata and assemblage character) (Underwood 1989 & 1991a).

In an effective monitoring program it is necessary to score the presence and magnitude of the pollutant or perturbation of interest (in conjunction with an assessment of the abundance of the bioindicator(s)) and to consider physical parameters which may be important modifiers of patterns of distribution and abundance of biota. These may include site aspect and shelter (Womersley and Thomas 1976), substrata type and complexity, (Emson and Faller-Fritsch 1976, McGuiness 1987a & b, Underwood and Chapman 1989, Connell and Jones 1991, Lohse 1993, Lemire and Bourget 1996) and special features such as pools (Metaxas, Hunt and Schiebling 1994, Metaxas and Schiebling 1993 & 1994, Schneider and Frost 1996, van Tamelen 1996).

To quantify surface complexity a number of techniques were considered (see McCormick 1994, Sanson, Stolk and Downes 1995). However, since sampling time needed to be kept to a minimum, the quickest and easiest field method to adequately quantify surface complexity in a rocky area appeared to be the contour length versus linear length ('chain-and-tape') method described by Risk (1972). This method can successfully discriminate between broad habitat types (see Aronson *et al.* 1994, McCormick 1994).

Non-destructive assessment of biota was necessary in this study due to the plan for repetitive sampling of study sites. Two broad quantitative techniques for assessing intertidal assemblages are transect or quadrat sampling (Jan *et al.* 1994), with the latter technique often using 0.25m^2 quadrats (Andrew and Mapstone 1987). Either of these techniques can be used in conjunction with *in situ* field counts, video sampling (see Carleton and Done 1995) or photographic sampling (Holme and Barrett 1977, George 1980, Foster *et al.* 1991) to quantify biota. The use of video techniques has been useful in underwater surveys (Potts *et al.* 1987) and the video image can be frame-grabbed and input into a computer program using suitable software/hardware and then computer analysed (Jan *et al.* 1994). Photographic or video recording of assemblages saves field time but has potential disadvantages such as expense, photographic failure (and thus data loss), increased laboratory time and failure to find cryptic species, while *in situ* field counts provide an immediate and inexpensive method of collecting data but are more costly in terms of field time.

An overview of general features of GSV, with specific reference to the eastern coast in the vicinity of Port Stanvac has been given previously (Chapter 1 & Appendix A). This part of the thesis deals with a closer examination of the section of eastern GSV which was likely to provide a suite of study sites suitable for biological monitoring and inclusion in the preliminary and possibly ongoing monitoring phases of this study.

3.2 Pilot Study Aims

The aims of the procedural pilot study were to examine a number of suitable rocky intertidal sites along eastern GSV and begin planning and testing sampling strategies for use in preliminary sampling (Chapter 4) and ongoing monitoring (Chapter 8).

The specific aims of this chapter were;

- to select suitable study sites within GSV for ongoing monitoring.
- to become familiar with the dominant animals and plants and their distribution patterns at these sites.
- to assess the efficiency of different sized quadrats for sampling dominant intertidal organisms.
- to compare the efficiency of photographic and video techniques of animal census with *in situ* field counts.
- to identify appropriate parameters which may affect biota abundance, such as substrata composition, weather conditions and oil presence.

3.3 Materials and Methods

3.3.1 Site Selection

Fifteen sites identified as 'rocky' on a 1:50,000 topographical map; "Noarlunga 6627-4 & PT 6527-1, 3rd Edition", were visited in February 1995. During this visit assessments of the topography, presence and distribution of intertidal biota, and the ease of access and wave exposure of sites were made. Nine sites were selected as study sites for the preliminary monitoring program to identify spatial and temporal trends (Chapter 4) and for consideration for inclusion in the ongoing monitoring program (Chapter 8). These nine sites are described in more detail in section 3.4.

Sites were sampled and visited at low tide and access was possible until they were submerged by the incoming high tide. At each site the distribution patterns and dominant animals and plants were noted and recorded. Based on these initial surveys data sheets for census of the most common species and assessment of physical parameters were generated and a photographic handbook compiled to assist with future field identification.

3.3.2 'Zones' of Interest

In general, two 'zones' of interest at selected study sites were identified for sampling. Broadly speaking these 'zones' corresponded to the mid-eulittoral zone (Womersley and Thomas 1976) and were divided into artificial 'upper' and 'lower' sub-zones for the purposes of this study. The 'upper' zone was typically dominated at most sites by one or a few species of gastropod molluscs, and the 'lower' zone supported a similar suite of animals but was characterised by a generally greater contribution of mussels (primarily *Xenostrobus pulex*) and/or specific gastropods (such as *Nerita atramentosa* and *Austrocochlea* spp.).

3.3.3 Biota Census

Plants were scored to genus where possible (e.g. *Ulva*, *Enteromorpha*, *Cystophora*, *Sargassum*, *Corallina* and *Gelidium*) but otherwise were classified at high taxonomical levels (e.g. filamentous brown algae), and quantified by the area they occupied within each quadrat. However, animals were the primary focus and were identified to species (apart for *Notoacmea* spp. which were difficult to identify in the field, and which were classified to genus). The abundances of all animal taxa present in a quadrat were recorded.

Species identification was primarily based on descriptions in Shepherd and Thomas (1989) and Quinn *et al*. (1992), although some specimens were taken to the South Australian Museum for identification by Karen Gowlett-Holmes and Wolfgang Zeidler. All animals which were clearly visible to the naked eye (e.g. greater than 2mm in diameter) were censused *in situ* and classified into three size classes for each species; 'small', 'medium' and 'large'. The 'small' size corresponded to a width up to a third of the adult animal's width, 'medium' corresponded to a width greater than a third and up to two-thirds of the adult width, and 'large' incorporated any width greater than this, with adult size as defined in Quinn *et al.* (1992).

3.3.4 Optimal Sampling Strategies

A number of different procedures, parameters and sampling protocols were tested during this phase of the project. These included the optimal number and size of quadrats to deploy, *in situ* versus other methods of animal census, and the 'chain-and-tape' method of quantifying topographic complexity.

Quadrats: Size and Sampling Efficiency

The use of quadrats seemed most applicable to the study (due to the focus on 'zones'). Two sites, Hallett Cove and PS1, were randomly selected and used to assess the efficiency of different sized quadrats in sampling dominant animals in the two arbitrary zones. The quadrat sizes tested were: 0.25m^2 ,1m^2 and 2.25m^2. Quadrats (positioned using a random numbers chart) were placed in each of the defined intertidal zones to sample the animals present and test the sampling precision obtained when up to ten quadrats were deployed. Precision, calculated by dividing the standard error by the average abundance of a species per quadrat (Zar 1984), was graphed against increasing quadrat number. Cumulative species capture was also compared using the different sized quadrats. When trialing the different quadrat sizes the small quadrat was randomly positioned first and then consecutively replaced by the larger quadrats to save censusing time.

Photographic and Video Census Versus Field Counts

A Pentax P30 camera with zoom lens was used to obtain a photographic record (using 35mm colour slides) for each small quadrat which was deployed at Hallett Cove. The abundance of each animal species present in each quadrat were also censused *in situ* by eye. This study took place in late February 1995 and slides were processed, brought back to the laboratory and enlarged on a screen to determine species composition and abundance. Video recording of quadrats was performed on a single day in March 1995 and the image extracted by freezing the film and projecting it onto a screen. In both cases, census methods were compared to the appropriate *in situ* field counts (for the same quadrats). Seven replicates were used for each of the trialed methods (photographic, video and field counts) and comparisons were made only in relation to the dominant animal species present. Video recording was carried out in the 'upper' zone at Hallett Cove, while the photographic pilot study was performed in both the 'upper' and 'lower' zones at the same site.

Analysis of how well the photographic and video techniques compared to *in situ* animal census involved paired student's *t*-tests. The two trialed methods of photographic and video recording were separately compared with the 'control' method (*in situ* counts), with all differences between the treatment pairs being normally distributed (based on the Anderson-Darling (AD) test statistic) (refer to Snedecor and Cochran 1989), after a $\log_{10}(x+1)$ transformation (Zar 1984). All statistics were computed using "SYSTAT" V5.0 (Wilkinson 1990). It was hypothesised that photographic and video techniques would underestimate the abundance of the dominant species recorded at study sites, so one-tailed hypotheses were used in the analyses.

Parameters Assessed in Conjunction with Biota Abundance

It appeared that substrata complexity was an important modifier of biota patterns and the 'chain-and-tape' method was trialed during the pilot study to attempt to roughly quantify this parameter. A four metre galvanised steel chain consisting of interlocked couplet links (1.5cm apart) was used to quantify substrata topography as described by McCormick (1994). As hydrocarbon analysis would be costly and time consuming, oil (or hydrocarbon) presence was assessed using a subjective score ranging from no oiling to heavy levels of oiling (Table 3.1).

Table 3.1 Assessment of the level of oil contamination in quadrats was based on a subjective scoring system ranging from 0-4. Both crude and refined product can be quantified by this scoring system although category '1' cannot be applied to a petroleum oil spill.

Score	Description
0	no visible oil or oil product
1	old weathered tar-like aggregation
2	fresh oil present as a taint or sheen
3	fresh oil present as obvious oil (globules or thin film)
4	fresh oil present in large amounts (e.g. thick oil film)

In addition to scoring substrata complexity and hydrocarbon presence, a number of other parameters were deemed relevant to this study. These included weather conditions such as sun presence versus the degree of cloud cover, air temperature, rain (nil, light, medium or heavy), wind strength and direction, wave action and human visitation (the latter discussed in Chapters 4 & 7). Wind and wave strength were subjectively ranked on a scale of 0-4; 0=nil, 1=light, 2=moderate, 3=strong, 4=storm or gale-force conditions.

In each quadrat the amount and type of substrata (sand, pebble, cobble, boulder, bedrock), percentage shade, maximum water depth, maximum elevation of substrata and the percentage of retained water were recorded. The pH, conductivity (and salinity) and water temperature (at a depth of 20cm) were also recorded in the closest water, other than a tidal pool, at each site using a hand held YSI 600 water-meter. As tidal pools were clearly different to adjoining substrata, when random numbers positioned a quadrat in a distinct permanent pool the quadrat was reassigned to the closest adjacent non-pool substrata. A full sampling run involving all sampling parameters and protocols identified as optimal in this phase of the project, was carried out over two days in February to determine any difficulties and the time costs likely to be incurred in preliminary monitoring. However, only data pertaining to the abundance and precision associated with *in situ* sampling of *B. nanum* at the full set of study sites has been included in this chapter.

3.4 Study Sites

Potential study sites situated along approximately 24 km of the eastern side of GSV, stretching from Seacliff to Moana, were visited during February 1995 to assess their suitability as study sites (Fig. 3.1 and Plates 3.1, 3.2 & 3.3). The rocky intertidal area within the boundary of the Port Stanvac Oil Refinery was visited first and used as a reference against which other potential sites were compared. Sites were judged as suitable for monitoring if they had similar topography to Port Stanvac (e.g. 'rocky', with a preference given to stable bedrock strata) and a similar suite of animals.

Following initial assessment, nine sites which met the criteria for inclusion as monitoring sites were randomly selected (Fig. 3.1). Three of these were situated to the north of Port Stanvac, designated as 'Northern' study sites, three to the south, designated as 'Southern' study sites, and three positioned within the boundaries of the refinery, were designated as 'Central' study sites. Two arbitrarily defined 'zones' within the mid-eulittoral region, classified on the basis of clearly different assemblages, were defined at each study site apart from Witton Bluff.

The selected study sites gave a reasonable cover of 18km of coastline, with Port Stanvac being roughly centrally located (Fig. 3.1) and were also relatively easy to access. These sites will be briefly described in "*Specific Site Descriptions*". It must be noted that when a site is said to be worked in two directions, for example west and south, this means that quadrats are positioned using two random numbers one of which is allocated to each of the designated directions. To assist in locating study sites, road maps copied from "UBD Street Directory, Adelaide, 1994: (31st Edition)" have been presented as Appendices E-I.

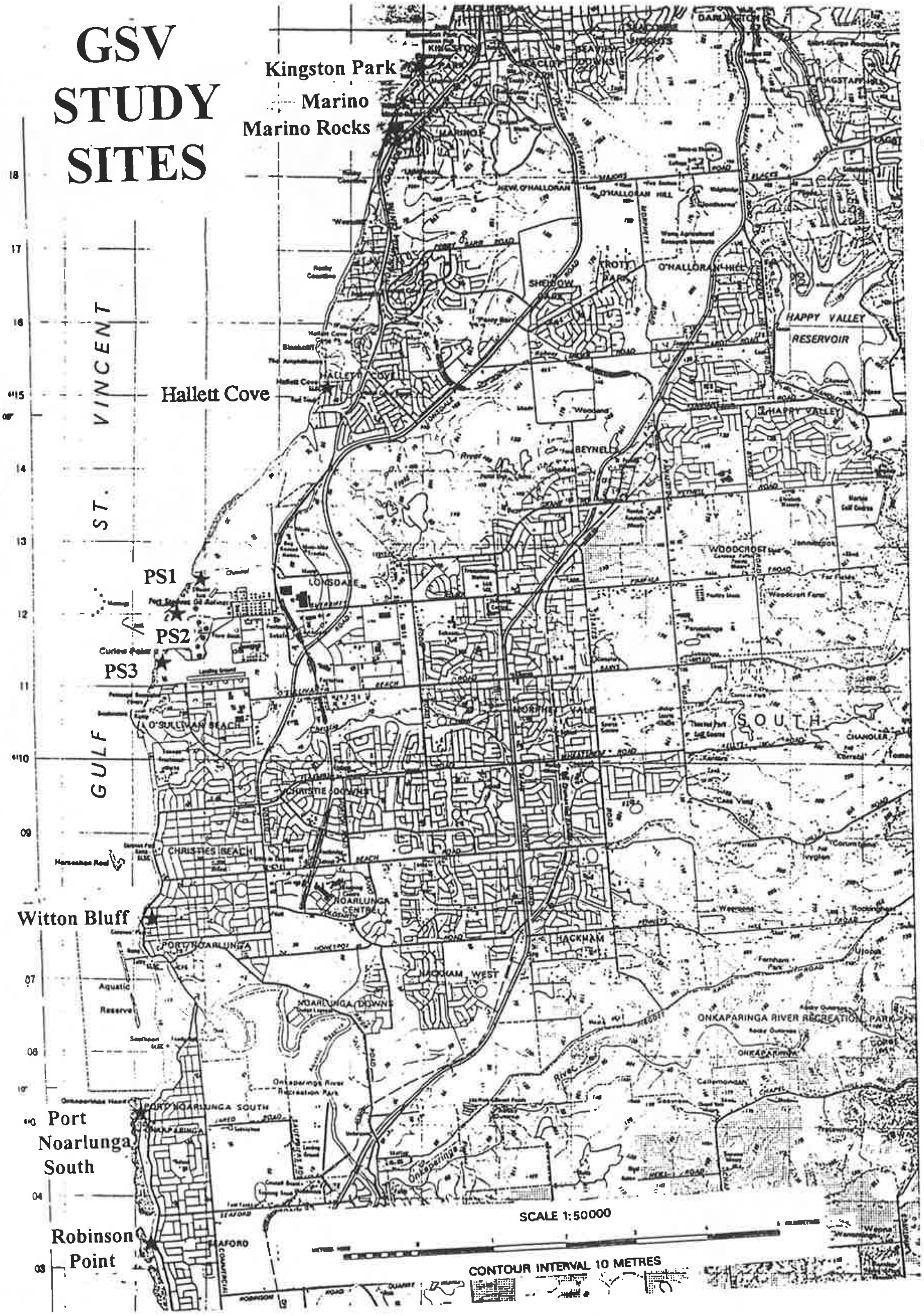


Fig. 3.1 The position of study sites along the eastern coast of GSV. The study sites are designated with a star and (from north to south) are; Kingston Park, Marino Rocks, Hallett Cove, PS1, PS2, PS3, Witton Bluff, Port Noarlunga South and Robinson Point (Modified from 1:50,000 topographical map "Noarlunga 6627-4 & PT 65271, 3rd Edition").

Plate 3.1 Aerial view of two of the 'Northern' study sites (Kingston Park and Marino Rocks) that are situated on the eastern coast of GSV. Original photo from an 'Environmental Protection Board' Aerial Survey (obtained from 'Map Land', Netley).

Plate 3.2 Aerial view of the remaining 'Northern' study site (Hallett Cove) and the 'Central' study sites (situated within Port Stanvac and designated PS1, PS2 and PS3). Study sites are situated on the eastern coast of GSV. Original photo from an 'Environmental Protection Board' Aerial Survey (obtained from 'Map Land', Netley).

Plate 3.3 Aerial view of the 'Southern' study sites (Witton Bluff, Port Noarlunga South and Robinson Point). Study sites are situated on the eastern coast of GSV. Original photo from an 'Environmental Protection Board' Aerial Survey (obtained from 'Map Land', Netley).

Specific Site Descriptions

Kingston Park (Plate 3.4)

Kingston Park is located next to the Kingston Park Caravan Park and may be prone to recreational pressure especially during school holidays and weekends. It is situated in a relatively sheltered bay and is flanked to the east by a cliff.

This site is situated at the end of a Service Road which is entered from Esplanade Road (Appendix E: Map 152, coordinates E & 14.5). At the end of the Service Road is a seawall with a cemented lower section. The 'upper' zone commences 24m from the start of this seawall and extends for a further 11m. The substrata is predominantly flat bedrock with fissures and shallow eroded depressions and occasional interspersed areas of rounded pebble, cobble and boulder. The 'lower' zone commences 48.5m to the west of the seawall and is restricted to the last flat strata before the cobble section that extends from the low water mark to the sublittoral zone. This substrata is similar to that seen in the 'upper' zone but is generally more elevated and has a more 'cracked' and fissured surface. Assemblages in the 'lower' zone are characterised by the presence of areas of mussels. Both zones are worked towards the west and the south.

Marino Rocks (Plate 3.5)

This site is located to the south of Kingston Park, is relatively sheltered and is the central of the 'Northern' study sites. It is flanked on its landward side by very steep clay cliffs and is accessed from a car park at the end of Jervois Road (Appendix F: Map 164, coordinates D & 0.5). The sampled area is located 250m south of the boat ramp which is situated at the end of the track leading from the car park to the beach. The 'upper' zone commences 32m from a cairn which has been built at the base of the cliff, and consists of bedrock strata (some of which is elevated) and areas of loose cobble and boulder which entraps sand. The 'lower' zone commences 50m west of the cairn and is similar in substrata composition but supports a more diverse fauna. Both zones are worked towards the west and south.

Hallett Cove (Plates 3.6 & 3.7)

The Hallett Cove site is adjacent to a Surf Life Saving Club and a reserve with playground and barbecue facilities. It is flanked by a man-made boulder retaining wall situated behind the path which leads to the beach and is bordered by sandy hills which increase in size on either side of the site.

The sampled area is situated south of the Surf Life Saving Club at Herron Way, adjacent to the car park that is entered from Grand Central Avenue (Appendix G: Map 175, coordinates Q & 1). The 'upper' zone consists of very flat bedrock strata marked with occasional shallow (less than 1.5cm) depressions. It is located immediately north of a cobble and boulder field. Sampling of the 'upper' zone commences 15m west of the start of the flat bedrock strata and extends for a further 10m. The 'lower' zone begins 35m west of the start of the flat bedrock, continuing for a distance of 10m. This zone predominantly consists of bedrock strata and is characterised by an increase in diversity and the presence of mussels. The area is worked to the west and south for both designated zones.

Port Stanvac Study Sites

The refinery is entered via Refinery Road (Appendix G: Map 175, coordinates N & 15). All Port Stanvac sites are accessed by car via the coastal track within the refinery. The coastline within the refinery is predominantly rocky, with flat bedrock interspersed by heavily upthrust bedrock and overlaid in parts by large amounts of mobile substrata. Topographically this substrata tends to be less homogeneous than that seen at the majority of the other study sites. PS1 and PS2 are bordered by high shale cliffs on their landward side, while PS3 has a sand hill backdrop. The 'lower' zones at the Port Stanvac study sites are distinguishable from the equivalent 'upper' zones by an increase in species diversity.

PS1 (Plate 3.8)

This is the most northern of the 'Central' study sites and is located close to the northern boundary of the refinery. Refinery effluent is discharged via a pipe which lies 30m to the north of PS1. Mitsubishi Motors operates a plant adjacent to the refinery, and discharges manufacturing and other runoff via a pipe on the cliff just outside the northern refinery boundary. Both the Mitsubishi outfall and Mobil's effluent outfall can potentially affect assemblages at PS1 and possibly other adjacent sites depending on seasonal factors and prevailing wind, wave and tidal conditions (see Appendix A).

The PS1 site is situated at the end of the coastal refinery road. The actual area to be sampled is located at a point 30m to the south of the join on the effluent discharge pipe, and 7m to the west. The 'upper' zone begins at this point and extends a further 15m west, and consists predominantly of flat bedrock with occasional upthrust sections and interspersed areas of cobble and boulder. The 'lower' zone begins in a region of cobble that overlies bedrock a further 5m beyond the 'upper' zone and is restricted to this area. Both zones are worked to the west and south.

PS2 (Plate 3.9)

This site is accessed from the coastal refinery road before PS1 is reached. The 'upper' zone is located 7m west of an obvious upthrust rock which is situated 48m to the west of survey peg no. 302 (the second blue surveyor's peg to the north of a large rock column). The 'upper' zone consists of flat bedrock strata which extends for approximately 30m in a north-south direction. Another region of flat bedrock strata is found to the west, but the most easterly strata is the one which is worked upon. Sampling is restricted to this strata and continues in a southerly direction. The 'lower' zone commences 3.5m beyond an area of upthrust rock which is seaward of the 'upper' zone and is sampled towards the west and the south.. The substrata in this zone is mainly bedrock, some of which is upthrust.

PS3 (Plate 3.10)

This site is located to the south of the Port Stanvac wharf beyond the fuel tanks adjacent to the beach. A large boulder is found embedded in the sand midway along the beach, approximately 25m west of a 1m high sand dune. The 'upper' zone is located at a point 19m south-west of this rock, heading towards the last beacon situated on the southern stone breakwater. The strata is flat bedrock with some upthrust areas, overlaid in parts by cobble and boulder, among which is trapped smaller substrata (including sand). The 'lower' zone commences to the west of the 'upper' zone, 1m beyond a small region of upthrust strata, and does not extend beyond the next region of upthrust rock. This zone consists of a mix of cobble and pebble amid areas of flat bedrock and is characterised by an increase in species diversity. Both zones are worked towards the west and the south.

Witton Bluff (Plates 3.11 & 3.12)

Witton Bluff is designated as a marine reserve and is situated north of the Port Noarlunga Jetty and the Onkaparinga River Estuary. The sampled site consists of a stable reef comprised of bedrock which is heavily eroded to form areas that tend to retain water at low tide and form rock pools. It is low-lying, and is exposed to the air for a much shorter time than the other study sites.

It is accessed from Esplanade Road which is entered from Beach Road (Appendix H: Map 185, coordinates E & 3). The site is reached from a path that runs behind a toilet block. The reef is located by climbing down a man-made boulder retaining wall. A steep cliff comprised of a mix of clay and sand sediment, reinforced by the retaining wall, flanks the landward edge of the reef.

Due to access difficulties only the 'upper' zone was sampled at this site. This commences 30.3m west of the stone breakwater wall and extends for an additional 20m. This reef had a uniquely different animal assemblage to the other sites, being dominated by the gastropod *Turbo undulatus* which was not seen within the defined zones at the other sites. The reef itself is elevated on its northern side which has extensive mussel beds, while the southern edge has an extensive spread of *Ulva* spp. The man-made retaining wall at this location supports high numbers of diverse animals including abalone, *Notoacmea* spp. and *Cellana tramoserica*.

Port Noarlunga South (Plates 3.13 & 3.14)

This site is some distance from the Port Stanvac sites and is entered from Esplanade Road beyond the Onkaparinga River. It is on the southern side of Onkaparinga Head, to the north of a Trig Point which is located in a car park (Appendix I: Map 195, coordinates E & 12). The site is reached via a path from the car park and the reef to be sampled is the last one north of the path immediately adjacent to deep water. The 'upper' zone commences 24m to the west of an eroded hole in the centre of a small natural seawall landward of the intertidal reef and extends a further 18m from this point. The 'lower' zone commences 50m from the eroded hole in the cliff and can continue to low water mark and is characterised by an increase in mussel density. The centre of the reef is worked in a west and south direction for both zones. Port Noarlunga South consists of a stable rock platform with large eroded holes which tend to retain water and form small rock pools, so topographically it resembles Witton Bluff. The site is flanked by a high landward cliff composed of sand and clay type material.

Robinson Point (Plate 3.15)

This site is the most southern study site and is again reached from Esplanade Road (Appendix I: Map 195, coordinates E & 8). The car park adjacent to bus stop 84 is entered and the reef accessed via stairs from the top of the high cliff flanking the site. The reef being sampled is the first to the south of the stairs and is low-lying and therefore difficult to access at times. A stormwater outfall pipe lies approximately 50m south of the site and may influence the reef under high rainfall conditions.

Robinson Point consists of a relatively homogeneous substrata of embedded boulder and cobble stabilised in sand. The tendency to be embedded affords the substrata a high degree of stability, made even more so by the sheltered aspect of the reef. It is considered to be equivalent to sites with stable bedrock substrata since it is unlikely the substrata would be readily mobilised. However, sand scour may be a feature of the area.

Sampling of the 'upper' zone begins 68.5m from the base of the cliff, extending a further 26m from this point. The 'lower' zone is characterised by an increase in mussel density and is defined as beginning 104m from the base of the cliff and extending to the low water mark. The reef is worked to the west and south for both zones.

Plate 3.4 The area sampled at the Kingston Park study site. The study region extends from just beyond the darker bedrock in the foreground and stops before the cobble is reached.

Plate 3.5 The Marino Rocks study site primarily consists of elevated substrata interspersed by regions of loose cobble and boulder.

Plate 3.6 The Hallett Cove site is located on the flat bedrock strata seen in the centre of this plate and is flanked on both sides by cobble and boulder fields. At the time this photo was taken sand had covered sections of the substrata in the sampled area.

Plate 3.7 The flat bedrock substrata which dominates the Hallett Cove study site is shown in this plate. Note the shallow eroded holes which retain small volumes of water at low tide. The main animals shown within the wooden quadrat are *Bembicium nanum* and *Austrocochlea constricta.*

Plate 3.8 The wooden 0.25m^2 quadrat in position at the PS1 site. The substratum is predominantly stable bedrock with fissures and small eroded holes. The small molluscs present as brown specks on the rock are mainly *Bembicium nanum*.

Plate 3.9 The position of the PS2 site to the north of the refinery wharf. Note the large amount of mobile boulder and cobble substrata at this site. The position of the quadrat marks the start of the sampled region.

Plate 3.10 The PS3 site lies to the south of the refinery wharf and ship-to-shore pipeline. The strata is flat bedrock, with some upthrust areas, overlaid in parts by cobble and boulder, among which smaller substrata (including sand) is trapped.

Plate 3.11 Witton Bluff is located by climbing down a man-made boulder retaining wall (shown in the foreground of this plate). A steep cliff comprised of a mix of clay and sand sediment, reinforced by the retaining wall, flanks the landward edge of this reef.

Plate 3.12 Witton Bluff consists of a stable low-lying reef dominated by bedrock which is heavily eroded to form areas that tend to retain water at low tide (forming rock pools).

Plate 3.13 A view of the natural seawall which lies to the east of the Port Noarlunga South site. The area that is sampled at this site is shown in the foreground. A sand and clay-mix cliff is situated landward of the seawall.

Plate 3.14 The Port Noarlunga South site consists of a low-lying limestone reef which has formed from bedrock which has been eroded by constant wave action to form some quite deep holes.

Plate 3.15 The Robinson Point site is shown being sampled. The reef consists of cobble and boulder substrata much of which is embedded and stabilised by sand and mussel beds. A high cliff lies landward of the site which is low-lying and relatively sheltered.

3.5 Results and Discussion

3.5.1 Assemblage Structure at Study Sites

The preliminary examination of the study sites was used to assess assemblage patterns and composition. All selected study sites had relatively stable substrata (bedrock or embedded cobble), but Marino Rocks and two of the Port Stanvac sites also had patches of less stable substrata.

The 'Northern' Study Sites

The 'upper' zone at Hallett Cove was dominated by the gastropod *Bembicium nanum*, interspersed with small patches of the mussel *Xenostrobus pulex*. This zone was also characterised by occasional appearances of the gastropods *Austrocochlea constricta*, *Austrocochlea concamerata* and *Siphonaria diemenensis* and the limpet *Cellana tramoserica*. The 'lower' zone at Hallett Cove was heavily dominated by *X. pulex* (in terms of space occupied and numerical abundance). *B. nanum* was also present in this zone at similar abundances to those found in the 'upper' zone. In addition, slight increases in the densities of the other gastropods, and rare appearances of *Nerita atramentosa* and *Lepsiella vinosa* occurred in this zone. The 'upper' and 'lower' zones at Marino Rocks revealed very similar patterns to the equivalent Hallett Cove zones. However, Marino Rocks generally supported lower densities of all species compared to Hallett Cove, although the relative contribution by *N. atramentosa* increased. Patches of *X. pulex* mussels were seen in the 'lower' zone at this site.

Kingston Park had similar assemblage patterns to Marino Rocks and *B. nanum* was again the most common species in the 'upper' zone. *Littorina* spp. were noted at high regions of the shore at Kingston Park and Marino Rocks, with the greatest densities being seen in the supralittoral zone. However, some of these animals extended their distribution into the 'upper' zones at these sites. At all 'Northern' sites *N. atramentosa* and *Austrocochlea* spp. were seen in greater abundance in the 'lower' zones than in the corresponding 'upper' zones.

The 'Central' Study Sites

Similar patterns to those seen in the 'Northern' sites were observed in the three 'Central' sites. However, the 'lower' zone at PS2 was the only Port Stanvac site with high densities of *X. pulex*. The Port Stanvac sites, particularly their 'lower' zones, showed a greater numerical contribution by rarer gastropods (such as *Austrocochlea* spp. and *N. atramentosa*). *Littorina unifasciata* and *Littorina praetermissa* were noted to occur infrequently in small aggregations in the 'upper' zone at PS1.

The 'Southern' Study Sites

The 'Southern' sites consisted of reefs where the primary difference between the 'upper' and 'lower' zones were heavier densities of *X. pulex* in the latter, a characteristic which was gradual rather than abrupt. Witton Bluff was unusual in that it was the only designated study site where the large gastropod *Turbo undulatus*, which is typically found in rock pools and in the lower littoral zone, occurred (Quinn *et al.* 1992). It should be mentioned that this animal was seen at Port Stanvac and Hallett Cove but was found in the lower littoral region at these sites, and was rarer at Hallett Cove. *Austrocochlea* spp. (particularly *A. constricta*) also occurred at Witton Bluff.

The Witton Bluff site was difficult to access and relatively homogeneous in terms of its assemblage structure. Only one 'zone' was targeted for preliminary monitoring although two were examined during the pilot study phase of this project. The 'lower' zone at Witton Bluff supported very high densities of *X. pulex* in association with reduced densities of *T. undulatus.* The densities of algae (such as coralline and mat algae) were conspicuously high at Witton Bluff presumably due to a topography which promoted water retention and a short period of air exposure during low tide. This site supported low densities of the two *Austrocochlea* spp.

Port Noarlunga South was a relatively homogeneous site in terms of its substratum and species assemblage. *X. pulex* occurred throughout the site but higher densities and larger animals were seen in the 'lower' zone. *B. nanum*, *S. diemenensis* and *A. constricta* was also present at high densities in both zones but tended to be most abundant in the 'upper' zone.

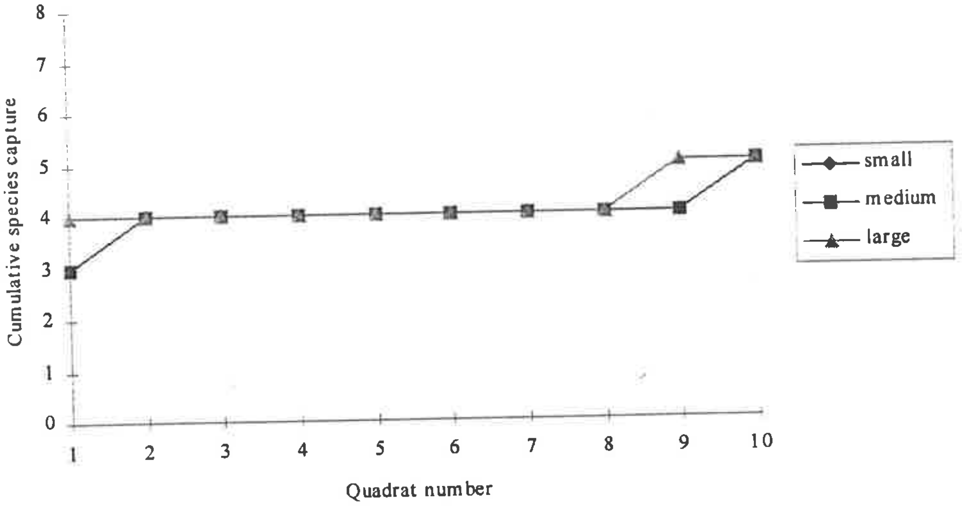
Robinson Point was the most southern of the study sites and its 'upper' zone was dominated by *B. nanum* and characterised by high numbers of *A. constricta* and low densities of *L. vinosa.* In contrast, the 'lower' zone was dominated by *X. pulex* and supported high densities of *S. diemenensis.* Low densities of the limpet *C. tramoserica* were seen at all sites apart from Kingston Park. Barnacles (primarily *Chthamalus antennatus*) occurred at the majority of sites but were inconspicuous at Hallett Cove and Robinson Point and most abundant at Port Noarlunga South and the 'lower' zone of PS1.

3.5.2 Optimal Quadrat Size and Number

Species Capture

The pilot testing of the efficiency of three different sized quadrats occurred at Hallett Cove and PS1 in February 1995 and involved animal species only. No association between species capture and the trialed quadrat sizes was found at PS1, and the majority of species were captured after three quadrats (of any size) had been deployed (Fig. 3.2). Hallett Cove was more diverse than PS1 and at this site the larger quadrat was slightly more efficient, in terms of early species capture, than the other quadrats (Fig. 3.3). However, after seven quadrats had been deployed in both zones the majority of animal species were accounted for. Therefore, in terms of species capture, the use of seven small quadrats was recommended to efficiently sample animals in both the 'upper' and 'lower' zones at the two selected sites (which were considered representative of the suite of study sites).

a) PS1, 'upper' zone



b) PS1, 'lower' zone

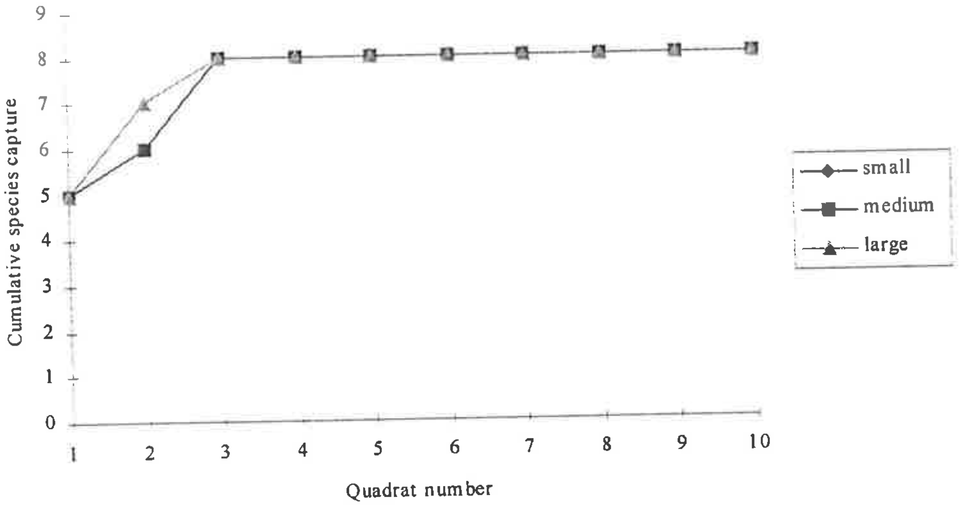
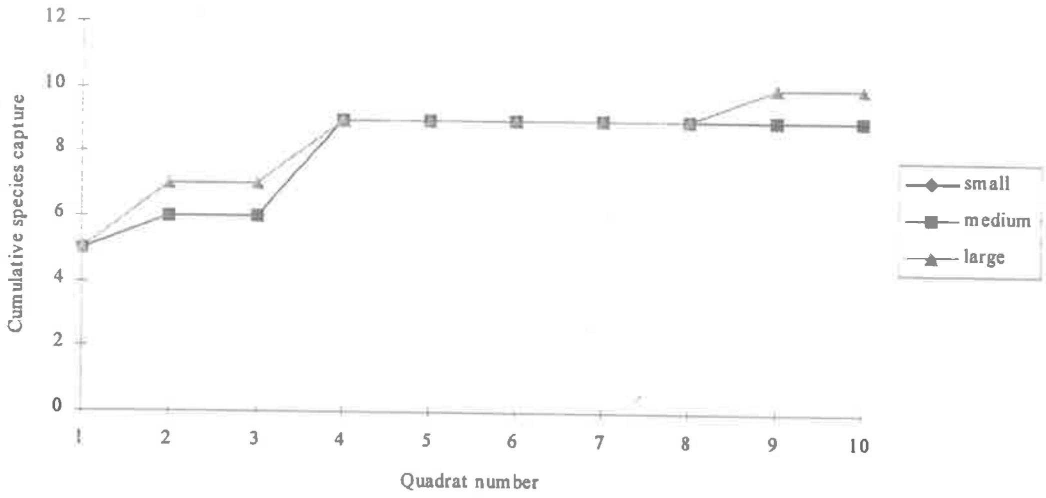


Fig. 3.2 Pilot study examination of the efficiency of animal species capture at PS1 using three different sized quadrats. The *x*-axis indicates the number of quadrats deployed and the *y*-axis indicates the cumulative species capture as the number of deployed quadrats increases from 1-10. The quadrat sizes trialed were; small (0. 25m^2), medium (1m^2) and large (2.25m^2). Note that the lines for species capture overlap for the small and medium sized quadrats.


a) Hallett Cove, 'upper' zone

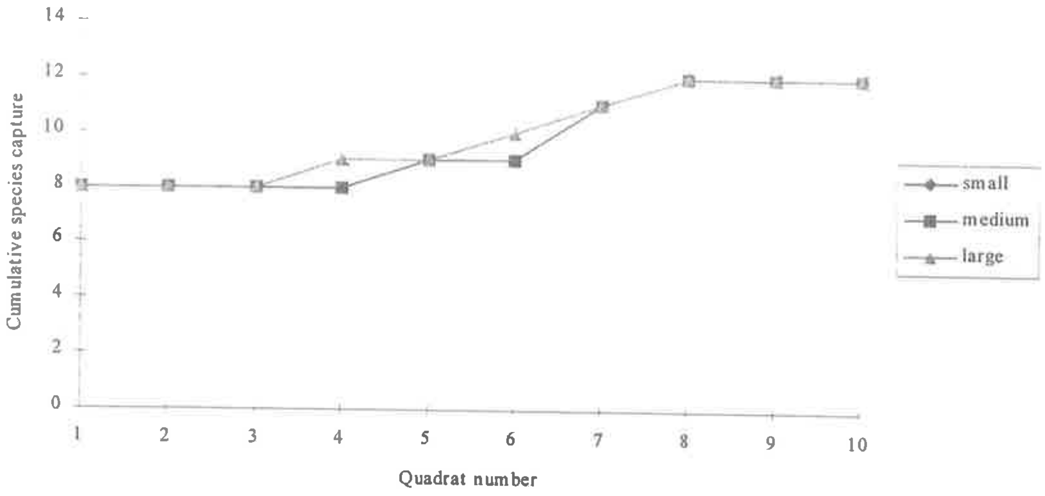

b) Hallett Cove, 'lower' zone

Fig. 3.3 Pilot study examination of the efficiency of animal species capture at Hallett Cove using three different sized quadrats. The *x*-axis indicates the number of quadrats deployed and the *y*-axis indicates the cumulative species capture as the number of deployed quadrats increases from 1-10. The quadrat sizes trialed were; small ($0.25m^2$), medium ($1m^2$) and large ($2.25m^2$). Note that the lines for species capture overlap for the small and medium sized quadrats.

Abundance and Sampling Precision

B. nanum was the most abundant animal in the 'upper' zones at PS1 and Hallett Cove and displayed a more homogeneous distribution pattern that the majority of other species, including *X. pulex* which was characterised by a high degree of spatial patchiness. Sampling precision and the average abundance per quadrat (and standard error) associated with *B. nanum* census have been separately plotted against number of quadrats deployed for both the PS1 and Hallett Cove sites. However, only precision graphs have been presented for the rarer and/or more spatially variable species. The lower the precision value, the less fluctuation exists about the mean, and the more satisfactory the outcome.

The graphs relating to PS1 reveal a plateau of *B. nanum* abundance after three quadrats were deployed in the 'upper' zone (Fig. 3.4a), but little evidence of stabilisation of numbers after ten quadrats were deployed in the 'lower' zone (Fig. 3.4b). A satisfactory precision of 0.2 was achieved after seven quadrats had been deployed in the 'upper' zone, and there was no discernible difference in precision between the different sized quadrats (Fig. 3.4c). Sampling precision remained higher for *B. nanum* in the 'lower' zone at PS1, but underwent a steady decline after deployment of six quadrats (Fig. 3.4d). Only after ten quadrats had been deployed did the sampling precision approach 0.2 in the 'lower' zone at PS1. The precision obtained in reference to two other species found in the 'lower' zone at PS1 did not differ significantly according to the size of the quadrat deployed, but a general tendency to reach an asymptote after seven quadrats had been deployed was noted (Fig. 3.5). The values calculated for sampling precision remained above 0.2 for both *S. diemenensis* (Fig. 3.5a) and the barnacle *C. antennatus* (Fig. 3.5b) at PS1.

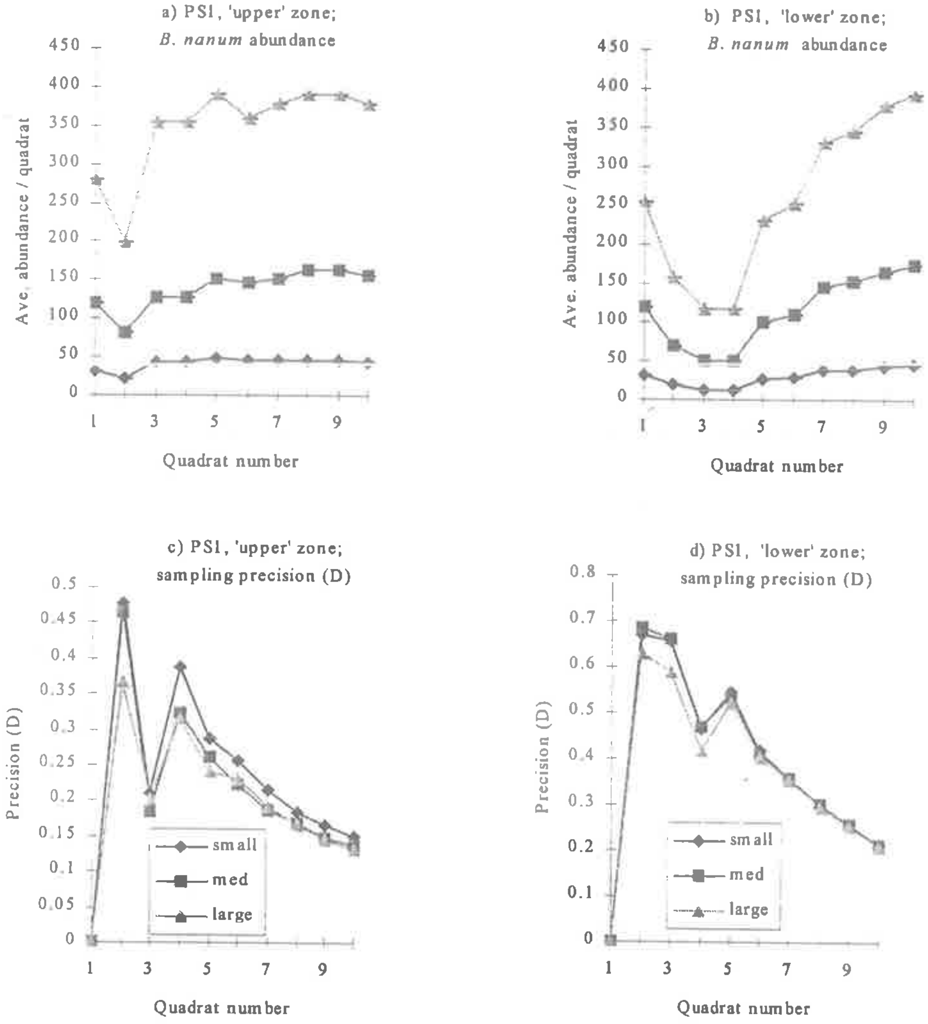
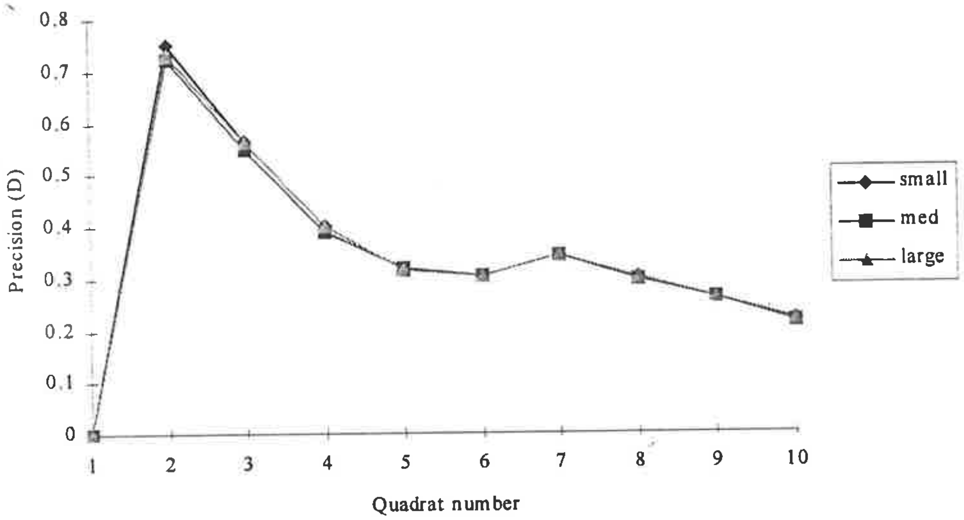


Fig. 3.4 A comparison of the average abundance of *B. nanum* per quadrat plotted against the number of quadrats deployed in both the 'upper' (a) and 'lower' (b) zones at PS1. Error bars represent standard errors. The sampling precision (D) has also been calculated from the abundance graphs for the 'upper' (c) and 'lower' (d) zones at PS1 following deployment of an increasing number of quadrats. The quadrat sizes trialed were small (0.25m^2), medium (1m^2) and large (2.25m^2). Note that the lines for sampling precision tend to overlap, or almost overlap, for the different sized quadrats.

a) PS1, 'lower' zone;
S. diemenensis



b) PS1, 'lower' zone;
Chthamalus antennatus

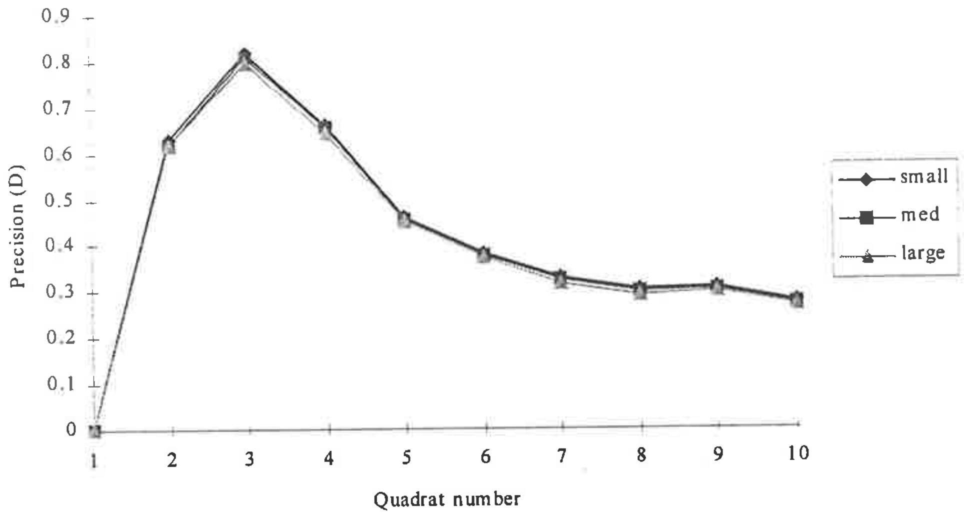


Fig. 3.5 Comparison of the efficiency of different sized quadrats in terms of the sampling precision (D) for *S. diemenensis* (a) and *C. antennatus* (b) in the 'lower' zone at PS1, when up to 10 quadrats were deployed. The quadrat sizes trialed were small (0.25m^2), medium (1m^2) and large (2.25m^2). Note that the lines for sampling precision tend to overlap, or almost overlap, for the different sized quadrats.

The abundance of *B. nanum* at Hallett Cove was different in the two zones, with the 'upper' zone supporting much higher densities than the 'lower' zone. An abundance plateau was seen in the 'upper' zone after deployment of 6 quadrats (Fig. 3.6a), while a similar trend appeared to be present when five to eight quadrats were used in the 'lower' zone, although an increase in abundance was noted when more quadrats were deployed (Fig. 3.6b). The standard error associated with the average abundance of *B. nanum* at Hallett Cove appeared to be greater in the 'upper' zone, particularly when the larger quadrat was used (Fig. 3.6a).

An examination of the sampling precision associated with *B. nanum* revealed differences between the various sized quadrats, with slightly better results being achieved with the smaller quadrat in both 'zones' at Hallett Cove (Fig. 3.6c & d). Greater precision was achieved in the 'lower' zone than in the 'upper' zone when the small quadrat was used, with scores of 0.08 and 0.24 being achieved respectively after seven quadrats had been deployed (Fig. 3.6c & d). *A. constricta* and *X. pulex* were found in the 'lower' zone at Hallett Cove, and the precision associated with their abundance and the different sized quadrats was also investigated (Fig. 3.7). This examination revealed attainment of precision values below 0.15 after five quadrats of any size have been deployed.

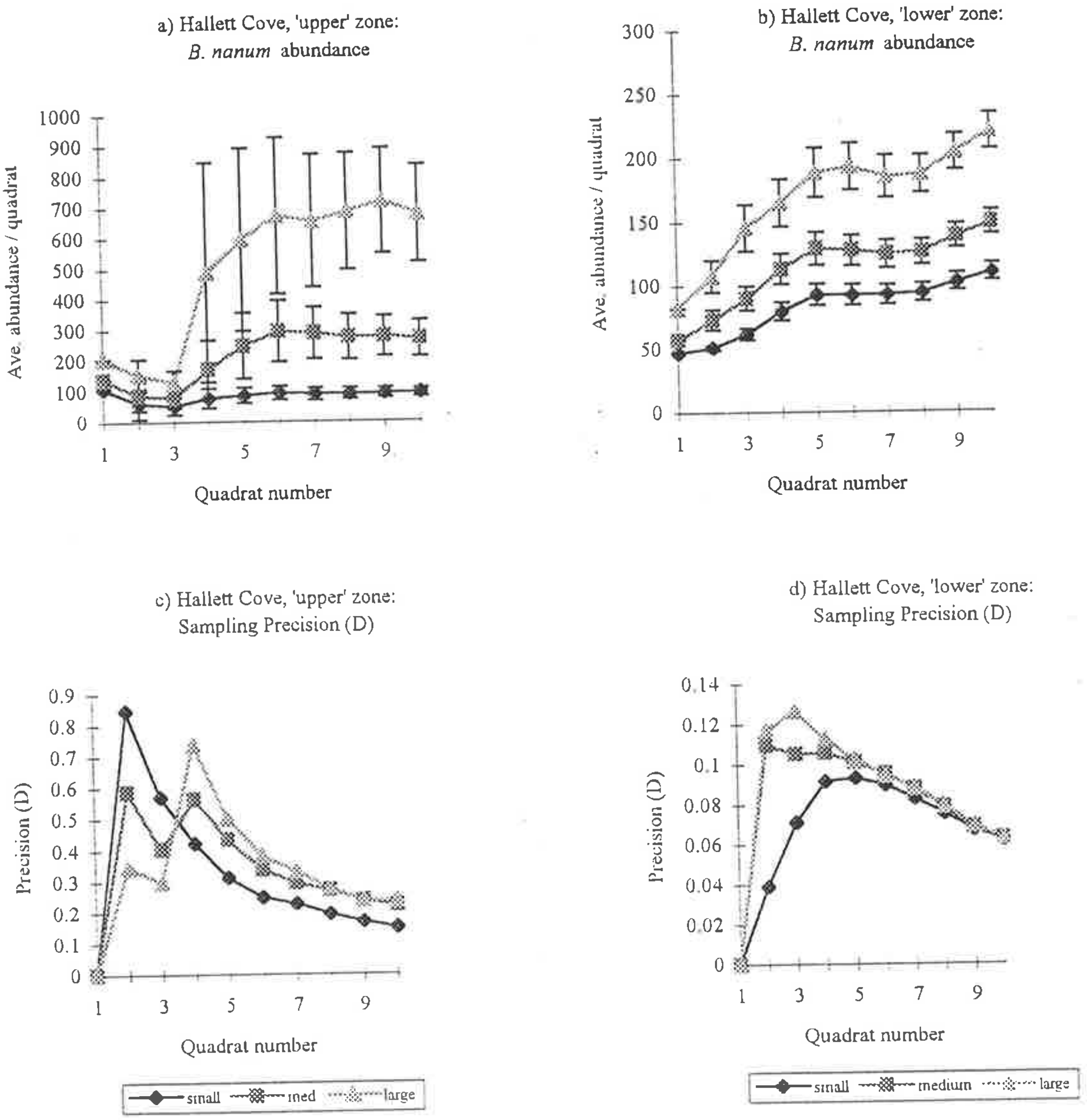
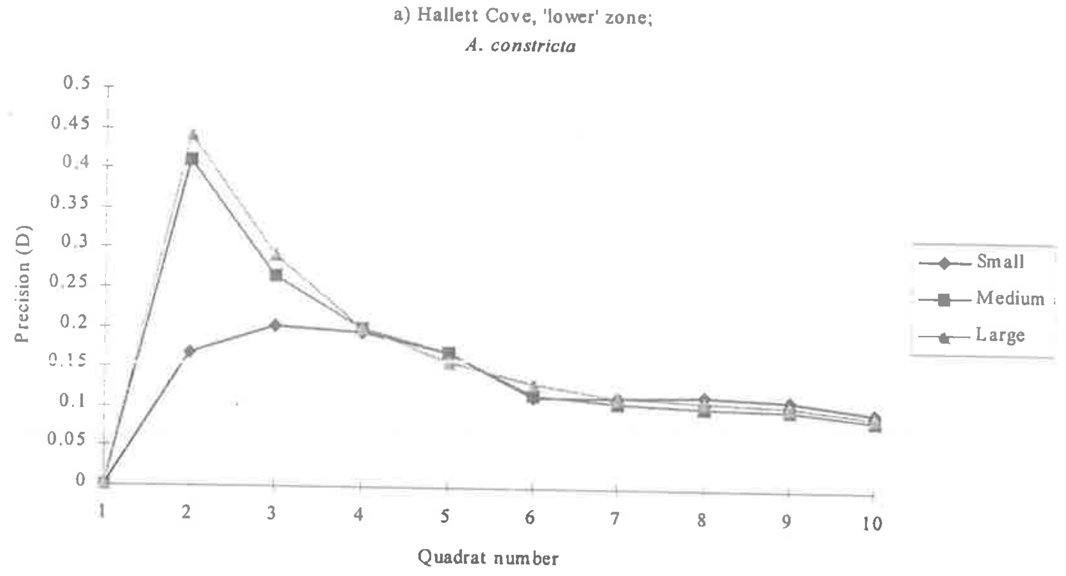


Fig. 3.6 A comparison of the average abundance of *B. nanum* per quadrat plotted against the number of quadrats deployed in both the 'upper' (a) and 'lower' (b) zones at Hallett Cove. Error bars represent standard errors. The sampling precision (D) has also been calculated from the abundance graphs for the 'upper' (c) and 'lower' (d) zones at Hallett Cove following deployment of up to 10 quadrats. The quadrat sizes trialed were small (0.25m^2), medium (1m^2) and large (2.25m^2).



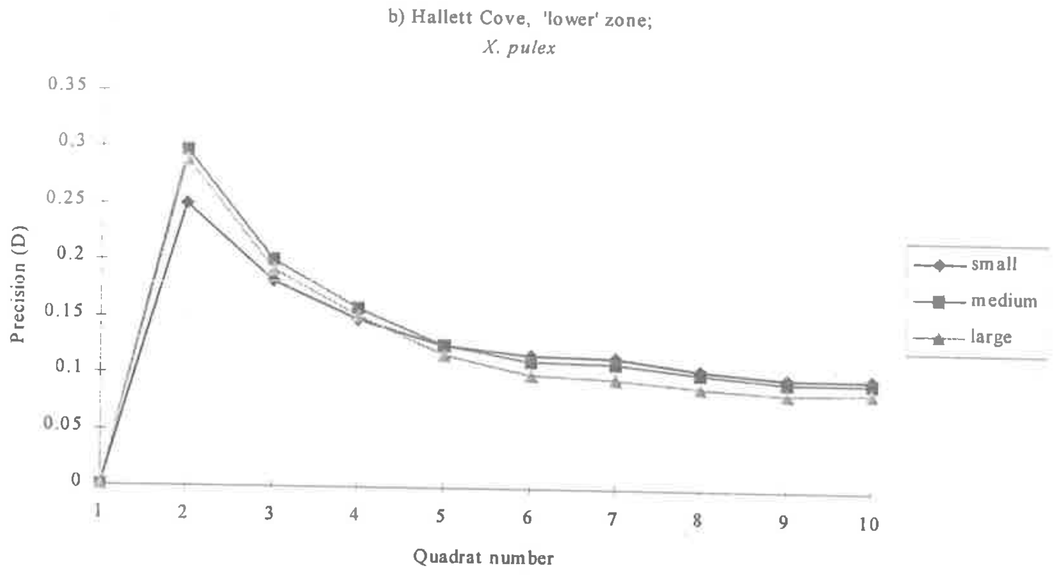


Fig. 3.7 Comparison of the efficiency of different sized quadrats in terms of the sampling precision (D) for *A. constricta* (a) and *X. pulex* (b) in the 'lower' zone at Hallett Cove, when up to 10 quadrats have been deployed. The quadrat sizes trialed were small (0.25m^2), medium (1m^2) and large (2. 25m^2). Note that the lines corresponding to the small and medium sized quadrats tend to overlap.

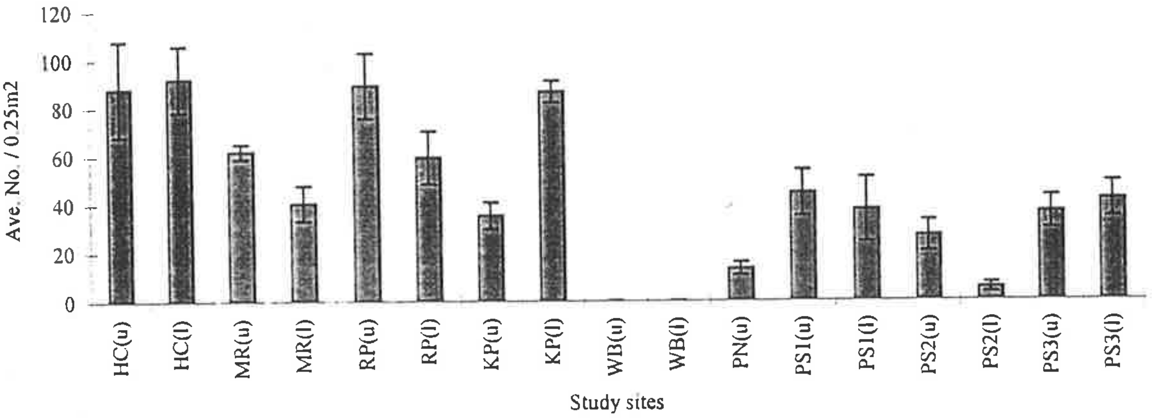
The precision and abundance results generated from the pilot study at Hallett Cove and PS1 support the use of the smaller quadrat (deployed at least seven times) for preliminary monitoring. This size saves sampling time which is important when censusing assemblages in an intertidal area. In some instances, as was seen with *B. nanum* in the 'lower' zone at PS1, more quadrats may be needed to achieve a sampling precision below 0.2 (Fig. 3.4d). However, a calculation of sampling time required to use the small quadrats revealed that it would not be possible to census all community data at study sites and use more than seven quadrats as the time cost was estimated to be too great (see Table 3.2). For example, the minimum time required to census animal assemblages at all nine study sites using 7 small quadrats would be 13.5 hours (Table 3.2), and yet tides allow maximum access to sites of 5-6 hours depending on tidal conditions and other relevant factors. This means that it would take between two to three days to complete all sites if seven small quadrats were used and two 'zones' were censused at each.

Since the Beyond-BACI monitoring design advocated *a priori* recommends the use of 'simultaneous' sampling of study sites (see Chapter 2) the time cost would be too great if more than 7 small quadrats (or fewer larger quadrats) were used. In addition, the calculations shown in Table 3.2 do not include extra travelling time and occasional 'poor' tides may restrict site access to well below 5 hours. Therefore, in terms of the time cost of sampling, seven small quadrats is the maximum number that can be considered if assemblage data is to be assessed.

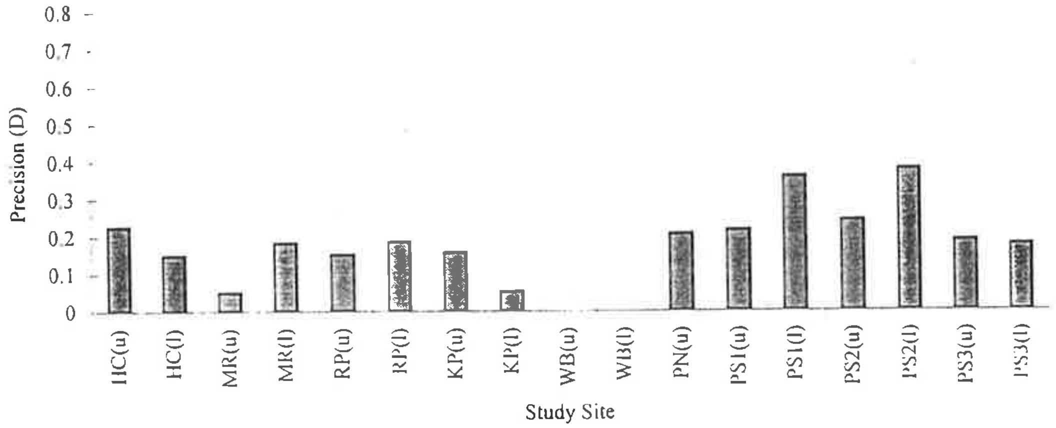
Table 3.2 The average time cost involved in deployment of seven small quadrats at the nine sites selected for preliminary monitoring. Number of quadrats (n) = 7, number of zones (m) =2. Site cost (C_s) = time cost of locating the sites and positioning the quadrats. Quadrat cost (Cq) = time cost of recording abundances of animals in each quadrat. Location cost (C_L) = time cost of completing sampling at each study site. Total cost (C_T)= time cost of sampling all nine study sites (excluding additional travel time) (After Keough and Mapstone 1995).

Parameter	Time Cost (minutes)
C_s	10
Cq	5
$C_L = m\,C_s + m\,n\,Cq$	90
$C_T = 9 * C_L$	810

A comparison of the average abundance of *B. nanum* for the full range of study sites after deployment of seven small quadrats revealed considerable variability between the study sites (Fig. 3.8a). *B. nanum* was never found at Witton Bluff, but occurred at densities ranging from 8-90 animals per quadrat at the other sites. Variability in *B. nanum* abundance was also evident between the two zones at the majority of study sites (Fig. 3.8a). Sampling precision similarly showed some variation, the two 'lower' zones at PS1 and PS2 having a higher value for this parameter than did any of the other sites and zones (Fig. 3.8b). Apart from PS1 and PS2, all sites were characterised by precision values close to 0.2 which was considered acceptable for the preliminary monitoring program.



a) Abundance of *B. nanum* at all study sites



b) Sampling Precision (D) for *B. nanum* at all study sites

Fig. 3.8 Comparison of the average abundance of *B. nanum* per $0.25m^2$ quadrat at all study sites after 7 quadrats had been deployed (a). The precision (D) associated with sampling is shown for the same sites in (b). Sites have been abbreviated and are: Hallett Cove (HC), Marino Rocks (MR), Robinson Point (RP), Kingston Park (KP), Witton Bluff (WB), Port Noarlunga South (PN), Port Stanvac 1 (PS1), Port Stanvac 2 (PS2) and Port Stanvac 3 (PS3). The bracketed letter represents the 'zone' sampled; (u)='upper' and (l)='lower'. Error bars shown in (a) represent standard error.

3.5.3 Parameters to be Scored

All parameters identified as important at the start of this phase of the project (apart from shade which was deemed to be too subjective to properly score) were readily obtainable and so were recommended for inclusion in preliminary sampling (Chapter 4). The chain-and-tape method of quantifying substrata complexity was found to be quick and easy to use in the field and so was also recommended for future use. It was found to take an average of one minute to deploy the chain and then measure the linear distance it covered within a single quadrat. This time, and the time taken to score the other physical parameters of interest within a quadrat, have been factored into the time taken to deploy a quadrat (C_q), used in the time costing breakdown (Table 3.2).

Two data sheets were produced during the pilot study for use in the preliminary monitoring phase of this project; one for recording physical parameters (Appendix J), and the other for biota entry (Appendix K). It was recommended that all biota should be censused during preliminary monitoring, but that the focus should be on animals which will be categorised into the three size classes previously described. Therefore, a photographic field record (Appendix L) was produced, which, in conjunction with Shepherd and Thomas (1989) and Quinn *et al.* (1992) will be used for *in situ* field identification of taxa during preliminary monitoring.

3.5.4 Preferred Method of Census

The differences between the treatment pairs of *in situ* field counts *versus* photographic assessment, and *in situ* field counts *versus* video assessment of animals (within quadrats) were normally distributed, with Anderson-Darling test statistics ranging from 0.230 to 0.477 ($ADcrit_{(0.05),2,6}$=0.525).

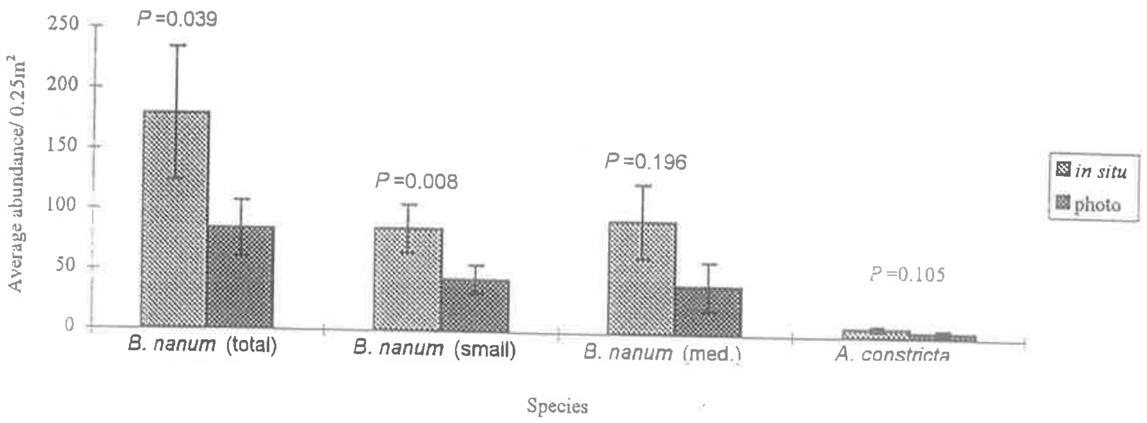
The abundance of *A. constricta* was not significantly different between photographic and *in situ* methods of census (performed in the 'upper' zone at Hallett Cove) (*P*=0.105), but a significant difference in total *B. nanum* abundance (*P*=0.039) was found between the two methods (Fig. 3.9a). The photographic method of animal census was found to severely underestimated the abundance of 'small' *B. nanum*

(*P*=0.008). However, no significant difference between the two census methods was found when 'medium' *B. nanum* abundance was the univariate measure of interest (*P*=0.196). Similar results were found when the same comparisons were made in the 'lower' zone at Hallett Cove (Fig. 3.9b), with no significant differences occurring in the abundance of *A. constricta* or 'medium' *B. nanum* (*P*=0.06 & 0.441 respectively) (Fig. 3.9b). However, significant differences were again found between the two methods when the total abundance of *B. nanum* and the number of this species categorised in the 'small' size class were considered (*P*=0.009 & 0.008 respectively).

The video method of animal census was found to underestimate the abundance of the 'small' animals, but no significant differences were seen in the numbers of *A. constricta* or 'medium' sized *B. nanum* at Hallett Cove (*P*=0.89 & 0.56 respectively) (Fig. 3.10). However, the total abundance of *B. nanum* and the abundance of the 'small' component of this species were significantly different between the two methods of census (*P*=0.016 & 0.015 respectively).

Clearly it was more accurate to use *in situ* field counts than the other two census methods trialed. This arises because the video and photographic methods underestimate the abundance of species which are small or which have a population structure heavily biased towards 'small' animals. This problem is compounded if species are similar in colouration to the substrata (e.g. *B. nanum*). Although not statistically tested, it was apparent that video and photographic techniques could not easily distinguish between individual animals in *X. pulex* beds, making accurate quantification of the abundance of this species, and similar animals, difficult. In this situation the *in situ* field count method is again preferred unless surface area occupied is to be used as the measure of abundance.

a) Hallett Cove 'upper' zone



b) Hallett Cove 'lower' zone

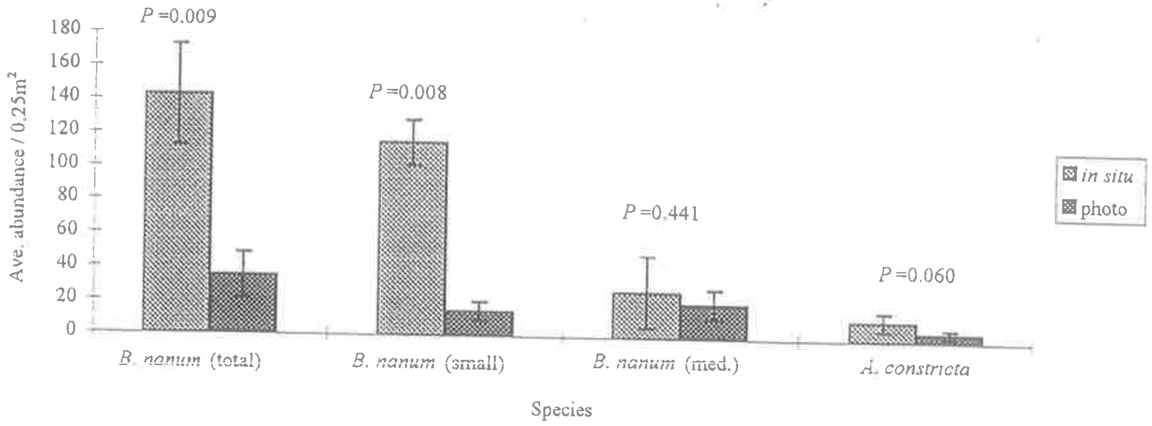


Fig. 3.9 Comparison of a photographic method of census with *in situ* counting of dominant animals recorded within seven 0.25m^2 quadrats deployed in the 'upper' (a) and 'lower' zones (b) at Hallett Cove. Error bars represent standard errors. The abundance of the dominant animals (*B. nanum* and *A. constricta*) were compared statistically using a paired student's *t*-test and a one-tailed hypothesis (see text for details). The numerical dominance of *B. nanum* enabled a statistical breakdown of how the two methods of census affected the main size classes ('small' and 'medium') which dominated the population at Hallett Cove as well as the total abundance of this species. The resultant probabilities (*P*) are shown on the graphs.

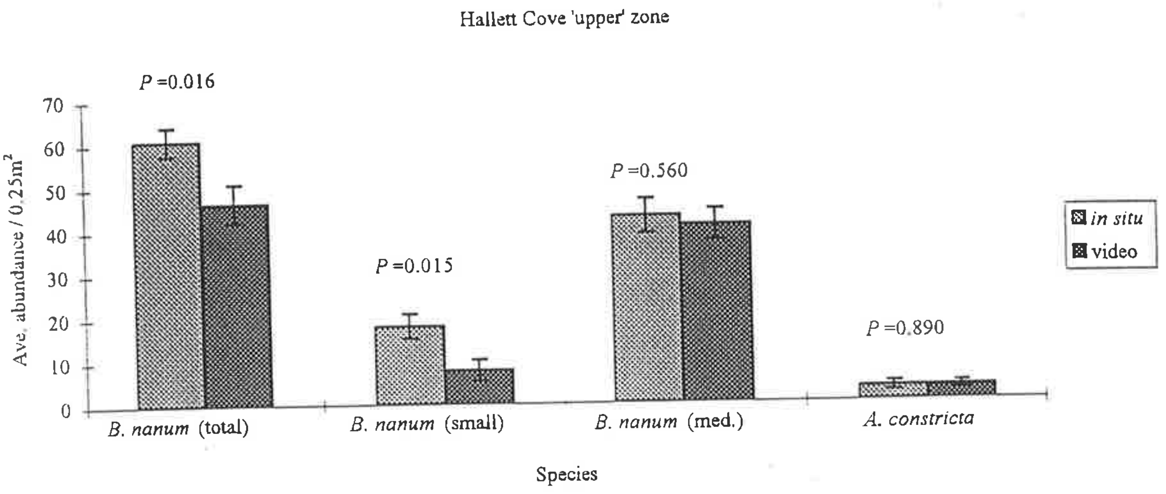


Fig. 3.10 Comparison of a video method of census with *in situ* counting of dominant animals recorded within seven 0.25m^2 quadrats deployed in the 'upper' zone at Hallett Cove. Error bars represent standard errors. The abundance of the dominant animals (*B. nanum* and *A. constricta*) were compared statistically using a paired student's *t*-test and a one-tailed hypothesis (see text for details). The numerical dominance of *B. nanum* enabled a statistical breakdown of how the two methods of census affected the main size classes ('small' and 'medium') which dominated the population at Hallett Cove as well as the total abundance of this species. The resultant probabilities (*P*) are shown on the graphs.

3.6 Conclusions

Based on the pilot study it is recommended that seven randomly assigned quadrats are deployed in each of the defined 'upper' and 'lower' zones at the nine sites selected for preliminary monitoring. The use of the smaller (0.25m^2) quadrat is advocated as it will allow comparison with other intertidal studies (see Andrew and Mapstone 1987) and does not result in a significant decline in sampling precision compared with the use of the larger quadrats, and may even achieve greater sampling precision depending on the site and zone of deployment.

Paired student's *t*-tests on the dominant species of intertidal animals censused by *in situ* field counts and photographic recording of quadrats indicated a significant difference between the two methods when 'small' animals (less than 1cm wide) were included in the analysis. No significant differences were seen between the two methods when only the larger size classes (or generally larger animals) were considered. The same result was seen when the two techniques of video recording and field counts were compared. Since smaller species (such as *B. nanum*) were often numerically dominant at many of the study sites and appeared to be heavily biased towards 'small' animals in their population structure, *in situ* field counts are expected to provide the most appropriate method of community census for this project.

Therefore, the methods recommended for use in the preliminary monitoring program are;

- Sampling of the nine selected sites (Fig. 3.1), with sampling being carried out at low tide and as close as possible to the same day (all sites sampled over a period of no more than 2-3 days).
- Two 'zones' within each site are to be sampled at each sampling time.
- Seven randomly assigned small ($0.25m^2$) quadrats are to be deployed in each zone.
- Assessment of oil presence (subjectively scored on a scale of 0-4), substrata complexity ('chain-and-tape'), substrata composition, substrata elevation, maximum water depth and percentage of retained water are to be recorded in each quadrat that is deployed.
- The following variables are to be scored at each site: water pH, temperature, conductivity, wind strength and direction, wave strength, air temperature, rain and general weather conditions, and human visitation. Human visitation will be scored as the number of people present on a study site over a period of observation and the activities they perform during this time (see Chapters 4 & 8 for more details).

Chapter 4 Monitoring of GSV Study Sites for Spatial and Temporal Trends

4.1 Introduction

Rocky intertidal communities show extreme temporal variability and are typically patchy in distribution on a range of scales (Appendix C). This is a function of the physical variability inherent in the rocky habitat, the dynamic and variable influences of wave and tide, the stochastic nature of planktonic transport, recruitment and disturbance and the interplay of biotic processes such as competition, grazing and predation. Disturbance can be natural or can arise as a consequence of anthropogenic activity (including recreational use of rocky shores or the introduction of pollutants into an area) and can result in effects at the level of the individual, population or community (Chapter 2 & Appendix C). The extreme unpredictability which is characteristic of rocky intertidal shores make optimising a monitoring program to detect anthropogenic disturbance in this medium difficult. The main challenge lies in partitioning changes associated with the perturbation of interest from background variability and effects introduced by confounding factors.

In order to address this problem and optimise a monitoring program for Mobil it was necessary to conduct a preliminary study to assess temporal change over the selected set of study sites and to investigate differences that existed between the study sites. Temporal and spatial variability could only be assessed in context if concurrent physical changes, known physical site differences and confounding factors operating in Gulf St Vincent (GSV) were simultaneously considered. This enabled determination of the contribution of different factors to the observed variance in taxa abundance and assemblage parameters, and partitioning of patterns in the data from 'noise'. Since an oil spill was likely to be widely dispersed by the action of wind and tide the spatial scale of interest in terms of the monitoring program was at the level of 'reefs' or equivalent areas of the coast. However, within this spatial scale two specified 'zones' were designated for sampling (see Chapter 3).

The data generated from preliminary monitoring formed a temporal baseline, which was used to investigate temporal and spatial variability. It was also used to refine the final design of the monitoring program including optimal sampling protocols, choice of study sites and selection of appropriate temporal sampling intervals. Time constraints limited this phase of the project to approximately 15 months although a longer term data set would have increased the ability to detect 'real' trends (Womersley 1988, Jan *et al.* 1994). It was decided to quantitatively monitor all organisms present in the intertidal region at all sites during the preliminary phase of the study. This approach focused monitoring at the level of the assemblage, allowing a broad examination of processes and structure operating at this level. It also meant that individual species could be assessed in terms of their potential as indicators for the ongoing monitoring program and as variables in a statistical analysis. The assemblage (or 'community') approach to monitoring was necessary, as no bioindicator had been identified *a priori* as a suitable tool to determine changes associated with an oil perturbation (Chapter 2).

Since an oil spill was predicted to differentially affect the study sites preliminary monitoring took the form of a Beyond-BACI design (Underwood 1991a, 1992, 1993a, 1994a & 1995a) incorporating two temporal scales. An oil spill was expected to be an acute, pulse event (relative to the longevity of intertidal organisms) and the relevant temporal scales of interest were therefore likely to be short. The shortest temporal scale of interest was 'weeks', which were expected to indicate immediate acute effects. This time frame was nested in the longer temporal scale of 'seasons', which were likely to indicate more persistent change. This design had the advantage of being able to detect either a short pulse or a longer term pulse disturbance (at any of the study sites) and enabled a test of the Beyond-BACI design should a perturbation intervene during this phase of the project.

4.1.1 Confounding Factors

The intertidal coastline within and adjacent to the Port Stanvac Oil Refinery is currently or may potentially be influenced by a number of anthropogenic disturbances. The majority of these factors have been introduced previously (Appendix A) but those of relevance to preliminary monitoring will be considered within the context of the preliminary monitoring program and will be further examined in the "Results" section of this chapter where appropriate.

Sand Dredging and Sand Influx

The Coast Protection Board conducted sand dredging in the study region between January and May 1991. This pulse disturbance was unlikely to impact on current intertidal conditions. However, the episode of sand dredging carried out by Mobil between the 2nd and the 29th of January 1996 was a perturbation that potentially impacted intertidal assemblages during the preliminary sampling phase. The dredged sand and associated water was discharged intertidally at a site to the north of the dredging point, between the wharf and PS2 (Appendix A: Fig. A.5).

Natural sand drift was noted at some of the study sites during preliminary sampling, impacting the 'Northern' sites, in particular Hallett Cove, in June 1995. The sand obliterated rocky substrata and clearly affected intertidal assemblages, necessitating selection of a second Hallett Cove site (designated HCB) in the boulder field adjoining the original site. The new Hallett Cove site served as a reference against which changes in the original site (HCA) could be compared.

The Christies Beach Wastewater Outfall

The Christies Beach sewage outfall introduces a chronic source of pollutants to GSV and has constituted a press disturbance to the eastern coastal waters since it commenced operation in 1971. However, it is more likely to affect local benthic communities (see March 1996) than it is to perturb intertidal biota. Of the selected study sites, 'Southern' sites, particularly Witton Bluff, are most likely to be impacted by this disturbance.

Storm Water Discharges

Storm water outfalls are located at a number of points along the coastline and in times of high rainfall and subsequent high runoff are likely to introduce stormwater and its contaminant load as point source discharges into the coastal region. Mitsubishi Motors Australia Ltd has a large outfall site on the cliff at close proximity to the northern boundary of the Port Stanvac Oil Refinery (Appendix A: Fig. A.4 & Plate A.1). During times of high rainfall (particularly winter) local land based runoff contributes freshwater, suspended solids and heavy metals to the region, with the outfall discharging down the cliff and onto the beach below. This source of pollutants is most likely to impact PS1 but is liable to be of concern only after high rainfall episodes.

Stormwater outfalls also occur in close proximity to the Hallett Cove and Robinson Point sites. The outfall at Hallett Cove has been observed to occasionally discharge very large volumes of water and contained material from street runoff directly across the Hallett Cove sites (Plate 4.1). The outfall at Robinson Point is less likely to cause a local impact as it is situated at a greater distance from the monitored site (about 40m north and high on the beach) (Plate 4.2). These outfalls contribute low salinity water and could contain variable contaminants including oil and grease, acids, suspended sediments, land based nutrients and heavy metals.

Plate 4.1 Discharge of stormwater across the Hallett Cove study sites (HCA & HCB) during a winter 1995 episode of high rainfall.

Plate 4.2 The position of the stormwater outfall pipe approximately 40m north of the sampled reef at Robinson Point.

Refinery Effluent Discharge

The refinery discharges a mixture of refinery effluent into the ocean at a point approximately 120m west of the low tide mark, close to the northern refinery boundary (Cove 1994). The refinery outfall introduces low salinity water carrying a mixture of refinery contaminants into the ocean and operates as a local press disturbance in the area. The mixed effluent is monitored by refinery personnel at the junction box (a holding chamber which receives water from the North Collection Basin and the Ballast Water Holding Pond) prior to its discharge into the ocean (Cove 1994). The average 1994 condition of effluent water and the levels of contained contaminants are presented in Table 4.1, and are below the "operational target" and "excursion target" levels set by the refinery (Cove 1994). Refinery water which is used for cooling purposes within the plant is recycled and not discharged with other refinery effluent (pers. comm. Cove).

Table 4.1 Average recorded levels of contaminants and water parameters in refinery effluent discharged to sea in 1994 (pers. comm. Cove).

Parameter or contaminant measured	Average level recorded
Furfural	4.916 ppm
Oil in water	11.85 ppm
Suspended solids	61.90 ppm
pH	6.91
Biological oxygen demand (BOD)	127.79 ppm
Chromates	0.370 ppm
Phenols	1.164 ppm
Sulphides	0.084 ppm

N.B. ppm = 'parts per million' which is equivalent to mg/L (milligrams per litre)

Rupture of the Refinery Effluent Pipe

On the 29th of August 1995 the refinery effluent pipe was observed to have ruptured around a join. At the point of rupture a large volume of brownish, turbid water with a visible oily surface scum and an offensive smell was spilling onto the beach close to the northern refinery boundary. I notified refinery personnel of the discharge and rechecked the site the following day. The mid-eulittoral zone close to the most northern of the 'Central' study site (PS1) received the majority of the discharged water on both days.

I returned to the site on the 11th of September 1995 to find that the damaged section of pipe was being repaired and that a new flexible pipe was diverting the effluent and discharging it directly onto the beach. Final repairs were in progress on the 13th of September when Transfield Co. staff reconnected the new outlet pipe to the old (repaired) pipe and refinery effluent was again discharged out to sea. In view of this unexpected pulse perturbation during preliminary sampling a new impact site (designated PS1A) was selected for preliminary monitoring. Sampling at this site commenced on the 11th of August 1995.

Recreational Use of Study Sites

A major confounding factor expected to differentially act across all study sites, was recreational shore use. The only sites protected from this disturbance were located within the refinery where private ownership precluded public access. Damage caused by recreational use of intertidal areas includes removal of biota as aquaria specimens, food, or bait, and crushing of delicate animals or plants as rocks are overturned or the substrata is trampled (Underwood 1993b). Any or all of these activities can upset the natural processes operating on an intertidal shore and either directly or indirectly affect the abundance of various taxa and/or the assemblage composition.

In December 1995 the Primary Industry Minister, Mr Kerin, announced that regulations would be introduced to protect shellfish from scavengers. These regulations were aimed at preventing reef destruction and poaching of shellfish and other marine forms and made it illegal to take biota from any intertidal reef in South Australia (Appendix M). Offenders faced fines of up to $2000 for breaching the new conditions. However, since the regulations came into force fossickers have been observed collecting buckets of *Nerita atramentosa* and *Austrocochlea* spp. from Hallett Cove and Kingston Park and continuing to do so even when told of the risk of fines. Recreational use of the study sites and the effects of various intensities of trampling will be discussed in detail in Chapter 7 of this thesis.

4.1.2 The Design of the Preliminary Study

The preliminary study involved monitoring the sites selected during the pilot study for a period of about 15 months. Sampling protocols identified during the pilot study as optimal in terms of precision and time costs were adopted during this component of the study (see Chapter 3).

A Beyond-BACI design was used to allow investigation and assessment of any perturbations occurring during preliminary monitoring even though the final monitoring program was not yet designed and implemented. The advantage of this approach was that a number of different temporal and spatial scales of relevance could be investigated in reference to a perturbation without a huge increase in sampling effort (Underwood 1992 & 1993a). An added advantage was that if a perturbation occurred during preliminary monitoring the power of the Beyond-BACI analysis to detect any change coincident with the event could be tested and informed design refinements could then be made to the ongoing monitoring program (discussed in Chapter 8).

The animal assemblages occurring at study sites were investigated during the 15 months of this study in relation to physical factors (such as site characteristics and weather conditions) and all animals were considered as potential 'oil spill' indicators (discussed in Chapter 6).

4.1.3 The Aim of the Preliminary Study

The overall aim of the preliminary study was to assess assemblage (or 'community') level change occurring at the study sites over a period of 15 months.

Specifically the preliminary study addressed the questions of:

- Were the study sites similar in terms of their community composition (in particularly the size structure and relative abundance of dominant animals)?
- How did the main species and assemblages fluctuate over the 15 months of the study?
- Were fluctuations in the relative abundance and size distribution of animals within sites responding to environmental parameters (such as weather conditions) or particular processes (such as recruitment)?
- Which animal (or animals) would appear to be suitable indicators for the long term monitoring program (considered in detail in Chapter 6)?
- How effective was the Beyond-BACI design for use in an intertidal monitoring program (considered in detail in Chapter 8)?

4.2 Study Sites

The nine main study sites selected for preliminary monitoring have been described previously (Chapter 3). The sites extend from Kingston Park (north of the Port Stanvac Oil Refinery) to Robinson Point (south of the refinery), and represent about 18 km of coastline with Port Stanvac being approximately centrally located (Chapter 3: Fig. 3.1). In addition, two new sites (PS1A and HCB) were selected during the course of preliminary monitoring. An overview of site characteristics, particularly the dominant substrata composition, is given in Table 4.2.

The study sites formed three geographically distinct groups; 'Northern', 'Central' and 'Southern'. The 'Northern' sites consisted of Kingston Park, Marino Rocks and the two Hallett Cove sites (HCA & HCB), the 'Central' (Port Stanvac) sites were called PS1, PS1A, PS2 and PS3, and the 'Southern' sites consisted of Witton Bluff, Port Noarlunga South and Robinson Point. Two zones were generally selected for sampling at each site; the 'upper' zone which was characteristically dominated by one or a few gastropods, and the 'lower' zone which was lower on the shore (seaward) and was generally typified by an increase in mussels and/or a greater animal diversity. The focus on two 'zones' was continued during the preliminary phase of this project but due to time constraints and frequent access difficulties the 'lower' zones were less frequently censused than the 'upper' zones.

Table 4.2 An overview of the 'geographical' location ('Northern', 'Central' & 'Southern') of study sites and the character of the dominant substrata at each site. Sites were described as 'stable' if their dominant substratum was bedrock with little loose rocky overlay, or rock stabilised through the presence of mussel beds or embedded sand and protected by its position on a sheltered shore. The main factor defining a site as 'stable' was a low risk of substrata mobilisation even under relatively severe storm conditions.

Location	Study Site	Substrata Description
'Northern'	Kingston Park (KP)	Mainly flat bedrock with minor fissures and occasional shallow holes; overlaid by cobble and boulder close to the low water mark. Considered to be 'stable', particularly the 'upper' zone.
	Marino Rocks (MR)	Mainly bedrock strata elevated in parts and interspersed by large amounts of mobile substrata ranging from sand to boulder. Considered to be relatively 'unstable' due to the high cobble and boulder component.
	Hallett Cove A (HCA)	Mainly flat bedrock with shallow eroded depressions; prone to sand inundation. Considered to be 'stable' in terms of the dominant substrata which lacked a mobile rock overlay.
	Hallett Cove B (HCB)	Adjacent to HCA and consisting of a mobile, rounded cobble and boulder field interspersed by sand. Considered less 'stable' than HCB although the reef was fairly sheltered.
'Central'	Port Stanvac 1 (PS1)	Mainly flat bedrock with minor cracks, fissures and eroded holes; interspersed by areas of upthrust strata and overlaid in parts by small amounts of mobile substrata. Considered a 'stable', relatively sheltered site.
	Port Stanvac 1A (PS1A)	As for PS1 but with larger amounts of mobile substrata (ranging in size from pebble to boulder). Less 'stable' than PS1 but relatively sheltered.
	Port Stanvac 2 (PS2)	Mainly bedrock strata some of which was upthrust; interspersed by areas of mobile rock (ranging in size from pebble to boulder). The presence of the latter made this site less 'stable' than PS1.
	Port Stanvac 3 (PS3)	As for PS2.
'Southern'	Witton Bluff (WB)	A low-lying limestone reef platform, exposed for a limited time at low tide and tending to retain water in heavily eroded areas. Considered an extremely 'stable' site.
	Port Noarlunga South (PNS)	As for WB but not as low-lying and with a higher proportion of deeply eroded holes which retain water at low tide.
	Robinson Point (RP)	A relatively low-lying reef consisting mainly of potentially mobile cobble and boulder substrata which was stabilised by embedded sand and large numbers of mussels towards the lower aspects. Considered to be equivalent to the other 'Southern' sites in terms of its stability and long immersion times.

General Study Site Characteristics

Substrata at the Kingston Park and HCA sites was predominantly flat bedrock with little intrinsic elevation and only shallow eroded depressions, the latter resulting in minimal water retention at low tide. However, the 'lower' zone at Kingston Park consisted of more complex bedrock than was seen in the 'upper' zone and also had a greater proportion of loose cobble and boulder. HCA was more low-lying than the other 'Northern' sites and was difficult to access at times.

The base rock at Marino Rocks was similar to that of the other 'Northern' sites but was slightly more elevated in parts and interspersed with increased amounts of cobble and boulder which were mobilised under certain tide and wave conditions. The area selected for sampling was essentially free of the mobile rock found in closely adjoining regions. The 'lower' zone sampled at Marino Rocks was similar to the equivalent zone at Kingston Park.

The 'Central' study sites consisted of a mix of flat and uplifted bedrock strata interspersed with areas of boulder, cobble and pebble. The relative contribution of the mobile substrata varied between these sites, resulting in differences in 'stability' (Table 4.2).

The 'Southern' sites were composed of stable substrata and all were relatively sheltered and low-lying. Witton Bluff and Port Noarlunga South were very stable rocky reefs with no obvious loose rock overlying their bedrock bases. The bedrock at both sites was eroded in parts and promoted water retention at low tide. Witton Bluff was the most low-lying of all the study sites and its marine reserve status ensured considerable protection from collecting pressure even before the new regulations prohibiting removal of reef animals were implemented. It was also more difficult to access by foot than the other sites, which may afford protection from trampling and related recreational disturbance. Robinson Point was a relatively stable reef dominated by embedded cobble and boulder. It's sheltered aspect and the stabilisation of the rock afforded by embedded sand and mussel beds combined to reduce the likelihood of severe storm related perturbation effects (Sousa 1979a & b, McGuiness 1987a & b, Lieberman *et al.* 1984, Underwood 1994b). This reef was similar to Witton Bluff in that it was low-lying and submerged for longer periods than most of the other sites. This was expected to diminish the risk of desiccation stress to animals and plants, and possibly afforded protection from heavy trampling.

The Additional Study Sites

The sand influx to 'Northern' sites (particularly Hallett Cove) and the effluent pipe rupture at Port Stanvac necessitated the addition of two new study sites to the original suite of nine. Only one 'zone' was sampled within each of these new sites as the substrata was relatively homogeneous and species distribution patterns appeared consistent within each site. The new sites were designated HCB and PS1A respectively.

Hallett Cove B (HCB)

The new Hallett Cove site (HCB) adjoined the original Hallett Cove site (HCA). HCB consisted of a mix of boulder and cobble with entrapped sand between the larger rocks, which did not stabilise them to the degree seen at Robinson Point. This site was prone to natural disturbance including sand drift and mobilisation of substrata under certain weather conditions. However, the risk of the latter was reduced by the presence of entrapped sand between the rocks and the sheltered nature of the reef. The sampled area commenced 33m from the base of the ramp allowing access to the beach, and continued for an additional 16m from this point. The site was sampling from the south and west (refer to Chapter 3).

PS1A

The PS1A site was situated immediately north of PS1 and was bordered by the refinery effluent pipe. PS1A had a bedrock base overlaid with cobble and occasional boulder (see Table 4.2). The area to be sampled commenced 1m east of the join in the effluent pipe, extending for a further 15m west of this point and was worked to the south and west.

4.3 Materials and Methods

The nine original study sites selected for preliminary monitoring were assessed over a period of 15 months beginning in March 1995 and finishing in June 1996. Sites were visited at low tide and both 'zones' were sampled when access was possible. Only one zone was sampled at Witton Bluff due to the relative homogeneity of the substratum and the assemblage it supported and the restricted sampling time and access difficulties associated with its low-lying status. Once the two impacts (the sand drift and effluent discharge) intervened, the additional 'impact' sites (PS1A and HCB) were included in the sampling schedule.

Sampling utilised the strategies identified as optimal during the pilot study (Chapter 3). At each site (within each zone) a $0.25m^2$ quadrat was randomly deployed seven times. Care was taken to remain within the designated sampling area at each site and permanent rock pools were not sampled (the next closest region being selected if the quadrat was assigned to a permanent rock pool).

Fishing line was used to divide the quadrat (used as the sampling unit) into four equal sections. This facilitated estimation of parameters such as the percentage of each substrata type in the quadrat and aided in assemblage census. To avoid destructive sampling no rocks were overturned to census animals or plants and only those organisms visible on the tops or sides of rock were included in the count. Assemblage census was aided by the use of a hand-held counter and animals and plants were identified as described in Chapter 3. All data were entered and managed in the "MICROSOFT OFFICE" data base program: "ACCESS", Version 2.0 (© 1989-1992).

Within each quadrat maximum elevation of the substrata and its composition (the percentage of substrata categorised as sand, pebble or gravel, cobble, boulder and bedrock (or reef-rock)) were determined. Maximum water depth, the percentage of retained water, surface topographic complexity (quantified using the 'chain-and-tape' method), and a subjective scoring of the presence of oil (see Chapter 3) were also recorded for each quadrat. Site parameters assessed were: ambient air temperature; maximum and minimum daily air temperature (obtained from the National Tidal Facility at Flinders University); wind strength (subjectively categorised as nil, light, medium, strong or gale-force) and wind direction; the height and time of high and low tide (obtained from the National Tidal Facility at Flinders University); and wave strength. The nearest body of water (other than a rock pool) was then selected and a hand-held YSI 600 water-quality meter was used to determine water temperature (at a depth of 20cm), pH, conductivity (and salinity) and oxygen saturation. Maximum and minimum water temperatures at Port Stanvac were also obtained from the National Tidal Facility at Flinders University.

At each sampling time (during low tide) recreational visitation was scored and the activities of people present at sites recorded. A full description of the methodology and results relating to recreational shore use and trampling are given in Chapter 7. To assess the quality of the water discharged from the ruptured effluent pipe at Port Stanvac duplicate one-litre water samples were collected in glass bottles on the 30th of August 1995 and sent to ANALAB (a chemical analysis centre in Melbourne) to independently test for the main contaminants. The water samples were kept on ice from the time they were collected until they were processed. The YSI 600 water-quality meter was used *in situ* to measure the pH, conductivity and temperature of the discharged refinery water.

4.3.1 The Beyond-BACI Sampling Design

The two temporal scales of interest in the preliminary sampling program were weeks and seasons. Changes at the shorter temporal scale in relation to a perturbation were of interest as they were likely to reflect immediate short-term effects, whether or not they persisted. The seasonal temporal scale was relevant to perturbations affecting processes (such as recruitment) which were driving changes over a longer temporal scale. Sampling used three sampling 'Times' two-three weeks apart nested in 'Periods' which were 2-3 months apart (Table 4.3). Within each of the two temporal scales actual sampling times were randomly chosen from the days when tidal conditions allowed site access. All sites at each time were sampled as close as possible to the same day, generally over 2 days, which was considered to be 'simultaneous' sampling. Sampling continued in this pattern until a disturbance intervened, when the post-impact sampling immediately commenced. Tidal and weather conditions occasionally prevented access to some of the low-lying sites.

Table 4.3 The sampling schedule used during preliminary monitoring in relation to the 'effluent' perturbation. Two sampling 'Periods' were completed before the pipe ruptured. Following the disturbance all sites were immediately sampled at the same intervals as the pre-impact sampling. 'Periods' (P) were 2-3 months apart and 'Times' (T) were two-three weeks apart and nested in P.

Before Impact						**Post Impact**					
Period 1 (P1)			Period 2 (P2)			Period 1 (P1)			Period 2 (P2)		
T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3

The two observed perturbations, which occurred during preliminary sampling, differentially affected the study sites. The 'sand' disturbance predominantly affected HCA (the 'sand' perturbed site) which had been monitored before this event occurred. The burst effluent pipe primarily affected PS1A (the 'effluent' perturbed site). PS1A had not been monitored prior to the effluent disturbance intervening (see "*Beyond-BACI Analysis of 1995 Impacts*" for additional comments). Both of these disturbances were analysed using a Beyond-BACI ANOVA (refer to Underwood 1993a).

In addition to the 'sand' and 'effluent' disturbances an operational oil spill occurred on the 23rd of September 1996. Fresh crude oil grounded at the Port Noarlunga South site (designated the 'oil-impact' site) but this occurred some time after preliminary sampling was completed and will be discussed in Chapters 5 & 6.

The only member of the biota occurring at the majority of sites and sufficiently numerous to be useful in a statistical analysis was *Bembicium nanum*. Therefore, the abundance of this animal was the dependent variable used in all statistical analyses, which were used to determine the significance of changes associated with the 'sand' and 'effluent' perturbations.

4.3.2 Analysis

Univariate Assessment of Temporal Change

The total abundance of *B. nanum* per 0.25 m^2 quadrat and the distribution of these animals within each of the three defined size classes (see Chapter 3) were plotted for each sampling time for the duration of this phase of the project. Where other animal species were present at relatively high densities, either in association with *B. nanum* or as the numerically dominant species, abundance and size distribution graphs were also generated if they were expected to be informative. To enable a number of series to be viewed on the one graph it was sometimes necessary to adjust the day of sampling so that sampling dates shown on the *x*-axis of graphs presented in the results section represent the date shown +/- 1-2 days.

The presence of eggs or egg capsules was recorded to provide additional qualitative information pertaining to the life-history strategies of the more common intertidal species at GSV sites. The presence of 'very small' newly settled animals (less than 2mm in diameter) were also noted and if possible classified to species. Animals smaller than the lower limit of the 'small' size class were not quantified due to time constraints and problems in accurately and quickly identifying them.

Variability in physical parameters which were relatively consistent between sites and were not thought to be directly contributing to inter-site differences over the study period were presented graphically only for the 1995 data since similar patterns were noted in 1996. These parameters included maximum and minimum daily air temperature, maximum and minimum daily water temperature (recorded at Port Stanvac), daily height of high and low tides, and wind speeds and directions along eastern GSV. For the majority of these parameters monthly averages were also calculated and have been presented graphically. These graphs were used to illustrate the variability in physical conditions faced on a range of temporal scales by biota inhabiting the intertidal region.

Variability between study sites was quantified by such parameters as maximum substrata height, composition and complexity, the percentage of retained water in quadrats, water conductivity, pH, water temperature and dissolved oxygen (DO). These data have been presented graphically and were useful in supporting and interpreting the results of the Beyond-BACI analyses. The parameters which appeared to be important in determining multivariate ordination patterns were used in the Pearson Correlations and the Principle Axis Correlations (abbreviated PCC by Belbin (1991)) to attempt to link them to positioning of sites in ordination space. PCC is essentially a multiple linear regression program, which can be used to assess how well a set of attributes can be fitted to an ordination space (Belbin 1991). The latter technique was considered a more appropriate way to relate physical conditions during the entire preliminary sampling period to the MDS Ordination of study sites according to the animal taxa they supported (see "*Analysis of Community Patterns*"). This is because it was known that many of the physical parameters used in the Pearson Multiple Correlation were not independent of each other. All Pearson Correlations used in this chapter were considered to violate the assumption of independence (see Zar 1984) but were considered a useful starting point to determine any apparent patterns before PCC was used.

The PRIMER program "DIVERSE" (Clarke and Warwick 1994b) was used to generate univariate indices from community data. Species richness (Margalef's Index (d)), Shannon-Wiener Diversity Index (H′), Pielou's Evenness Index (J′), and Simpson's Dominance Index (SI) were calculated for the 'upper' zones (Table 4.4). Assemblage data were summed over the seven quadrats for each 'zone' at each sampling time to generate the data from which these indices were calculated. In general, species level data were used, but where this was not possible e.g. with *Notoacmea* spp., genus level data were included.

Table 4.4 Univariate indices were generated from assemblage data during the preliminary sampling program using the PRIMER Program, "DIVERSE" (see Clarke and Warwick 1994b for further discussion of these indices).

Univariate Measure	**Formula**	**Definition of symbols**
Species richness; Margalef's Index (d)	$d=(S-1)/\log N$	S=total number of species N=total number of individuals
Dominance; Simpson's Dominance Index	$SI=\text{sum}(2p_i)$	SI=Simpson's Index p_i =proportion of total count arising from the (i)th species
Equitability; Pielou's Evenness Index (J′)	$(J')=H'_{(observed)}/H'_{max}$	$H'_{(observed)}$=observed diversity H'_{max}=maximum diversity achieved if all species were equally abundant (=log S)
Diversity; Shannon-Wiener Diversity (H′)	$H'=-\text{sum}_i\ p_i (\log p_i)$	p_i=proportion of total count arising from the (i)th species

Analysis of Assemblage Patterns

Assemblage change (based on animal abundance measures) was examined over the 15 months of preliminary monitoring. The data collected in relation to the oil spill perturbation were also analysed in conjunction with the preliminary data but the results are not presented in this chapter. Size classes were pooled for each animal species at each sampling time and rare taxa were removed from the data set before a square root transformation was performed to increase the weighting of taxa with a medium abundance. Following these adjustments a multivariate 'site x species' analysis was carried out (see below). A taxon was classified as rare if it occurred in less than five percent of samples (see Gauch 1982). Other scientists use different definitions of rare such as Clarke and Warwick (1994a) who define a rare species as one which comprises less than 5% of the total abundance in each sample. Rare taxa may be more sensitive to pollution than other biota and thus should be considered in any pollution-based study (Gray and Pearson 1982).

Multivariate analyses were undertaken using the "PATN" statistical package (Belbin 1992). The first part of the multivariate processing involved agglomerative hierarchical clustering using flexible UPGMA as an aid to interpreting the MDS patterns and to determine the degree of association between objects. Species averages for each site at each sampling time were used as the basic measure to investigate the similarity between the various study sites (in terms of their species composition) over time. The results of this clustering were presented as a dendrogram and the members of the dendrogram groups were defined using the GDEF option in "PATN" (Belbin 1991).

A Semi-Strong Hybrid (SSH) Multi-Dimensional Scaling (MDS) Ordination was performed in "PATN" to place the study sites (as a temporal series) in species ordination space (using the average animal abundances recorded for each site at each sampling time). This ordination method effectively combines some of the advantages of non-metric ordination with those of metric techniques (Faith 1990). SSH MDS Ordination treats a data group with low associations as 'ordinally accurate' while those with higher associations are treated as 'ratio accurate'. This leads to reasonable estimates of 'real' distances in the ordination even when object associations are poor (Belbin 1991). The point where the association values start to peak is called the 'cut-off point' and this was 1.0 in the case of the GSV animal data set.

The SSH MDS Ordination used 50 repeat random starts and the result which achieved the lowest stress value was used to generate the multivariate graphs. The stress value indicates how well the plot obtained compares with 'true' distances (Digby and Kempton 1987). In this ordination, three dimensions were informative, interpretable and gave a lower stress value (S=0.13) than two dimensions and all MDS graphs were plotted showing combinations of the three dimensions. It was felt that no additional information could be obtained by resorting to higher dimension solutions. The full set of data were analysed jointly, but graphs illustrating the position of the study sites in ordination space have been separated into those pertaining to 'upper' and 'lower' zones at study sites. The 'lower' zones represent a much smaller data set due to the difficulty in accessing them at various times during preliminary sampling and were thus expected to be less informative in revealing trends than the 'upper' zones. The ordination points were also separated on the basis of season to attempt to identify seasonal patterns.

In order to clarify the effects of the 'sand' and 'effluent' perturbations the data generated from the full ordination were manipulated further. The average position for the set of Beyond-BACI controls were calculated for each sampling time and compared to the position of the study sites of interest (e.g. HCA & HCB for the 'sand-impact', and PS1A & PS1 for the 'effluent-impact'), prior to and after the respective perturbations. The resultant series were then plotted against combinations of the three ordination axes.

To further simplify patterns linked to the sand influx at HCA, the average position of pre-impact and post-impact data points were calculated for each of the 'treatment' groups (namely control, HCA and HCB) and linked by vectors to show the direction and magnitude of change. Only the data used in the 'sand' Beyond-BACI analysis and collected over the Beyond-BACI sampling period was used in the 'sand' perturbation comparison, and post-impact data outside of this time frame was excluded from the calculations. This enabled a determination of the trajectory of change coinciding with the sand influx at 'control', HCA and HCB sites. The same treatment of ordination data relevant to the 'effluent' perturbation was performed to determine what changes (if any) occurred at the 'impacted' site (PS1A) compared to PS1 and the control sites (averaged). Again, only the data from the Beyond-BACI sampling period were used in this manipulation.

The physical parameters believed to be of importance to the observed ordination patterns were subjected to Pearson Correlations with a Bonferroni correction using the program "SYSTAT", Version 3.0 (see Wilkinson 1990), and a PCC analysis using "PATN" (Belbin 1992). These analyses were also applied to the main animal taxa used to generate the MDS ordination in an attempt to determine which taxa were predominantly responsible for defining ordination space.

Examinations of the secondary habitat at study sites (primarily the abundance of plant taxa and the animal species *Galeolaria caespitosa*) were conducted to assess their contributions to the placement of data points within MDS ordination space. A

Bonferroni corrected Pearson Correlation and PCC analyses were performed against the MDS ordination scores. However, since visible plant life was sparse at the majority of the study sites (apart from Witton Bluff and, to a lesser extent, Port Noarlunga South), the results were not informative and will not be mentioned further.

Beyond-BACI Analyses of 1995 Impacts

The only animal species sufficiently abundant at the majority of study sites to be useful as a biological variable in a Beyond-BACI analysis was *B. nanum*. However, this animal was not found at Witton Bluff, precluding its use as a control site in either of the two Beyond-BACI analyses. Specific 'impact' sites were only used for the appropriate impact analyses to avoid confounding the 'impact' data sets. Since PS1 was the closest monitored site to the burst effluent pipe but effluent discharge did not directly run across it, PS1A was used as the 'effluent' perturbed site and was assumed to have the same pre-impact abundances of *B. nanum* as PS1. This may be an incorrect assumption but was adopted so the 'effluent' analysis could be performed and was realistic in terms of the proximity of the two sites and the similarity of substrata and general assemblage composition.

The Beyond-BACI analyses made use of data collected from late February/early March 1995 until early November 1995. To simplify interpretation of the data within a Beyond-BACI framework, the sampling times included in the analyses have been coded e.g. the first Beyond-BACI sampling time was coded as P1T1 ('Period' 1, 'Time' 1) and the last sampling time was coded as P4T3 ('Period' 4, 'Time' 3). Period 3 corresponded to the commencement of post-impact sampling for both the 'sand' and 'effluent' perturbations.

Raw data for each of the seven quadrats deployed in the 'upper' zones at each of the selected study sites were used in the Beyond-BACI analyses involving the 'sand' and 'effluent' perturbations. Access to the 'upper' zones at Port Noarlunga South and Robinson Point were prevented at times by high tidal regimes and these sites were excluded from the analyses on these grounds. Missing data can be handled in an analysis of this type which would allow inclusion of the two most 'Southern' sites in the control data set (pers. comm. Leppard) but for the purposes of preliminary testing of the Beyond-BACI design, analyses proceeded using one impact site and five control sites.

The number of 'Times' nested in the longer temporal scale of 'Periods' was the only factor that varied between the two Beyond-BACI impact analyses (see Table 4.5). This difference was due to the restricted access to Hallett Cove associated with its low-lying status. To balance missing data some of the collected data had to be removed from the 'sand-impact' data set prior to beginning the analysis. Therefore, all P*x*T3 data (where *x*=1, 2, 3 or 4) were excluded from use in the Beyond-BACI analysis pertaining to the 'sand' perturbation.

To conduct the 'effluent' perturbation Beyond-BACI analysis using three 'Times' nested within 'Periods', data collected during the pilot study in February and early March 1995 was used as P1T1 data and all other sampling times within 'P1' were displaced by one integer e.g. the existing P1T2 data became P1T3. In all cases, physical data (such as substrata complexity and composition) and biological data (such as species abundance) collected during the pilot study deviated by less than 2% from the first data collected during preliminary monitoring (corresponding to P1T1 on all graphs presented later in this chapter). Data collected during the pilot study fell outside of the preliminary sampling schedule and has been omitted from graphs shown in the "Results" section of this chapter.

It became apparent during the first year of preliminary monitoring that using three 'Times' nested within the larger temporal scale of 'Periods' did not reveal enough extra information pertaining to temporal species patterns to balance the greater time investment required. Therefore, sampling of two 'Times' nested within each 'Period' was adopted in late 1995 and continued during 1996.

Table 4.5 The main factors and levels used in the Beyond-BACI Design for the 'sand' and 'effluent' perturbation analyses.

Factors	General Design	'Sand' Perturbation Number of levels	'Effluent' Perturbation Number of levels
1	**Before *vs* After (B)** orthogonal and fixed	2	2
2	**Periods (P)** nested in B, random	2	2
3	**Times (T)** nested in B and P, random	2	3
4	**Locations (L)** orthogonal and fixed	6	6

Data were entered in the "GMAV5" Program produced by Underwood (see Appendix N). "GMAV5" is a five-factor analysis of variance program capable of dealing with complex models comprised of orthogonal or nested, fixed or random factors. It also tests heterogeneity of variances using Cochran's test and compares means using Student-Newman-Keuls tests. The "GMAV5" package was used to analyse the data as described by Underwood (1993a). Four separate analyses were performed on each of the data sets (see Table 4.6). The data were first analysed as though all the locations constituted a set without division into 'control' and 'impact' sites (Analysis a). The analysis was then repeated leaving out the putatively impacted site (Analysis b). Then, to manage the nested factor of 'Times' within 'Before' (see Table 4.5), only the data from 'Before' were analysed (Analysis c). The final analysis again used the 'Before' data but this time omitted the 'impact' site (Analysis d). Final variances were obtained using subtractions and additions of the data generated from the four separate analyses (Tables 4.6 & 4.7).

Table 4.6 Calculation of sources of variation in an asymmetrical Beyond-BACI design. Analysis 'a' incorporates the full data set, while the other analyses involve subsets of the data. Details about how the analyses are performed can be found in the text above. The coded results within each of the analyses e.g. a*x*, b*x*, c*x* and d*x* (where *x* is a whole integer between 1 and 4) are used as shown in Table 4.7 to calculate the final variances. SS=sum of squares, df=degrees of freedom (Table after Underwood 1993a).

Analysis	**a (all data)**	**b (controls)**	**c (before)**	**d (before controls)**
Source of Variation	SS & df	SS & df	SS & df	SS & df
Before *vs* After = B			-	-
Periods = P(B)				
Times = T(P*B)				
Locations = L	a1	b1		
B x L	a2	b2	-	-
P(B) x L	a3	b3	c1	d1
T(P*B) x L	a4	b4	c2	d2
Residual				
Total				

Table 4.7 Calculation of final variances in a Beyond-BACI design following an impact. Final values are calculated from the results of the preliminary analyses shown in Table 4.6 (Table after Underwood 1993a).

Source of variation	**SS**	**df**	**MS**	**Calculated from**
Before *vs* After = B				a
Periods (P) = P(B)				a
Times (B) = T(B)				a
Locations = L				a1
Impact *vs* Controls = I				a1-b1
Among Controls = C				b1
B x L				a2
B x I				a2-b2
B x C				b2
P(B) x L				a3
P(Bef) x L				c1
P(Bef) x I				c1-d1
P(Bef) x C				d1
P(Aft) x L				a3-c1
P(aft) x I				a3-c1-b3+d1
P(Aft) x C				b3-d1
T(B*P) x L				a4
T(Bef) x L				c2
T(Bef) x I				c2-d2
T(Bef) x C				d2
T(Aft) x L				a4-c2
T(Aft) x I				a4-c2-b4+d2
T(Aft) x C				b4-d2
Residual				a
Total				a

The data used for the Beyond-BACI analyses were potentially serially correlated. If serial correlation existed to a significant level an adjustment would need to be made to accommodate it and render the results meaningful. The data were examined for serial correlation by Phil Leppard (Statistics Department, University of Adelaide) using "BMDP: V5, Statistical Software" (1990) and an unbalanced repeated measures model with structured covariance matrices. The results of this investigation were generated as a within subject correlation matrix for both data sets (see Appendix O).

Sand Drift

Northward sand drift perturbed the HCA site in late June 1995 and the sand influx continued as a long pulse disturbance (or a press disturbance relative to organisms with a short lifespan) at this site for some months. Access to HCA was difficult and the first post-impact 'sand' assessment took place at the end of August 1995. The 'sand' analysis used HCA as the 'impact site' and Kingston Park, Marino Rocks, PS1, PS2 and PS3 as control locations. The adjacent HCB site was monitored along with HCA to investigate how assemblage composition varied in a 'similar' but less disturbed site, but was excluded from the analysis due to its late inclusion as a monitored site.

The Ruptured Effluent Pipe

The rupture of the effluent pipe at Port Stanvac occurred on the 29th of August 1995 but PS1A was primarily affected as repair work continued and the pipe was allowed to discharge its contents directly across this site (11th-13th of September 1995). Therefore, the first sampling of PS1A was treated as pre-impact data collection, while all later data were considered to be post-impact. The same set of control sites used in the 'sand' perturbation analysis also served as controls for the 'effluent' perturbation analysis.

4.4 Results

4.4.1 Recreational Use of Study Sites

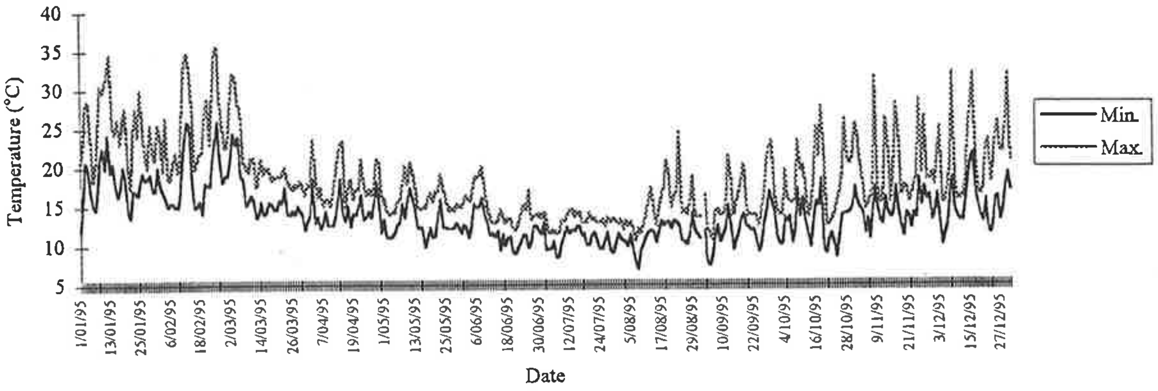
The range of activities seen at study sites included surfers walking across sites; and people fishing off the edge of reefs, inspecting intertidal animals *in situ*, walking dogs and collecting shellfish and crabs. The most commonly observed activity was walking (to exercise dogs, for personal exercise and enjoyment, or to inspect intertidal animals), implying that trampling was the most likely recreational disturbance to act at the study sites. This will be considered in Chapter 7.

4.4.2 Temporal Changes in Physical Parameters

4.4.2.1 Tide, Temperature and Wind Patterns in GSV

A brief overview of the type of variability to be tolerated by intertidal animals is presented in Figs 4.1-4.5. Daily air temperature fluctuated by as much as 12^{0}C especially in summer, while the temperature range was narrower in the cooler months e.g. June to August (Fig. 4.1a); trends which were especially evident when monthly average maxima and minima temperatures were compared (Fig. 4.1b). Similar fluctuations could be seen with water temperature (Fig 4.2) but the temperature range experienced by animals during water inundation was generally narrower and significantly lower than the corresponding air temperature experienced during exposure.

a) Daily maximum and minimum air temperature



b) Average monthly maximum and minimum air temperature

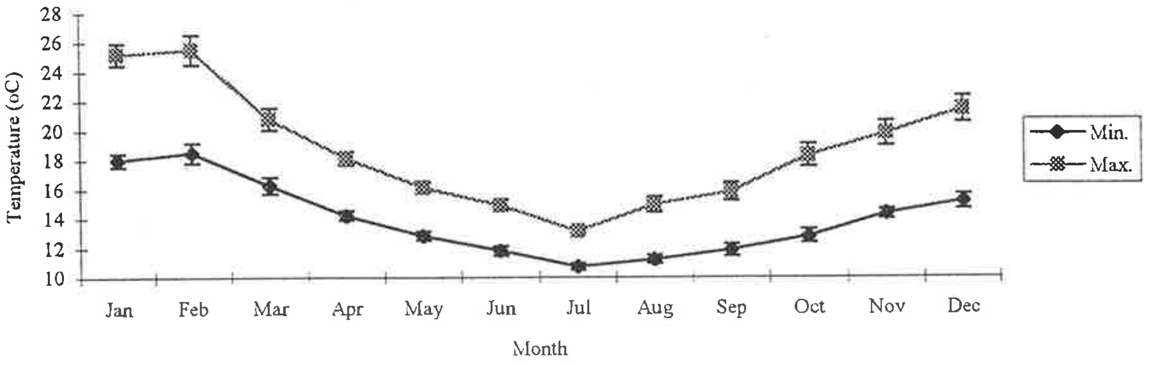
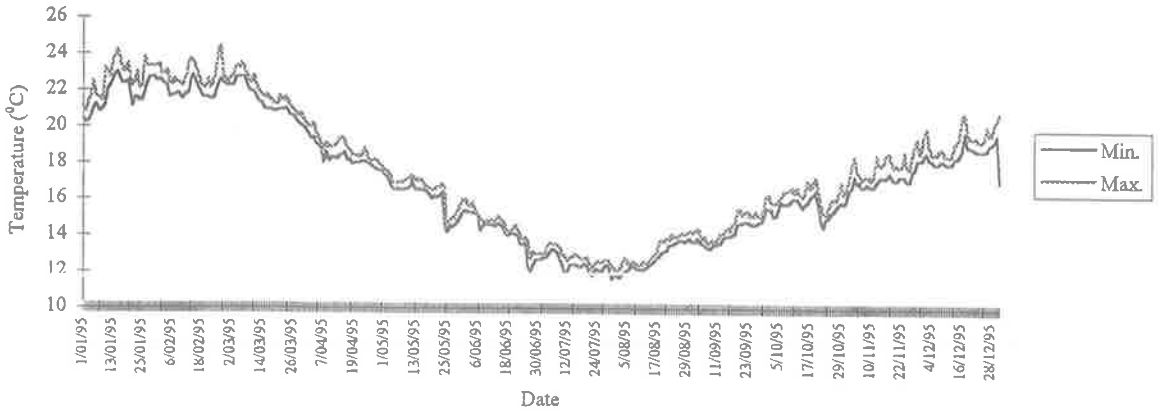


Fig. 4.1 The variability seen in the air temperature range at Port Stanvac daily (a) and monthly (b) during 1995. Monthly maximum and minimum air temperatures were calculated by averaging the respective daily maximum and minimum temperatures, shown in (a), for each month. Temperature is shown in degrees Celsius (°C). Error bars represent standard errors. Data provided by NTF, Flinders University.

a) Daily maximum and minimum water temperature



b) Average monthly maximum and minimum water temperature

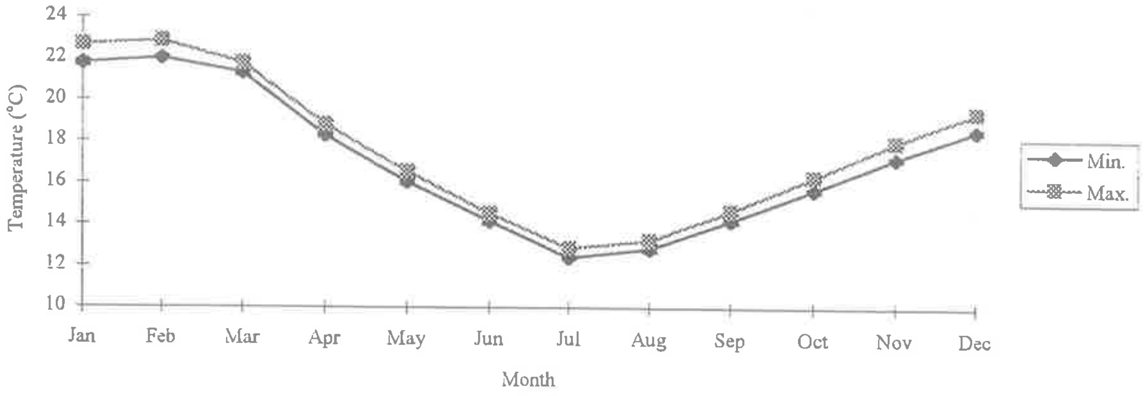
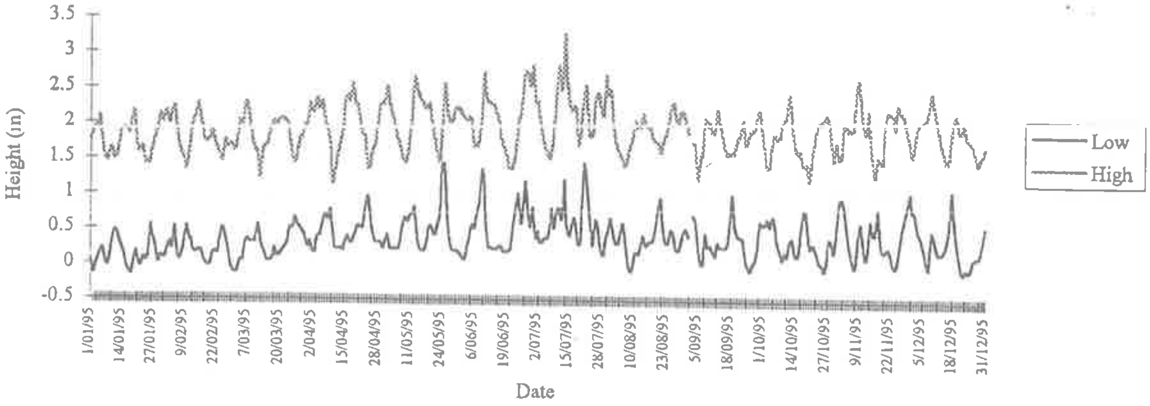


Fig. 4.2 The variability seen in the water temperature range at Port Stanvac daily (a) and monthly (b) during 1995. Monthly maximum and minimum water temperatures were calculated by averaging the respective daily maximum and minimum temperatures, shown in (a), for each month. Temperature is shown in degrees Celsius (°C). Error bars represent standard errors. Data provided by NTF, Flinders University.

Tidal height also exhibited considerable seasonal and cyclic variation, with the maximum variability in the heights of both high and low tides occurring in winter, particularly in July (Fig. 4.3a & b). Tidal height was closely linked to barometric pressure changes and the strength (Fig. 4.4) and direction (Fig. 4.5) of the prevailing winds. Wind speed and direction were highly variable over temporal scales of minutes and hours (as per data provided by The National Tidal Facility, Flinders University), days (Figs 4.4 & 4.5) and months, and were characterised by great seasonal variability. Consecutive days in winter typically exhibited extremely high variability in wind speed, most notably in July (Fig. 4.5b). The prevailing wind direction was presented as the deviation from degrees true in Fig. 4.5 and this can be placed into a general context using Fig. 4.6.

a) Daily height of high and low tides



b) Average monthly height of high and low tides

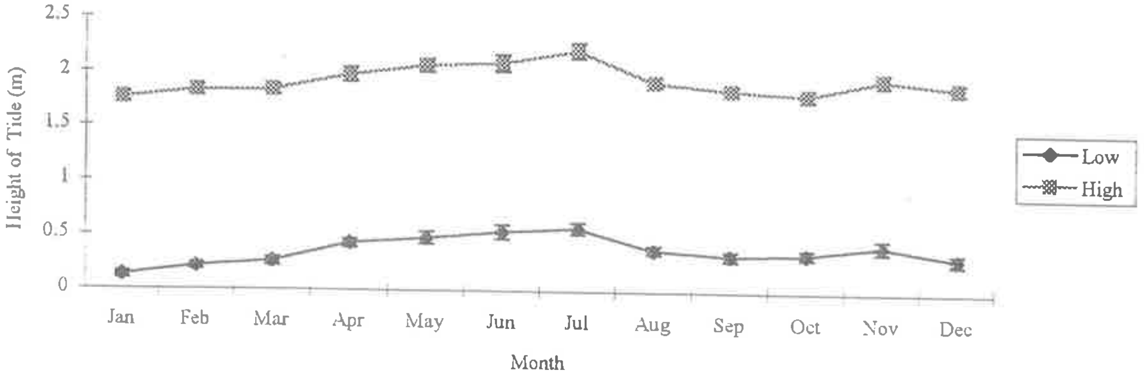
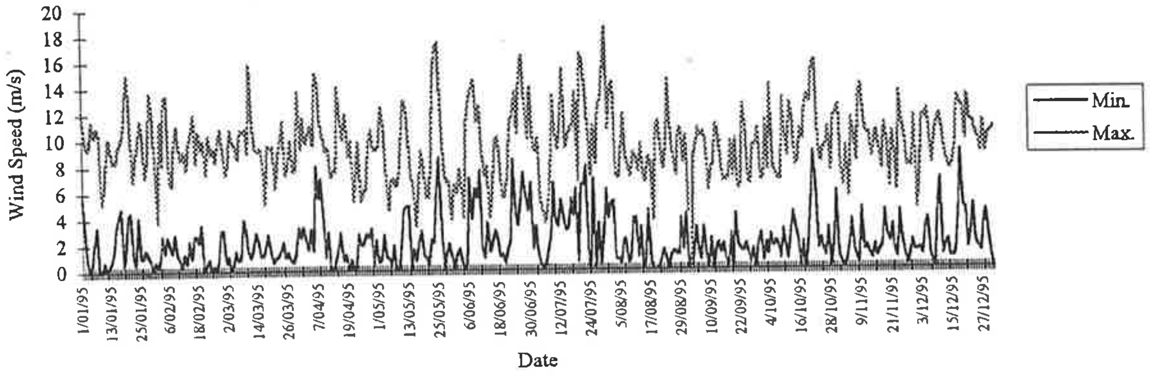


Fig. 4.3 The variability seen in the tidal range at Port Stanvac daily (a) and monthly (b) during 1995. Monthly maximum and minimum tidal heights were calculated by averaging the respective daily high and low tides, shown in (a), for each month. Tidal heights are shown in metres (m). Error bars represent standard errors. Data provided by NTF, Flinders University.

a) Daily maximum and minimum wind speed



b) Average monthly maximum and minimum wind speed

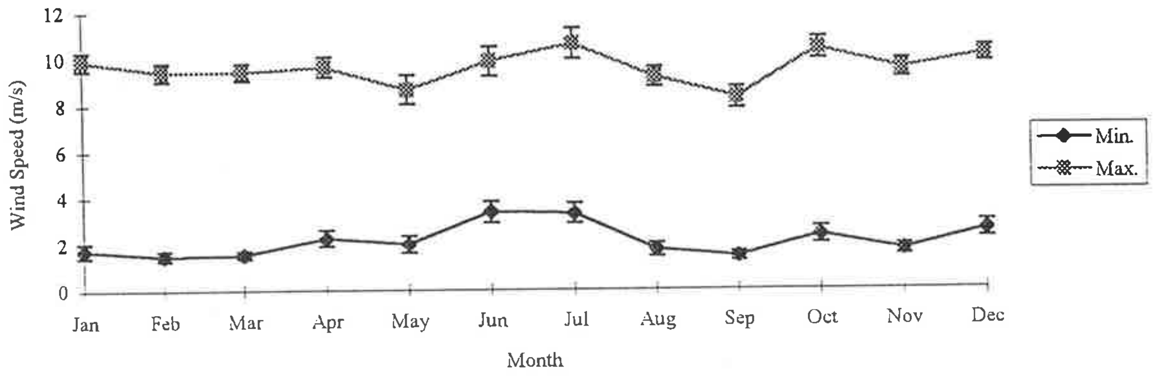
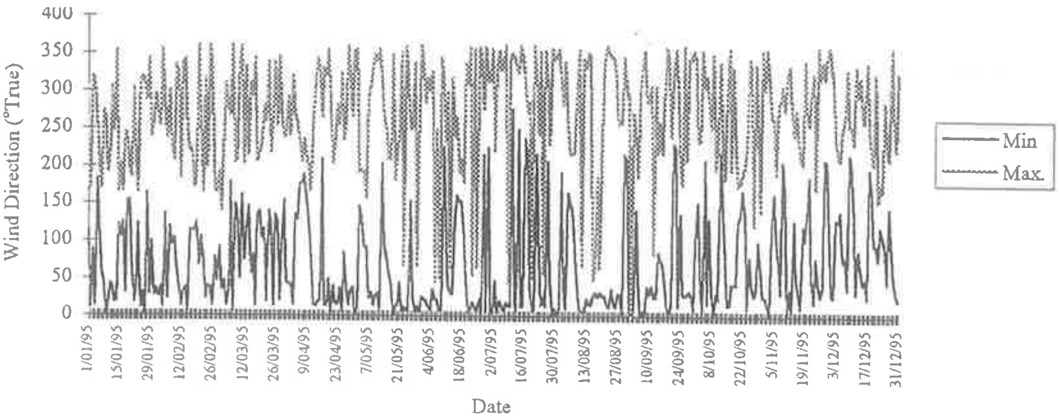


Fig. 4.4 The variability seen in wind speed at Port Stanvac daily (a) and monthly (b) during 1995. Monthly maximum and minimum wind speeds were calculated by averaging the respective daily maximum and minimum air speeds, shown in (a), for each month. Wind speeds are shown in metres/second (m/s). Error bars represent standard errors. Data provided by NTF, Flinders University.

a) Daily range of wind directions (from degrees true)



b) Average daily wind direction (from degrees true)

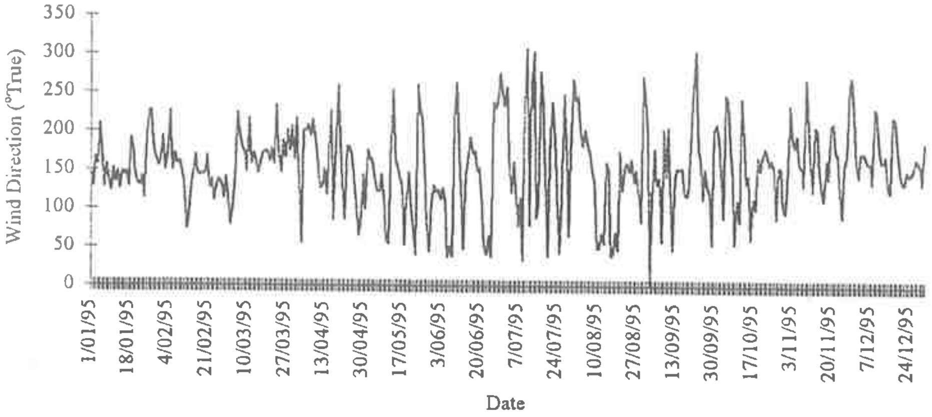


Fig. 4.5 The variability seen in the wind direction at Port Stanvac daily (a) and averaged over each day (b) during 1995. Wind direction is shown as deviations from degrees true North (°True). Data provided by NTF, Flinders University.

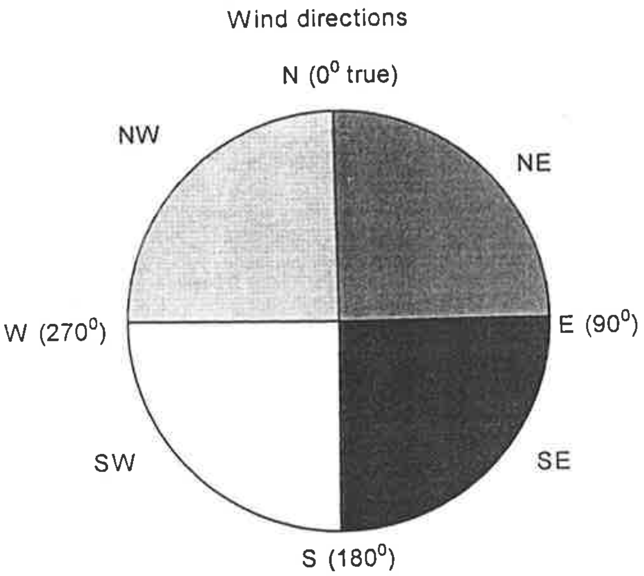


Fig. 4.6 The relationship between wind direction as degrees true North (°True), and the general wind direction scheme. NE= North-east, E= East (90°), SE= South-east, S= South (180°), SW= South-west, W= west (270°), NW= North-west, N= North (0° true).

4.4.2.2 Other Physical Parameters Assessed at Study Sites

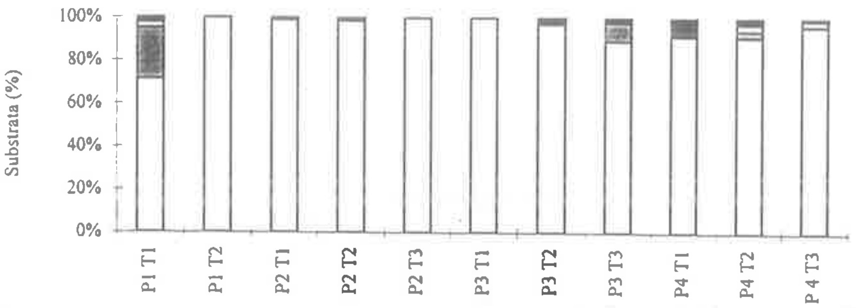
Substrata

Physical parameters tended to fluctuate consistently within and between sites apart from substrata character which changed markedly at exposed sites with mobile rock (designated as 'unstable') in response to rough conditions, and also at sites where northward sand drift occurred. The other notable changes observed during Beyond-BACI sampling were specific to water quality and were localised to PS1A.

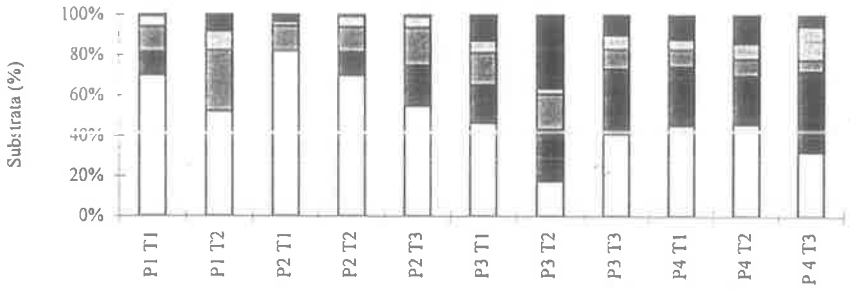
The average substrata composition at each zone within each site was calculated and graphed separately for 'Northern' (Fig. 4.7), 'Central' (Fig. 4.8) and 'Southern' study sites (Fig. 4.9). At 'Northern' sites a variety of changes were seen in substrata composition during Beyond-BACI sampling. For example, Kingston Park (a 'stable' site) underwent little change in substrata composition during 1995 (Fig. 4.7a), while Marino Rocks experienced slight increases in the relative percentage of sand from June, with sand comprising 40% of the total substrata by P3T2. The percentage of mobile boulder also increased and peaked by P4T3 at this site (Fig. 4.7b).

Substrata Composition at 'Northern' Sites

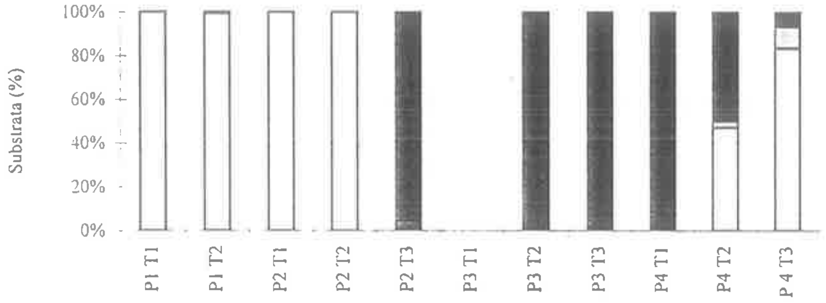
a) Kingston Park



b) Marino Rocks



c) HCA



d) HCB

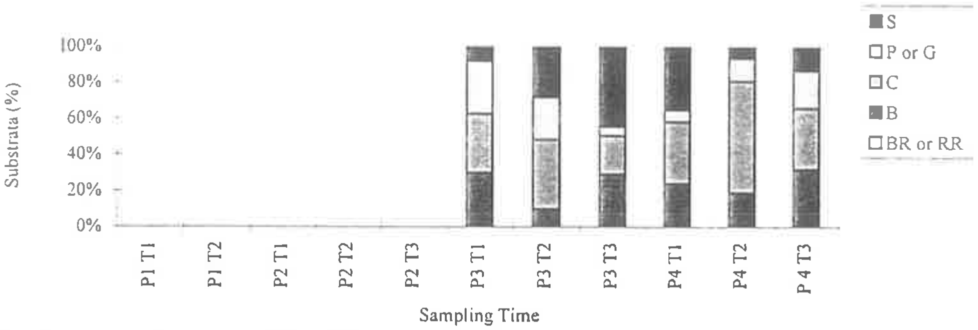


Fig. 4.7 The substrata composition (shown as the percentage of total substrata) in the 'upper' zones at 'Northern' study sites during the Beyond-BACI sampling period. Substrata composition was averaged for the seven 0.25m^2 quadrats used at each site. Recognised substrata grades (refer to legend) were sand (S), pebble or gravel (P or G), cobble (C), boulder (B) and reef-rock or bedrock (RR or BR) and these have been graphed on the *y*-axis as the percentage of the total substrata. Sampling times shown on the *x*-axis are as described in the text, with 'P' corresponding to the sampling 'Period' and 'T' corresponding to the sampling 'Time' (see Table 4.3).

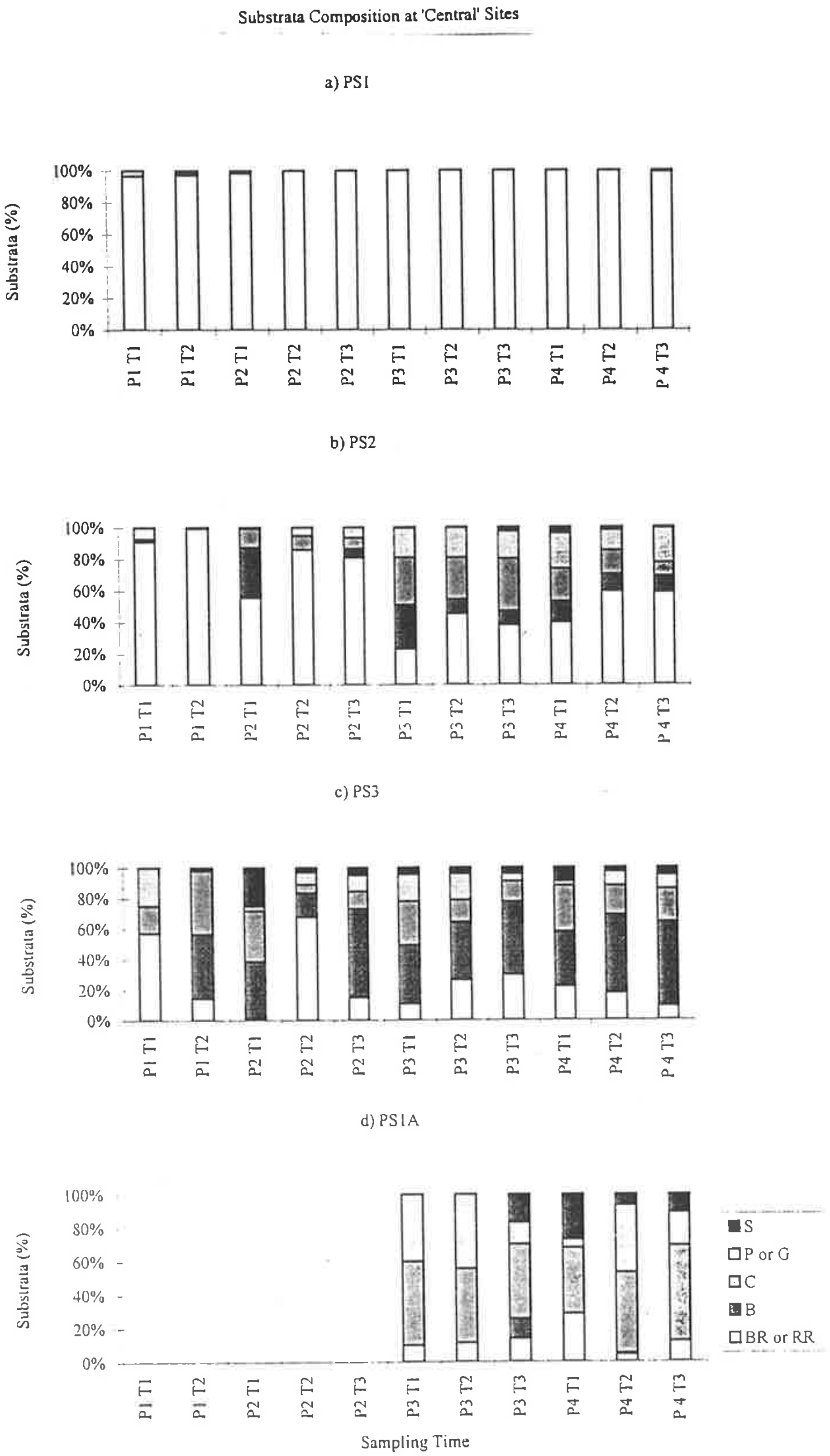
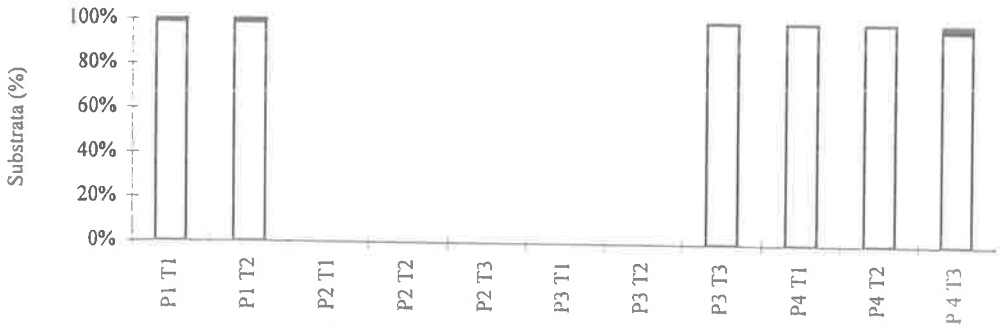


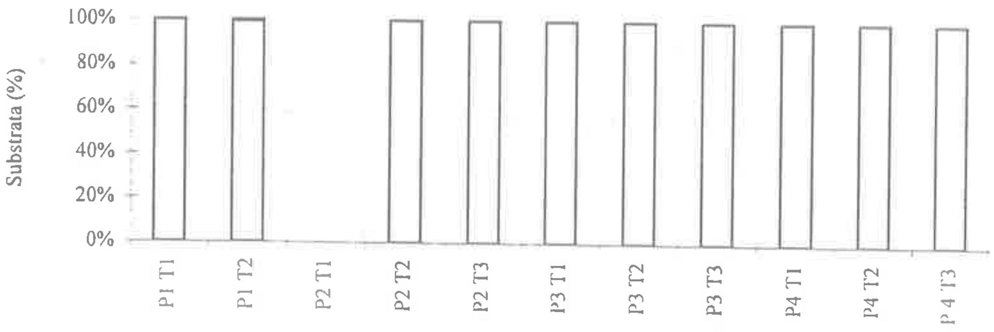
Fig. 4.8 The substrata composition (shown as the percentage of total substrata) in the 'upper' zones at 'Central' study sites during the Beyond-BACI sampling period. Substrata composition was averaged for the seven 0.25m^2 quadrats used at each site. Recognised substrata grades (refer to legend) were sand (S), pebble or gravel (P or G), cobble (C), boulder (B) and reef-rock or bedrock (RR or BR) and these have been graphed on the y-axis as the percentage of the total substrata. Sampling times shown on the x-axis are as described in the text, with 'P' corresponding to the sampling 'Period' and 'T' corresponding to the sampling 'Time' (see Table 4.3).

Substrata Composition at 'Southern' Sites

a) Witton Bluff



b) Port Noarlunga South



c) Robinson Point

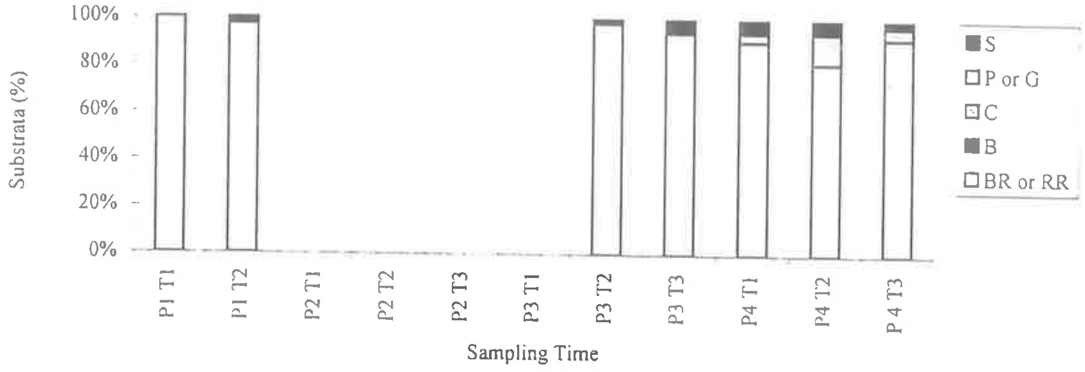


Fig. 4.9 The substrata composition (shown as the percentage of total substrata) in the 'upper' zones at 'Southern' study sites during the Beyond-BACI sampling period. Substrata composition was averaged for the seven 0.25m^2 quadrats used at each site. Recognised substrata grades (refer to legend) were sand (S), pebble or gravel (P or G), cobble (C), boulder (B) and reef-rock or bedrock (RR or BR) and these have been graphed on the *y*-axis as the percentage of the total substrata. Sampling times shown on the *x*-axis are as described in the text, with 'P' corresponding to the sampling 'Period' and 'T' corresponding to the sampling 'Time' (see Table 4.3).

The site most affected by sand influx during 1995 was HCA where sand comprised up to 100% of substrata from June. This represented a major substrata shift from the original domination of this site by bedrock (Fig. 4.7c). The increase in sand recorded at P2T3 represented a light covering which was not associated with any obvious change in animal numbers, unlike both the P3T1 and P3T2 sampling times when a thick sand cover (at least 5cm) was associated with marked reductions in animal abundance. This reduction could not be quantified at P3T1 due to access difficulties. The adjacent Hallett cove site (HCB) also showed evidence of a (less significant) sand influx (Fig. 4.7d) with the relative percentage of sand increasing from 6% at sampling time P3T1 to almost 50% by P3T3. However, at this site the greater elevation of cobble and boulder (compared to the virtually flat bedrock at HCA) meant that some rock was left free of sand.

Tide, wave and other weather influences differentially affected the substrata composition at 'Central' study sites (Fig. 4.8). PS1 was a relatively homogeneous and stable site dominated by bedrock for the duration of 1995 (Fig. 4.8a). PS2 was less stable and was characterised by increases in the relative abundance of boulder and cobble by P2T1 (Fig. 4.8b). The percentage of the different 'grades' of mobile substrata varied after this time but remained consistently higher than was recorded during the first two sampling times. Increased contributions by boulder and variable contributions by cobble also occurred at PS3 in association with increased amounts of sand, the latter peaking at about 12% of total substrata by P2T1 (Fig. 4.8c). PS1A was relatively consistent in its dominant substrata type but increased amounts of sand were noted from P3T3 until the end of the Beyond-BACI sampling period (Fig. 4.8d).

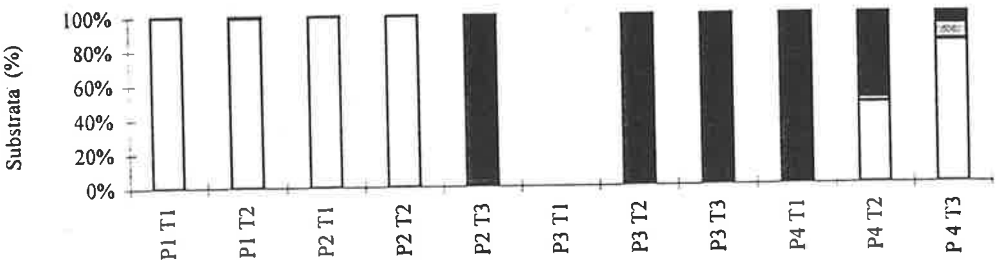
The 'Southern' study sites all displayed substrata stability during the Beyond-BACI sampling period (Fig. 4.9) and for the duration of preliminary sampling. Robinson Point was noted to have slight increases in the percentage contribution by sand and pebble towards the latter half of the Beyond-BACI sampling period, but this never amounted to greater than 20% of the total substrata (Fig. 4.9c).

To visualise how the control sites varied compared to the 'sand' perturbed site, the average substrata composition at the Beyond-BACI 'sand' control sites was compared to the average substrata composition at all control sites (all sites other than PS1A, HCA & HCB) and to the substrata composition at HCA (Fig. 4.10). An 100% increase in the contribution of sand occurred at HCA by P3T1 (Fig. 4.10a) while little change in the percentage of sand occurred, on average, for the full set of control sites for the same period (Fig. 4.10b). Since it was necessary to omit some of the intended control sites from the Beyond-BACI 'sand' analysis it was more informative to compare the substrata composition at HCA to changes in the set of controls used in the actual Beyond-BACI 'sand' analysis. This revealed that the Beyond-BACI control set experienced greater substrata variability (on average) than the full set of control sites (Fig. 4.10b & c).

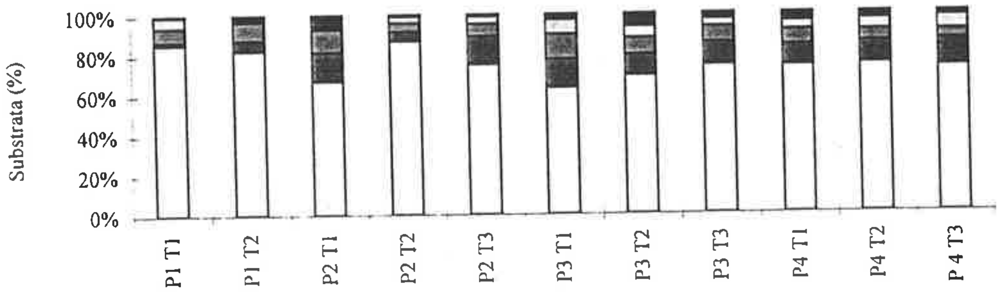
The increase in sand recorded at 'Northern' study sites in June 1995 was followed by a repeat influx in June of the following year. The 1996 sand influx mainly affecting HCA and Kingston Park, introducing the possibility that northward sand drift may represent a cyclic disturbance at 'Northern' study sites, particularly in winter.

Substrata Composition: Controls *vs* HCA

a) HCA



b) All control sites



c) Beyond-BACI controls

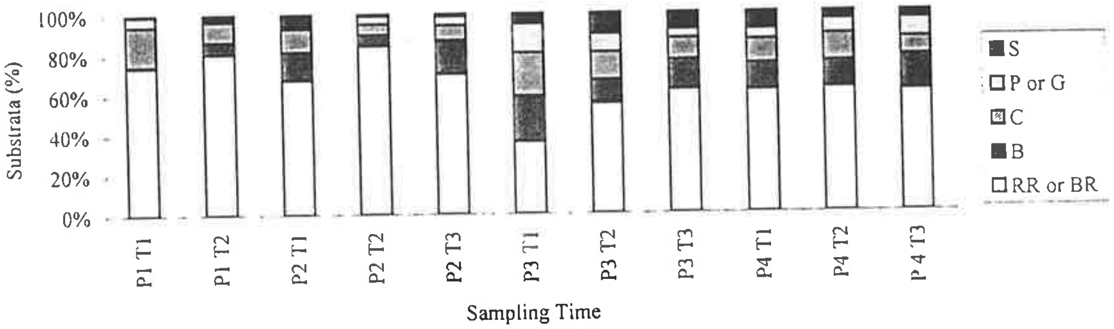


Fig. 4.10 The substrata composition (shown as the percentage of total substrata) in the 'upper' zones at HCA (a), the full set of control sites (b) and the Beyond-BACI set of control sites (c) during the Beyond-BACI sampling period. Substrata composition was averaged for the seven 0.25m^2 quadrats used at each site, and was further averaged across the appropriate set of control sites to generate graphs b & c. Recognised substrata grades (see legend) were sand (S), pebble or gravel (P or G), cobble (C), boulder (B) and reef-rock or bedrock (RR or BR). Sampling times shown on the *x*-axis are as described in the text, with 'P' corresponding to the sampling 'Period' and 'T' corresponding to the sampling 'Time' (see Table 4.3).

Changes Associated with the Ruptured Effluent Pipe at Port Stanvac

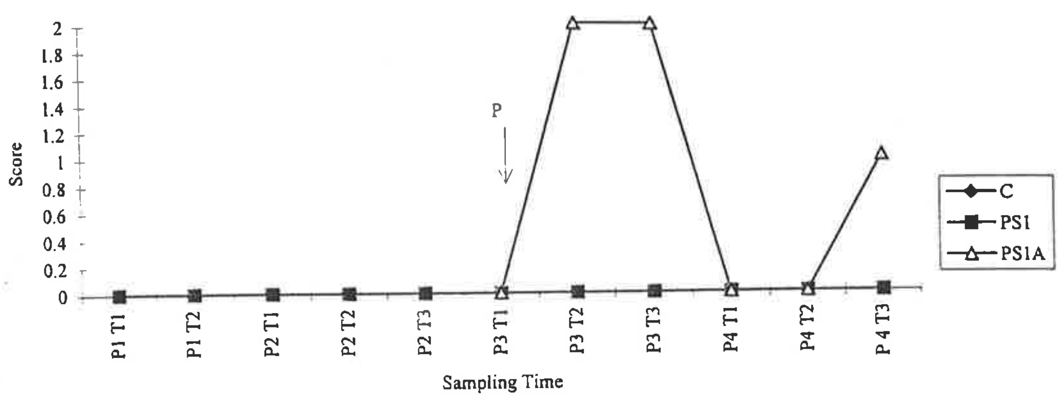
The ruptured refinery pipe spilled refinery effluent across PS1A but no discharge was observed to flow directly onto PS1. The intertidal release of effluent resulted in changes to a number of assessed parameters, namely the scored presence of oil, the water temperature, specific conductivity, pH, and the percentage of retained water at PS1A. These parameters remained within a consistent and narrow range at all other sites for the duration of preliminary sampling (Table 4.8).

Table 4.8 The range of assessed parameters at study sites which were unaffected by the ruptured refinery effluent pipe e.g. all sites other than PS1A. All parameters were assessed as described in section 4.3 and Chapter 3.

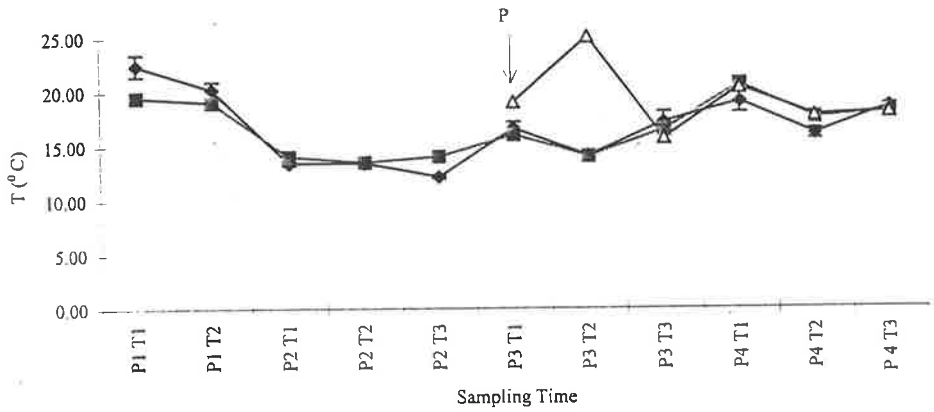
Assessed Parameter	Range encountered during preliminary sampling
Oil presence (median score per 7 quadrats)	0 (arbitrary units)
Water temperature (at a depth of 20cm)	12-22^{0}C
Specific conductivity	49-52mS
Water pH	8.0-8.6
Percentage of retained water (averaged over 7 quadrats)	0-60%

Refinery effluent at PS1A was detected as an 'oil' odour accompanied by a slight oil sheen (subjectively scored with a median value of 2 for the seven deployed quadrats) at P3T1. In comparison a median value of zero was recorded at all other sites during the Beyond-BACI assessment period (Fig. 4.11a). The water temperature at PS1A increased in the first two post-impact sampling times, peaking at almost 12^{0}C above that of the control and PS1 sites (Fig. 4.11b). Another change localised to PS1A was a sharp decline in water conductivity at times P3T1 and P3T2 (of greater than 30mS) which indicated that the effluent water was fresh (Fig. 4.11c). Water acidity initially increased, but an increase in alkalinity occurred at P3T3 before the pH reverted to the range exhibited by the other sites (Fig. 4.12a & Table 4.8). Retained water at all sites was more variable than the other parameters mentioned so far. However, PS1A was characterised by greater water retention than the control sites (on average) and PS1, peaking at 80% at P3T2 (Fig. 4.12b).

a) Median Oil Score



b) Water Surface Temperature



c) Specific Conductivity

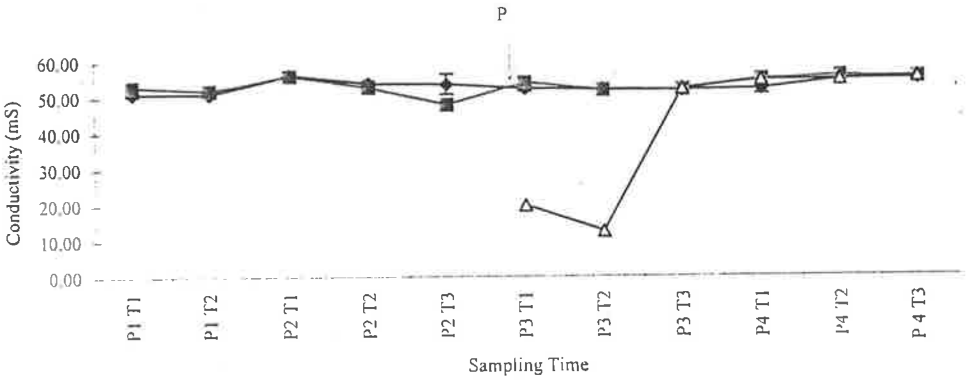
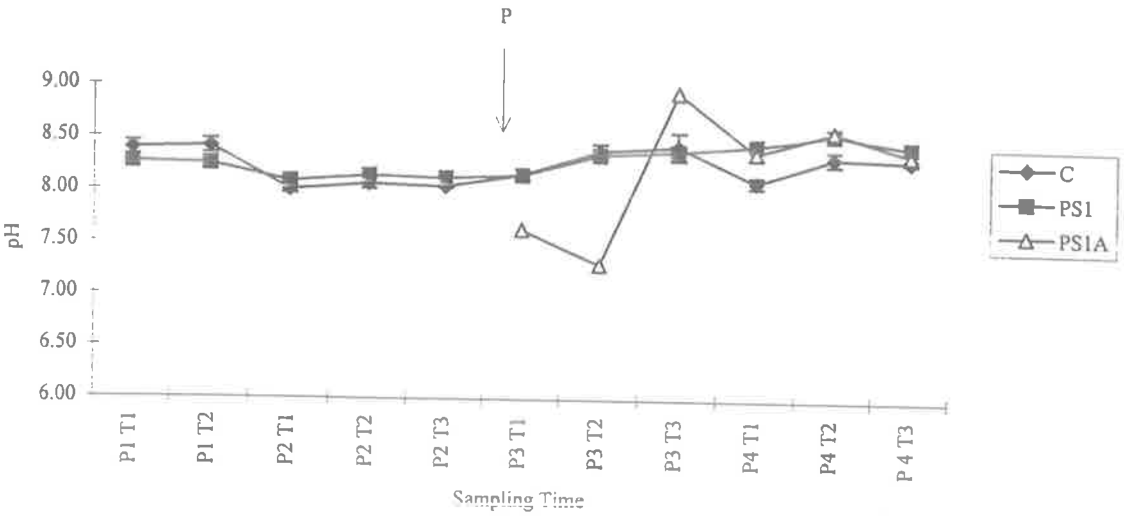


Fig. 4.11 The ruptured refinery effluent pipe resulted in changes in a) the scored presence of oil (assessed as the median oil score of seven quadrats), b) the surface water temperature (°C) and c) the specific conductivity of water in milli-Semens (mS) at PS1A. Similar changes did not occur at PS1 or the control sites used in the Beyond-BACI analysis. All parameters were assessed as described in the text (section 4.3). PS1 and PS1A parameters were determined by averaging (or determining the median value in the case of oil presence) across the seven quadrats, while parameters were averaged across the set of control sites to determine average changes at the unperturbed sites. The time of pipe rupture (P) is indicated by the arrow. Site abbreviations are; C= control sites, PS1= Port Stanvac 1 (adjacent to PS1A) and PS1A= the 'effluent' perturbed site. Error bars represent standard errors. Sampling times shown on the *x*-axis are as described in the text, with 'P' corresponding to the sampling 'Period' and 'T' corresponding to the sampling 'Time' (see Table 4.3).

a) Water pH



b) Retained water

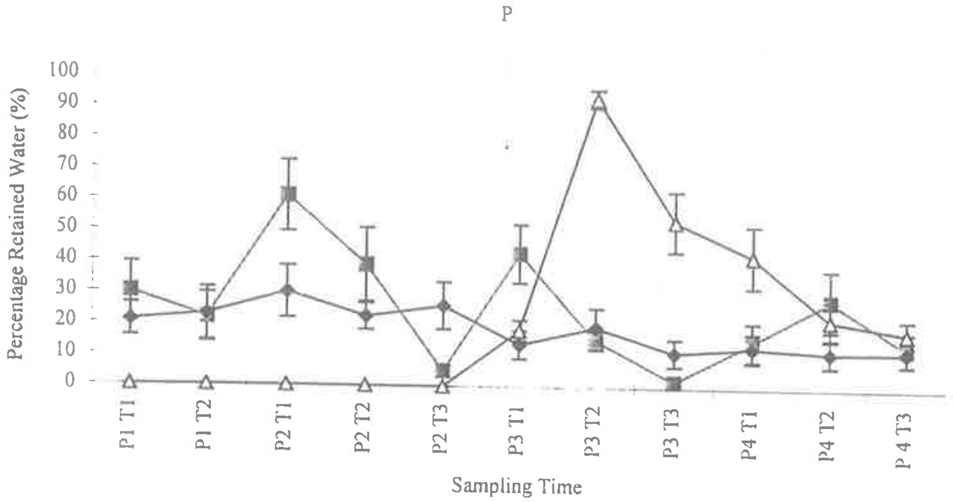


Fig. 4.12 The ruptured refinery effluent pipe resulted in changes in a) water pH and b) the percentage of retained water at PS1A. Similar changes did not occur at PS1 or the control sites used in the Beyond-BACI analysis. All parameters were assessed as described in the text (section 4.3). PS1 and PS1A parameters were determined by averaging across the seven quadrats, while parameters were averaged across the set of control sites to determine average changes at the unperturbed sites. The time of pipe rupture (P) is indicated by the arrow. Site abbreviations are; C= control sites, PS1= Port Stanvac 1 and PS1A= the 'effluent' perturbed site. Error bars represent standard errors. Sampling times shown on the *x*-axis are as described in the text, with 'P' corresponding to the sampling 'Period' and 'T' corresponding to the sampling 'Time' (see Table 4.3).

4.4.3 Temporal Fluctuations in Dominant Taxa at Study Sites

4.4.3.1 The Abundance and Size Distribution of *B. nanum*

The Total Abundance of B. nanum

B. nanum is a small gastropod often found co-existing with other gastropods in the mid-eulittoral zone and virtually ubiquitous at study sites. The only study site at which it was never found was Witton Bluff. All other sites had high densities of this animal relative to most other animal species although large differences existed between sites. A global trend at study sites where this species occurred was greater variability in its abundance (both within and between sampling times) in the 'lower' zones than was seen in the corresponding 'upper' zones.

The density of *B. nanum* in the 'upper' zone at Kingston Park remained between 40-60 animals per quadrat until September 1995 (spring) when numbers increased to 80-110 and the standard error also increased (Fig. 4.13a). The abundance then decreased during January and February 1996 to roughly approach the levels seen in March of the preceding year. Densities of *B. nanum* in the 'lower' zone at Kingston Park were generally greater than the corresponding numbers recorded in the 'upper' zone apart from September 1995 and July 1996. Sand influx to Kingston Park in May and June 1996 coincided with decreased abundances of *B. nanum* in both zones and no animals were recorded in the 'lower' zone at this site in June 1996.

Marino Rocks was generally characterised by low densities of *B. nanum* (Fig. 4.13b). In the 'upper' zone the abundance of *B. nanum* ranged from 6-62 animals for the duration of sampling while densities in the 'lower' zone remained between 2-68 animals per quadrat with an abundance peak occurring in July 1995. The original area selected for sampling at Marino Rocks was overlaid by mobile substrata early in the sampling period (Fig. 4.7b), an event which appeared to be associated with the sharp decrease in abundance seen in both zones between the two March 1995 sampling times (Fig. 4.13b).

In early 1995, HCA was characterised by high densities of *B. nanum* in the 'upper' zone, but numbers fluctuated widely between sampling times (Fig. 4.13c). Prior to the 1995 sand influx, densities of *B. nanum* in the 'upper' zone ranged from 60-144 animals per quadrat, but numbers declined rapidly following the sand influx and no animals were recorded from early September until October 1995. Population recovery at the site remained slow and numbers had not returned to pre-perturbation levels by early May 1996 when another sand influx occurred. The decline of *B. nanum* at the HCA site was matched by a simultaneous increase in the number of animals at HCB but by February the following year the 'upper' zone at HCA supported more *B. nanum* than HCB (Fig. 4.13c).

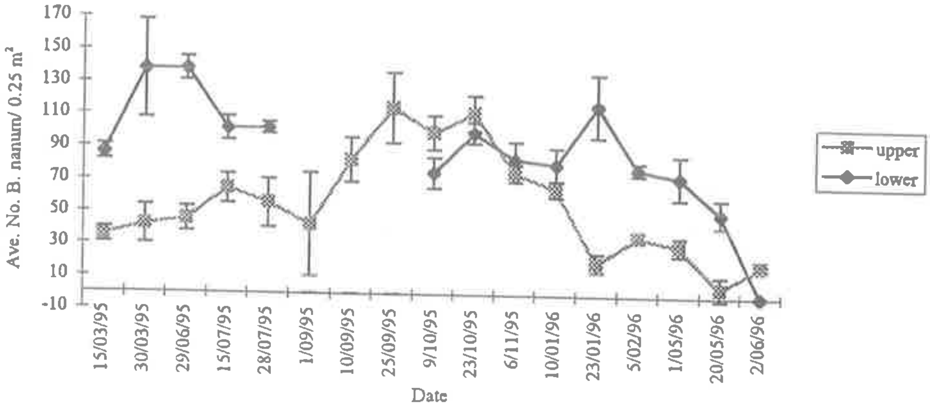
The Port Stanvac sites were differentially exposed to natural disturbance during early 1995 (Fig. 4.8). PS2, PS3 and the 'lower' zone at PS1 were all affected by mobilisation of cobble and boulder substrata during rough weather in late March and early April 1995. PS1A and the 'upper' zone at PS1 were considered to have greater substrata stability than the other Port Stanvac sites (refer to Table 4.2) and were generally typified by higher *B. nanum* abundances. Like all Port Stanvac sites, PS1 displayed large variations in *B. nanum* numbers for the duration of sampling (Fig. 4.14a). From late October 1995 until the end of sampling, the 'upper' zone at PS1 supported higher abundances of *B. nanum* than PS1A, which (in turn) had higher densities than the 'lower' zone at PS1. This pattern of abundances appeared to be related to the substrata stabilities of the sites since the 'upper' zone at PS1 was the most stable (Fig. 4.8) and the 'lower' zone at this site was the least stable of the three sampled areas. Peak abundances of greater than 120 animals were observed in the 'upper' zone at PS1 in October 1995 and again in May 1996.

PS2 generally supported higher densities of *B. nanum* than did PS3 (Fig. 4.14b & c). When it was possible to sample the 'lower' zones at these sites they often had higher numbers of *B. nanum* and greater variability (both within and between sampling times) than the 'upper' zones. The 'upper' zone at PS2 was characterised by a sharp decline in animal density between April and June 1995 followed by a small peak in late January

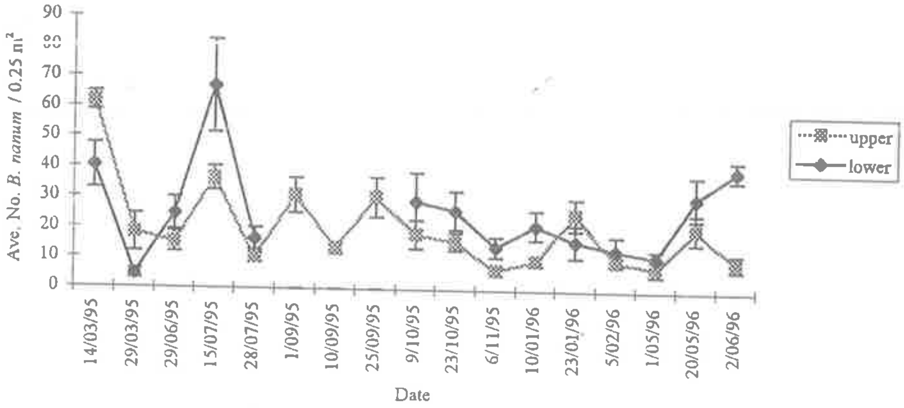
1996, although *B. nanum* numbers remained well below the 34 animals recorded in April 1995. In the 'upper' zone at PS3 the abundance of *B. nanum* decreased by about 50% between the April and July sampling times, remaining below 20 for the rest of the sampling period (Fig. 4.14c). Peak abundances occurred in the 'lower' zone at PS2 in late July and late October 1995 and in the 'lower' zone at PS3 in April and July 1995. A small secondary peak occurred at the latter site in February 1996.

The 'upper' zones at Port Noarlunga South and Robinson Point were characterised by a relatively narrow range of *B. nanum* densities, particularly the latter site (Fig. 4.15a & b). Peak densities of around 70 animals per quadrat were recorded in the 'lower' zone at Port Noarlunga South in late January and early February 1996, while trough densities of less than 15 animals per quadrat were recorded in May 1996. The 'upper' zone at Port Noarlunga South supported 12-50 animals for the duration of sampling with a small abundance peak in early October 1995 (Fig. 4.15a). The 'upper' zone at Robinson Point typically had densities of around 60 *B. nanum* per quadrat with small peaks occurring in March 1995 and late January 1996. The 'lower' zone at Robinson Point generally supported less *B. nanum* than the 'upper' zone at this site (Fig. 4.15b).

a) KP



b) MR



c) HCA & HCB

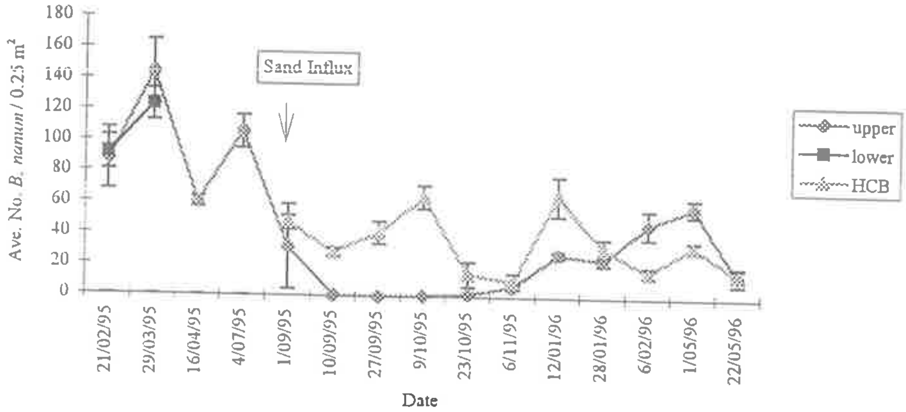
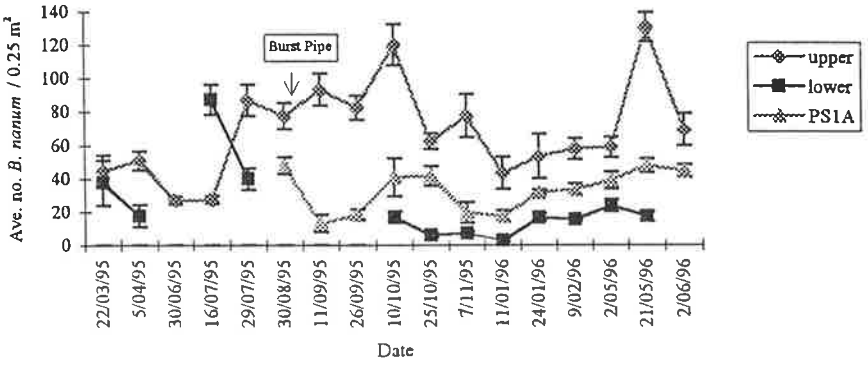
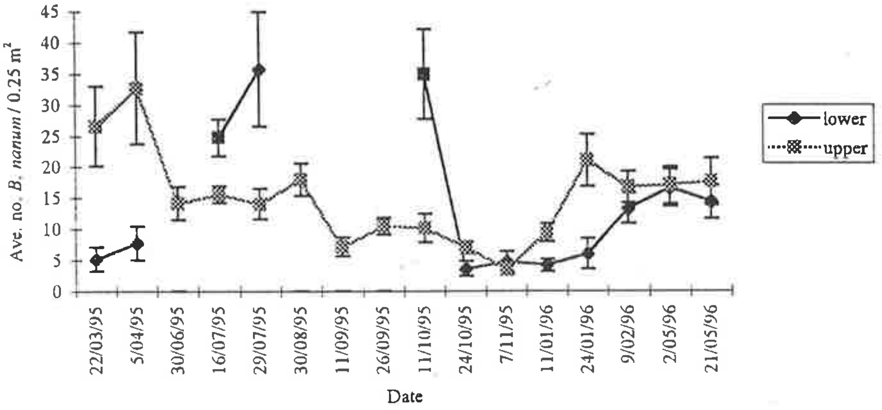


Fig. 4.13 The density of *B. nanum* at 'Northern' study sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove. Densities have been calculated as the average number of *B. nanum* (combined across 'small', 'medium' and 'large' size classes) per 0.25m² quadrat in both the 'upper' and 'lower' zones at sites. The 'upper' and 'lower' zones shown in the legend in c) correspond to HCA. The arrow indicates the commencement of post-impact sampling at HCA. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

a) PS1 & PS1A



b) PS2



c) PS3

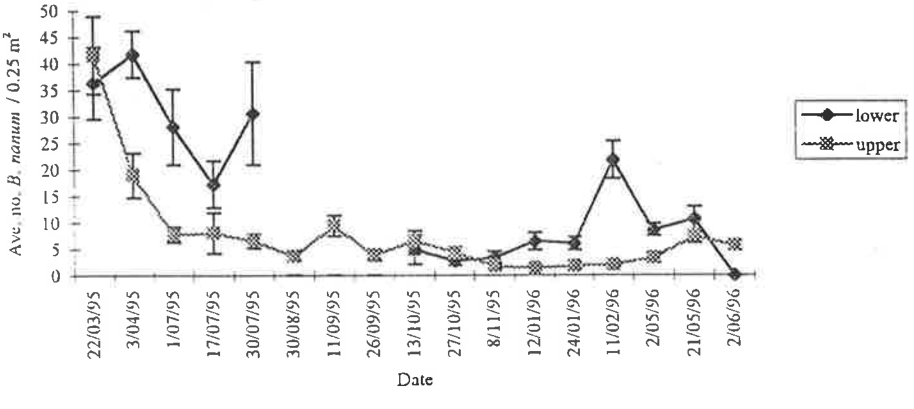


Fig. 4.14 The density of *B. nanum* at 'Central' study sites; a) PS1 & PS1A, b) PS2 and c) PS3. Densities have been calculated as the average number of *B. nanum* (combined across 'small', 'medium' and 'large' size classes) per 0.25m^2 quadrat in both the 'upper' and 'lower' zones at sites. The 'upper' and 'lower' zones shown in the legend in a) correspond to PS1. The timing of the effluent pipe rupture is arrowed in a). Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

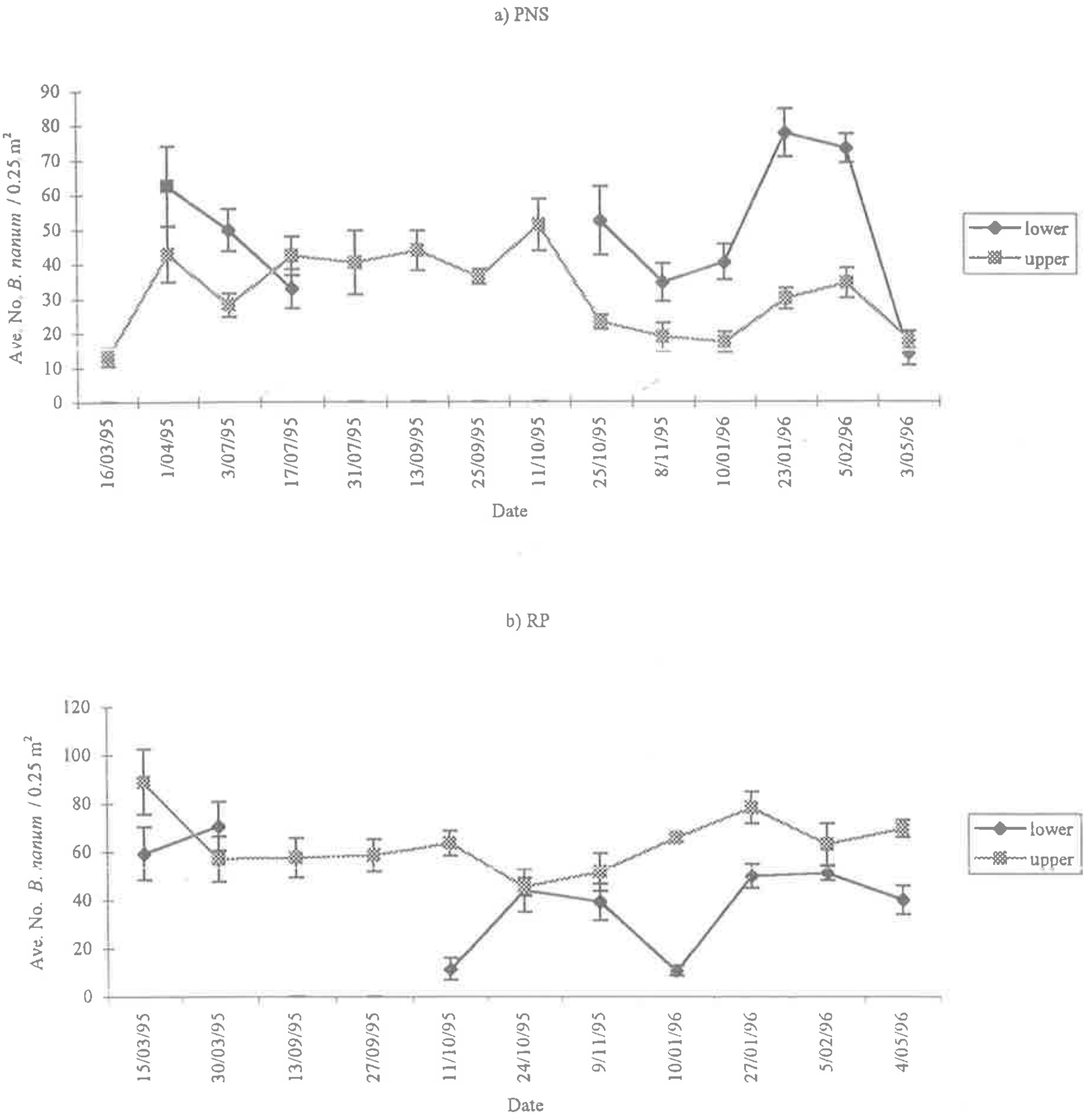


Fig. 4.15 The density of *B. nanum* at 'Southern' study sites; a) Port Noarlunga South (PNS) and b) Robinson Point (RP). Densities have been calculated as the average number of *B. nanum* (combined across 'small', 'medium' and 'large' size classes) per 0.25m^2 quadrat in both the 'upper' and 'lower' zones at sites. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to Section 4.3). Error bars represent standard errors.

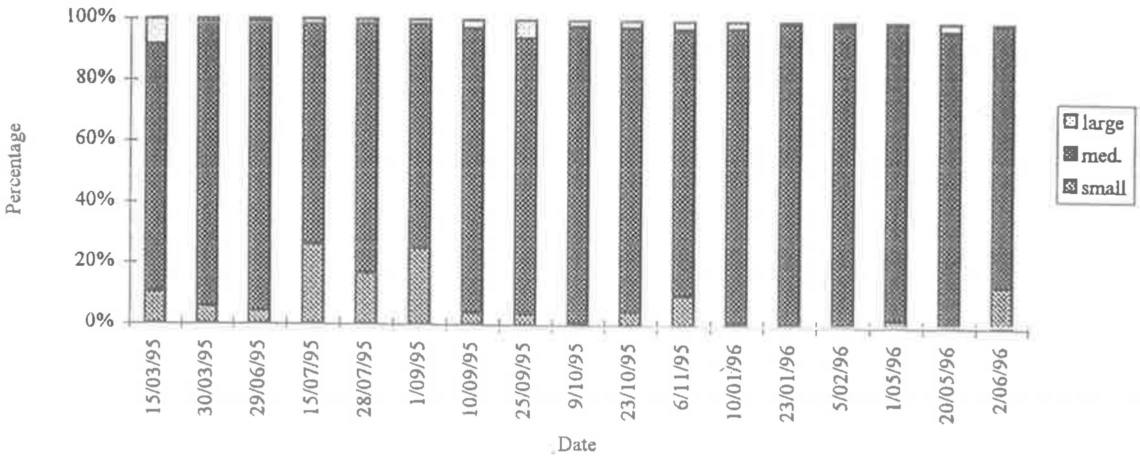
The Size Distribution of B. nanum

A general trend in terms of the contribution of different size classes of *B. nanum* to the population at a site was the domination by 'small' and 'medium' sized animals. However, this situation did not occur at Port Noarlunga South and Robinson Point where 'large' animals made a greater relative contribution.

In the 'upper' zone at Kingston Park 'medium' sized *B. nanum* accounted for 75% or more of the population for the duration of sampling (Fig. 4.16a). The 'lower' zone at Kingston Park was dominated by 'medium' sized *B. nanum* in March 1995 and February and May 1996 while at all other times 'small' animals dominated and accounted for as much as 85% of the population (Fig. 4.16b). 'Large' animals were occasionally seen in the 'upper' zone at Kingston Park but in comparatively low proportions.

Marino Rocks was consistently dominated by 'small' and 'medium' sized *B. nanum* with 'small' animals generally being more common (Fig. 4.17a & b). In the 'upper' zone, 'small' animals reaching a peak of 95% in early September 1995 and generally contributed greater than 60% to the population at all times. The notable exception occurred in mid March 1995 when 'small' animals comprised only 12% (Fig. 4.17a). 'Small' animals contributed at least 50% to the population at all times in the 'lower' zone at Marino Rocks with this size class peaking at 90% or more in late June, mid-July and October 1995 (Fig. 4.17b). It must be noted that the absolute numbers of *B. nanum* occurring at Marino Rocks were generally low and the percentage contribution of the various size classes may be a biased estimate of the 'true' size structure at the site.

a) KP: 'upper' zone



b) KP: 'lower' zone

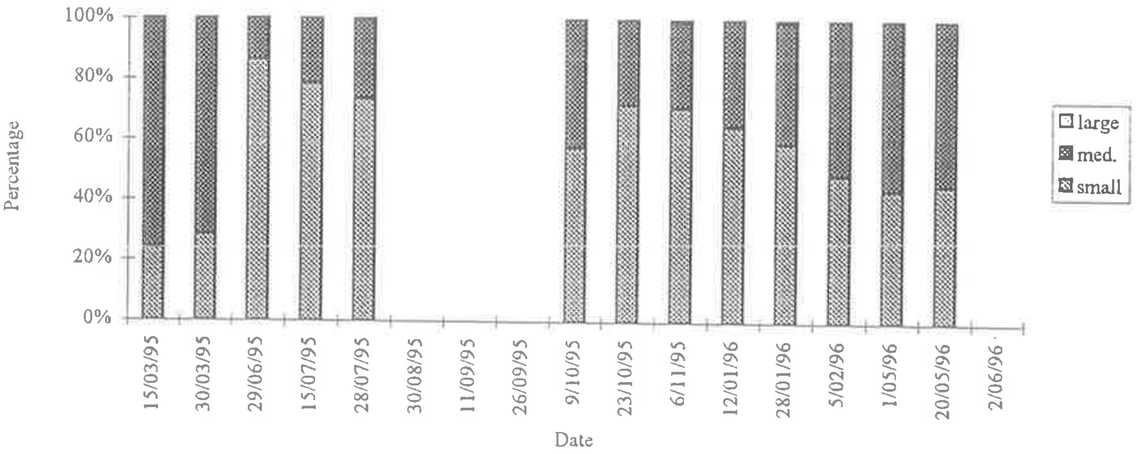
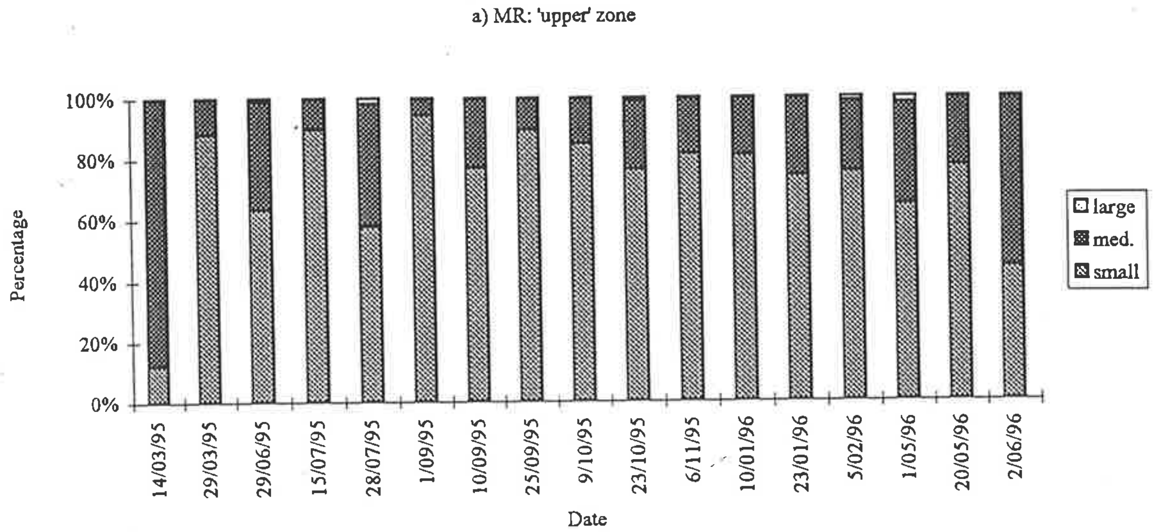


Fig. 4.16 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at Kingston Park (KP) which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).



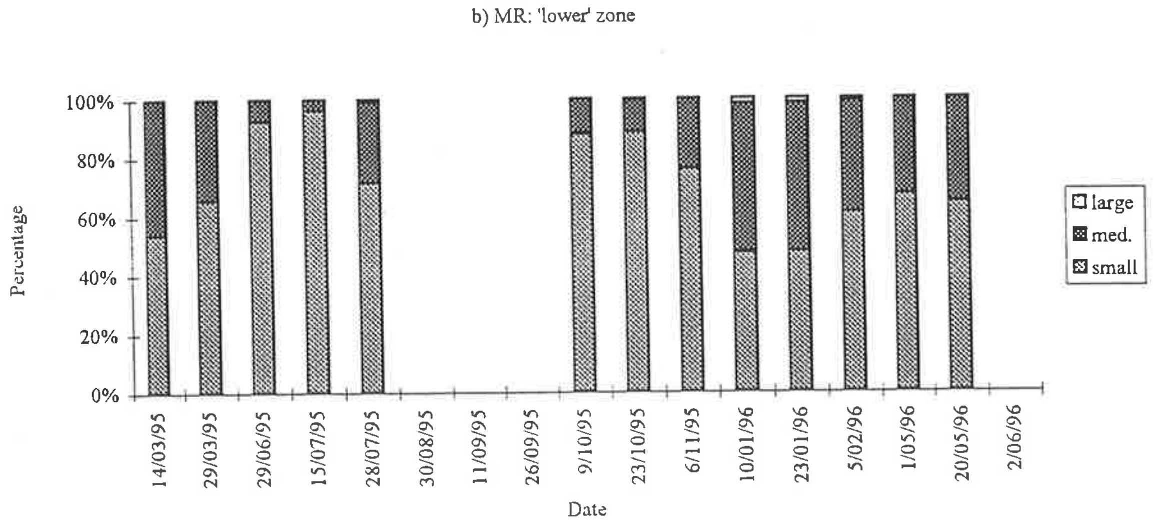
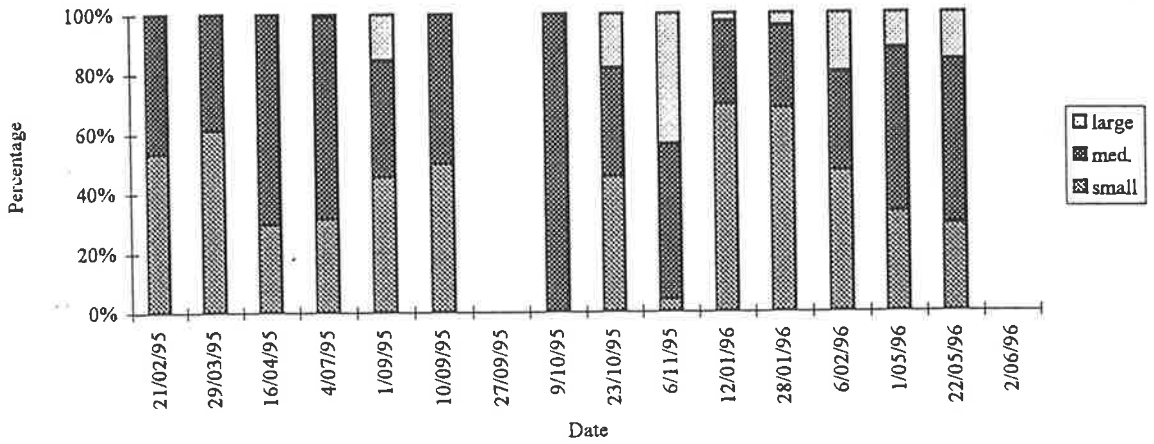


Fig. 4.17 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at Marino Rocks (MR) which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

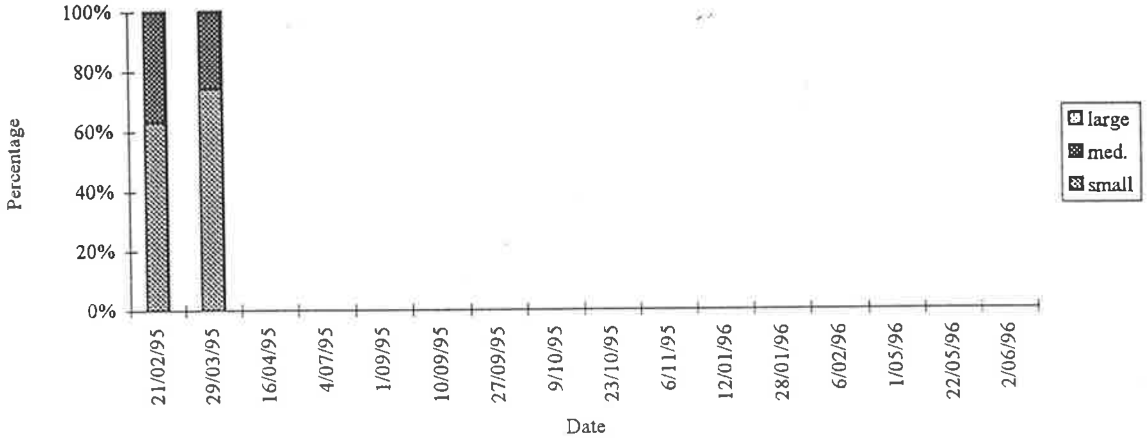
The size structure of *B. nanum* in the 'upper' zone at HCA was highly variable but 'small' and 'medium' sized animals were generally most heavily represented (Fig. 4.18a). Apparent trends in the size composition of *B. nanum* from mid-September to November 1995 were probably not informative as they were based on only a few individuals due to the population crash that occurred around this time. With the subsequent partial recovery of the population the size breakdown was considered more reliable and 'small' animals dominated in the early part of 1996 (as they did early in the previous year). The relative contribution by 'medium' animals increased during 1996 and they dominated the 'upper' zone by May. The 'lower' zone at HCA was only sampled twice and on both occasions 'small' *B. nanum* contributed greater than 60% to the population (Fig. 4.18b). HCB was generally dominated by 'medium' sized animals, with 'small' *B. nanum* typically contributing less than 38% but peaking at 50% in early September 1995 (Fig. 4.18c).

'Small' and 'medium' *B. nanum* dominated the 'upper' zone at PS1 although their relative contribution varied (Fig. 4.19a). 'Small' animals comprised 80% or more of the population in the first two sampling times and late July 1995 and contributed about 60% in late May 1996. 'Medium' sized *B. nanum* dominated the 'upper' zone from August 1995 until late January 1996 and again in June 1996. 'Small' animals dominated the 'lower' zone at PS1, representing 60% or more of the population from March to July 1995, late October and November 1995 and from late January 1996 until early May 1996 (Fig. 4.19b). An interesting feature of the 'lower' zone was a more obvious contribution by 'large' animals from October 1995 to February 1996, peaking at 45% in January 1996. The adjacent PS1A site was dominated by 'small' and 'medium' sized *B. nanum* with the latter being the most heavily represented in all months apart from August 1995 (Fig. 4.19c). At no time did 'large' animals account for greater than 10% of *B. nanum* censused at PS1A.

a) HCA: 'upper' zone



b) HCA: 'lower' zone



c) HCB

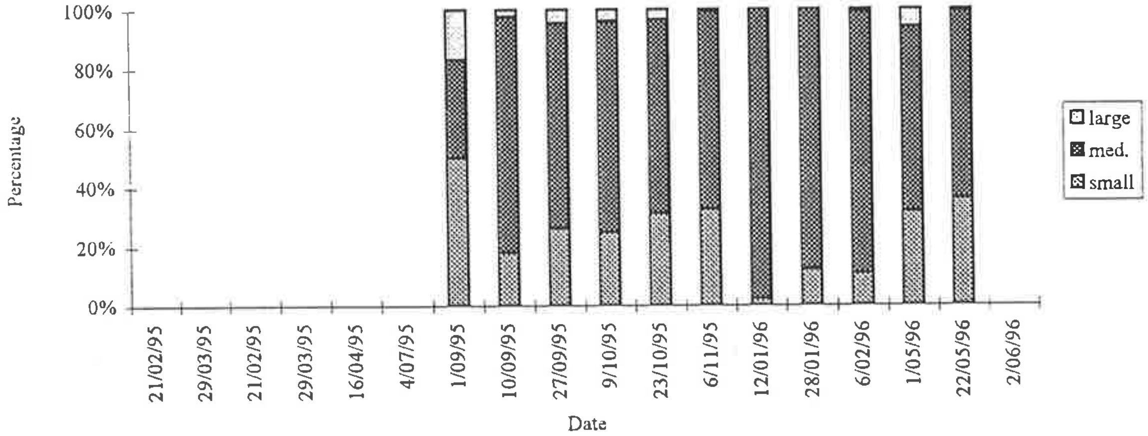
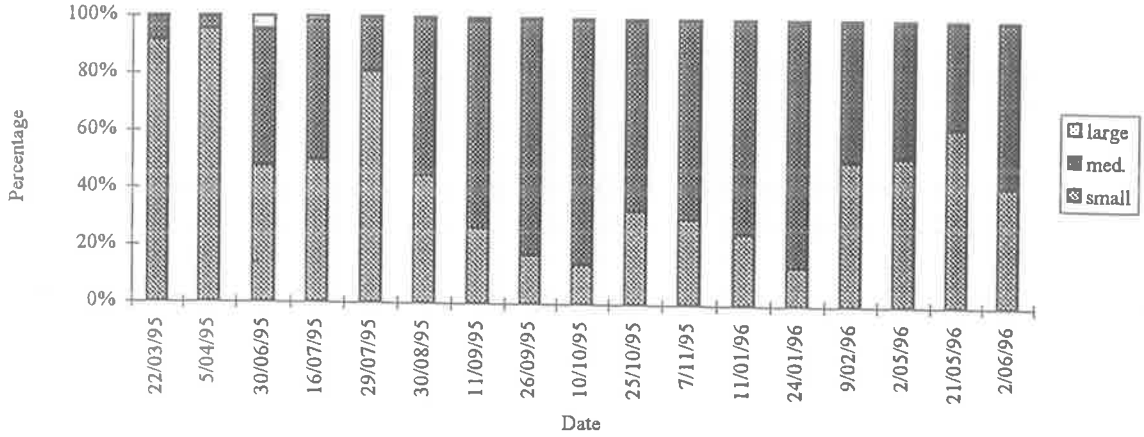
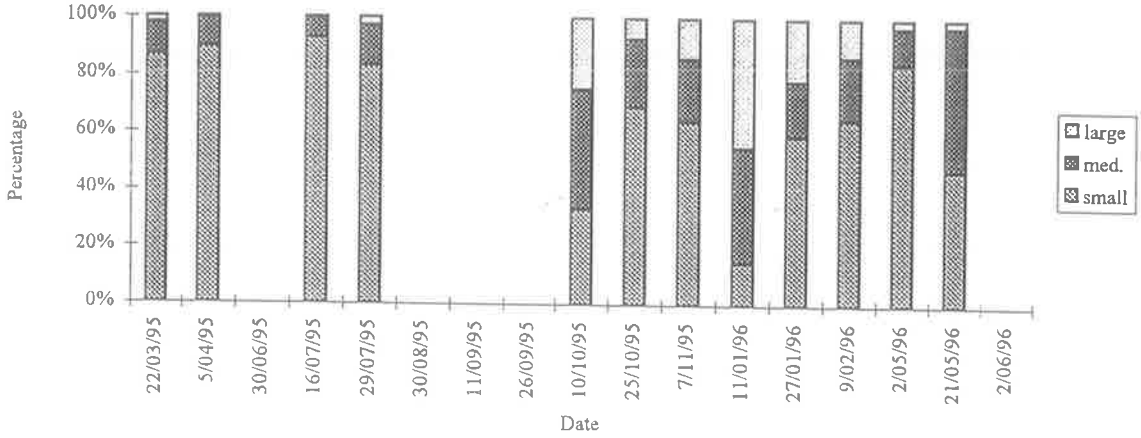


Fig. 4.18 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at Hallett Cove, and at HCB (c) which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1: 'upper' zone



b) PS1: 'lower' zone



c) PS1A

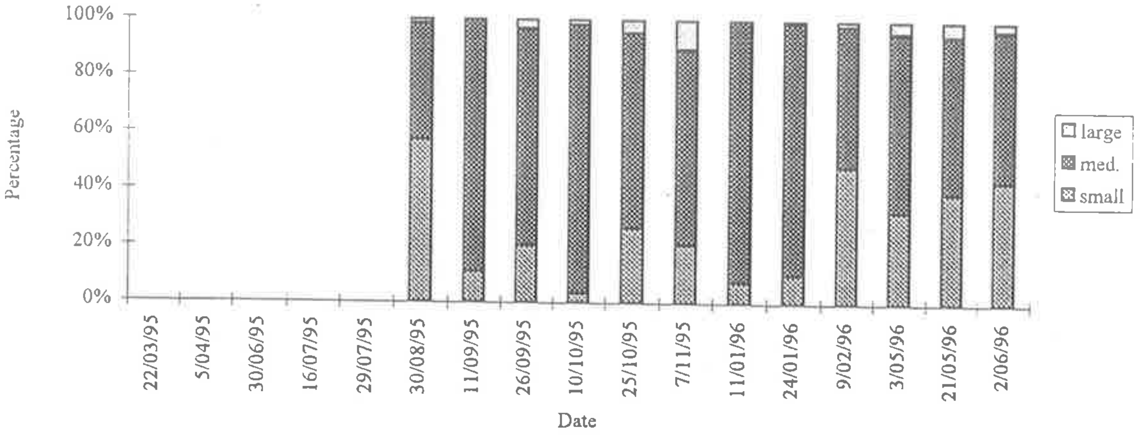
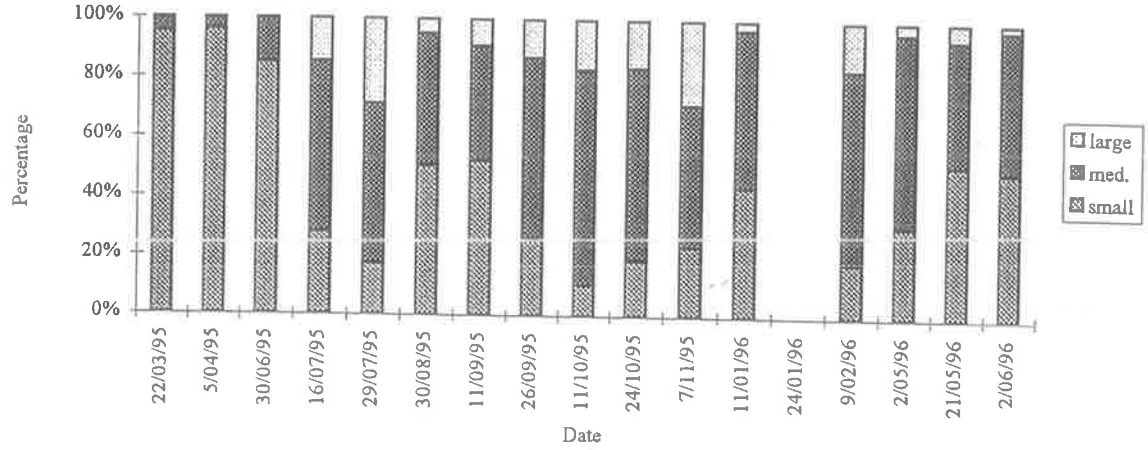


Fig. 4.19 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at PS1, and at PS1A (c) which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

The ‘upper’ zone at PS2 was similar to the ‘lower’ zone at PS1 in the greater contribution by ‘large’ animals. Approximately 30% of the population at PS2 were assessed as ‘large’ in July and November 1995 (Fig. 4.20a). ‘Small’ animals accounted for greater than 80% of censused *B. nanum* until June 1995, with secondary peaks of around 50% occurring in August and early September 1995, and late May and early June 1996. At other times ‘medium’ animals were the most heavily represented size class. Variable proportions of ‘small’ and ‘medium’ sized animals dominated the ‘lower’ zone at PS2. Peak percentages of ‘small’ animals (between 75-80%) were found in the sampling times to July 1995 and again in May 1996. ‘Small’ *B. nanum* comprised 64% and 50% of the population in the ‘lower’ zone at PS2 in late October and November 1995 respectively (Fig. 4.20b).

In the ‘upper’ zone at PS3 more than 70% of *B. nanum* fell into the ‘small’ size class in the first three sampling times (March through to early July 1995) and again in the last three sampling times (May and June 1996) (Fig. 4.21a). This domination was noted at all times apart from August, October and November 1995 and February 1996 when ‘medium’ *B. nanum* dominated. Low percentages of ‘large’ animals, comprising less than 10% of the population, occurred during nine of the sampling times (Fig. 4.21b). The observed size structure of *B. nanum* in the ‘lower’ zone was markedly different to what was seen in the ‘upper’ zone (Fig. 4.21b). ‘Large’ *B. nanum* contributed 45% or more to the censused population in October and November 1995 and early January 1996 and also made small but significant contributions in late January, February and late May 1996. Domination by ‘small’ animals occurred from March to July 1995, and February and early May 1996, with peak ‘small’ abundances of more than 75% occurring in July 1995 and February and early May 1996 (Fig. 4.21b).

a) PS2: 'upper' zone



b) PS2: 'lower' zone

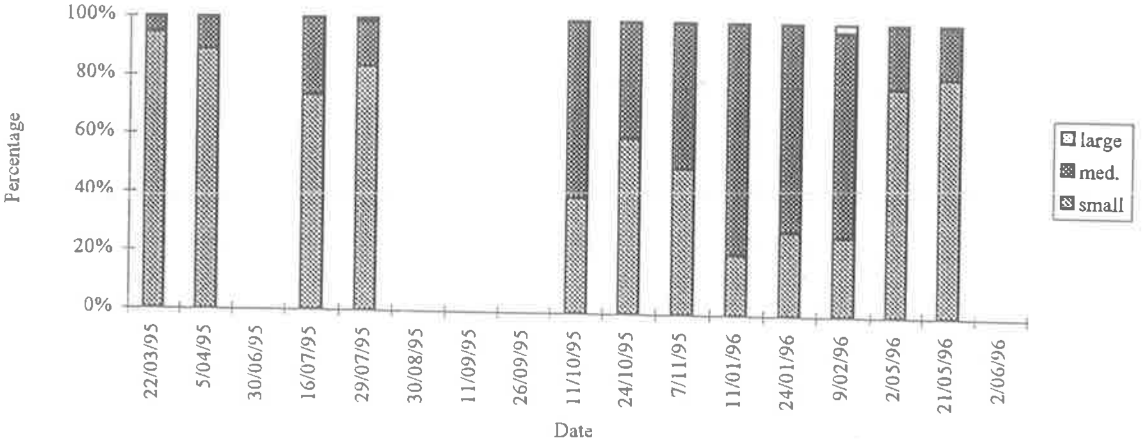
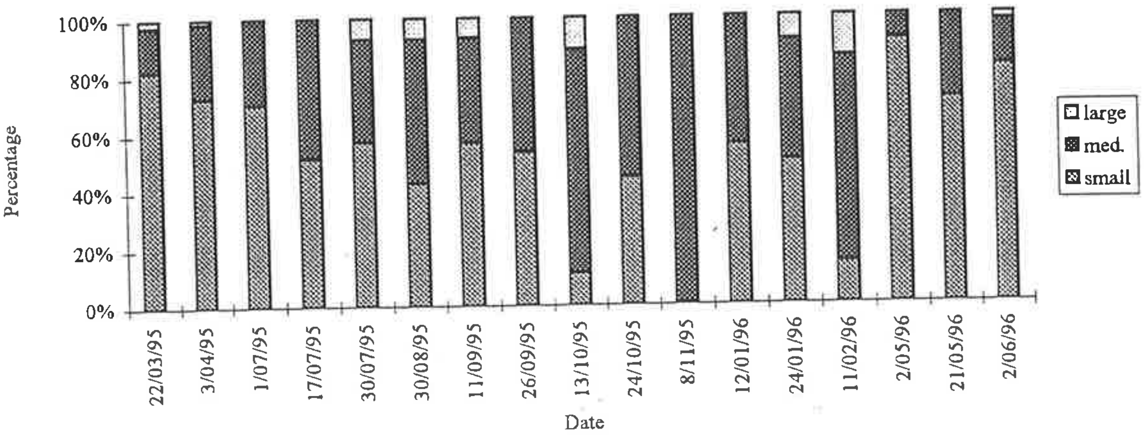


Fig. 4.20 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at PS2 which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS3: 'upper' zone



b) PS3: 'lower' zone

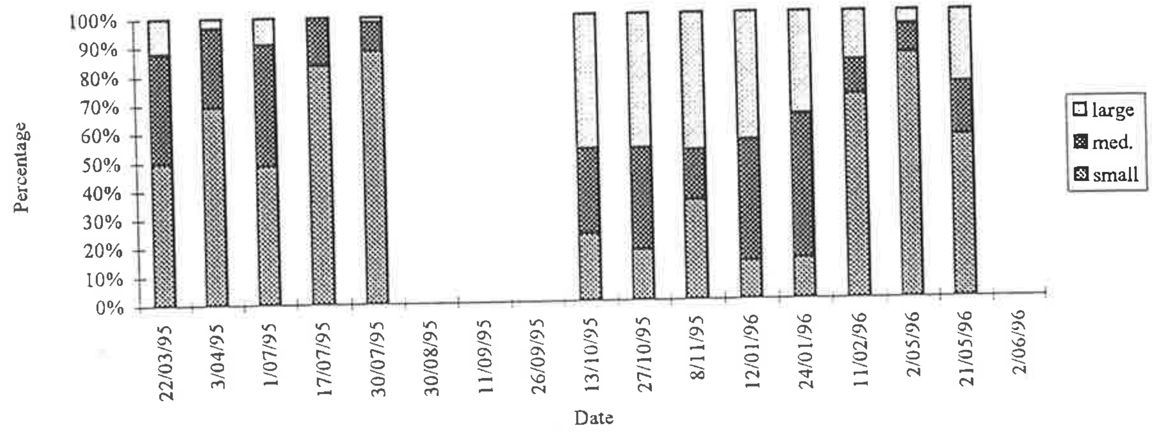
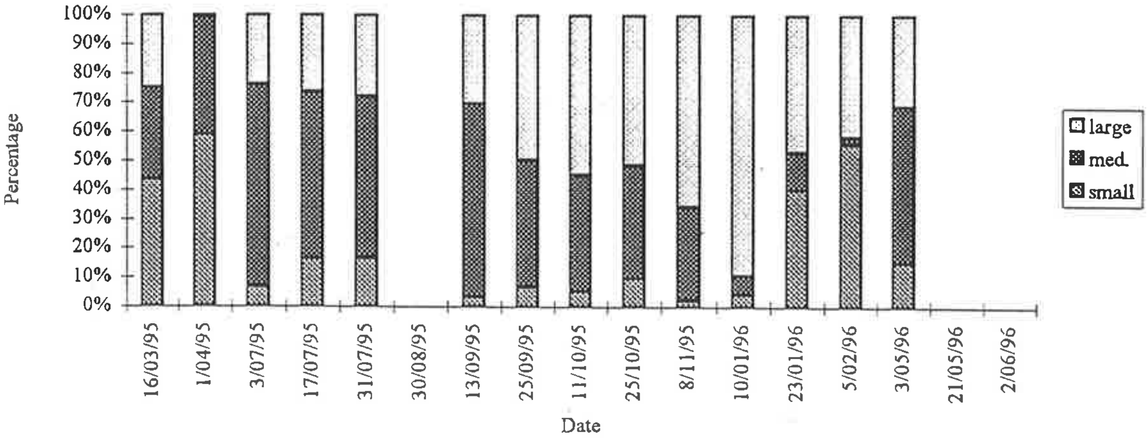


Fig. 4.21 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at PS3 which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

The two 'Southern' sites where *B. nanum* occurred were characterised by high percentages of 'large' animals. In the 'upper' zone at Port Noarlunga South 'large' animals comprised more than 25% of the population at all times apart from April 1995 (Fig. 4.22a). The relative contribution by 'large' *B. nanum* increased from late September to early January 1996 when they peaked at 95% before decreasing. 'Small' animals were the most heavily represented size class in March and May 1995 and February 1996 but 'medium' animals dominated from July to mid-September 1995 and again in May 1996 (Fig. 4.22a). The higher incidence of 'large' *B. nanum* was repeated in the 'lower' zone at Port Noarlunga South where they contributed more than 20% at all sampling times, peaking at 40% or more in mid-July, October 1995 to early January 1996, and early May 1996 (Fig. 4.22b). 'Small' animals were the most heavily represented size class in the 'lower' zone in April 1995, late January 1996 and February 1996. It must be noted that at Port Noarlunga South many of the 'medium' animals were almost large enough to classify as 'large'.

The 'upper' zone at Robinson Point was dominated by 'large' animals at all sampling times apart from March 1995 when 'medium' *B. nanum* accounted for more than 85% of the population (Fig. 4.23a). 'Small' animals never dominated but peaked at 35% and 25% respectively in late January and early February 1996. The 'lower' zone at Robinson Point showed a similar population structure with 'large' animals dominating from late October 1995 to the end of sampling (Fig. 4.23b). 'Medium' and 'small' *B. nanum* shared domination in March 1995, and a small secondary peak of 'small' animals was seen in late January and February 1996.

a) PNS: 'upper' zone



b) PNS: 'lower' zone

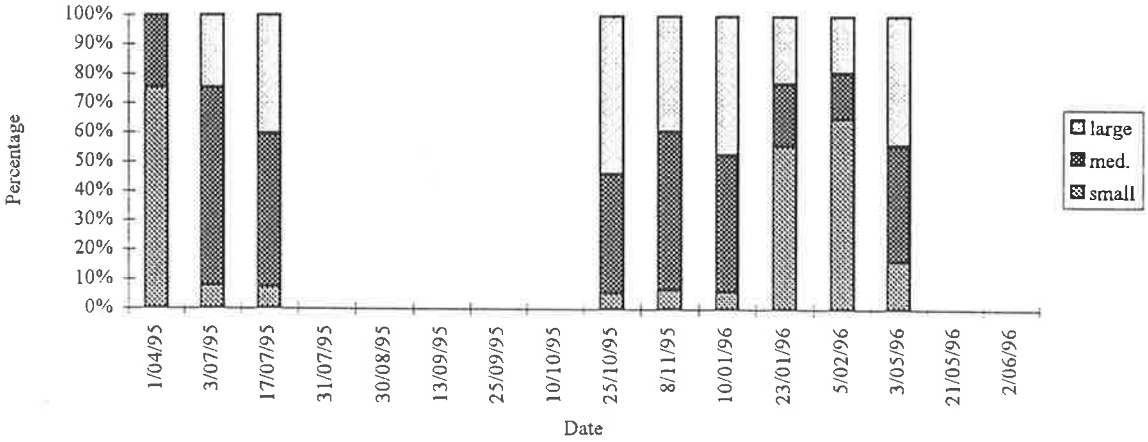
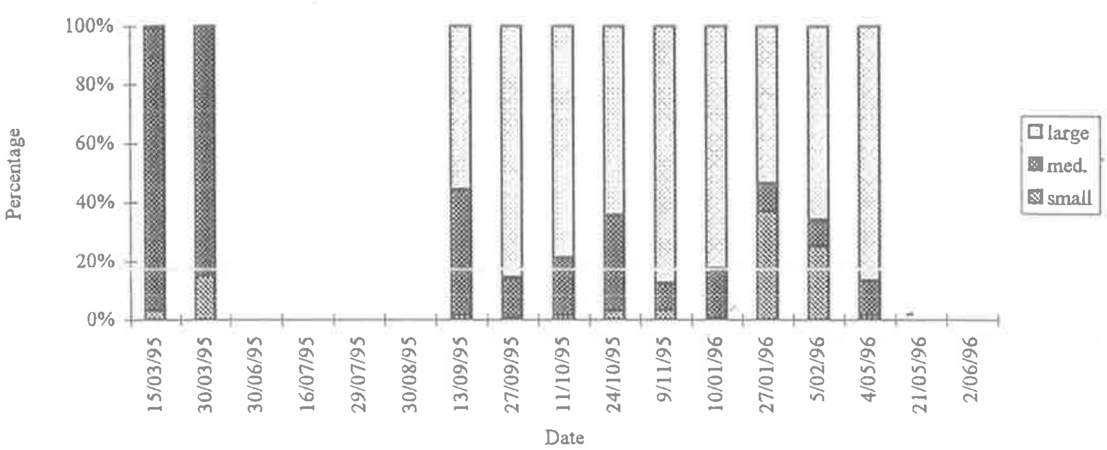


Fig. 4.22 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at Port Noarlunga South (PNS) which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) RP: 'upper' zone



b) RP: 'lower' zone

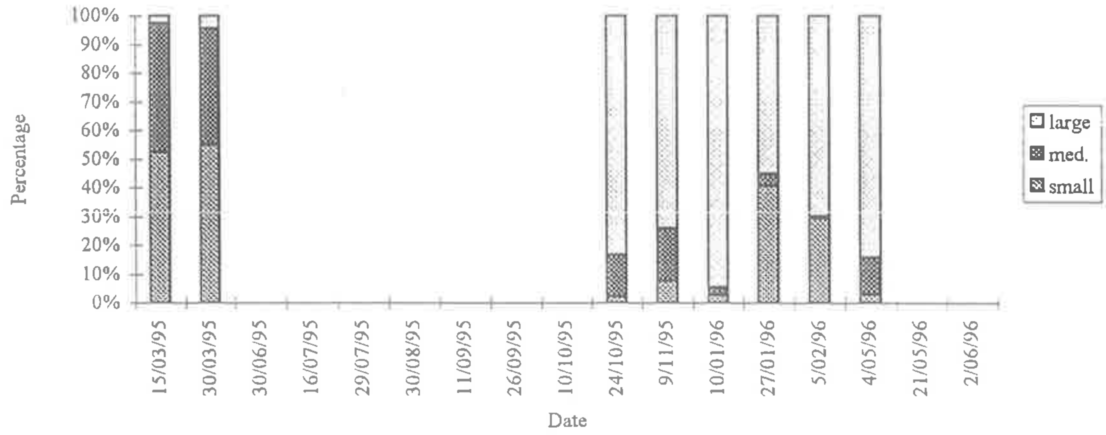


Fig. 4.23 The percentage of total *B. nanum* censused in the 'upper' zone (a) and the 'lower' zone (b) at Robinson Point (RP) which were classified in the 'small', 'medium' and 'large' size classes. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

4.4.3.2 The Abundance of *Turbo undulatus* at Witton Bluff

The high proportion of coralline and mat algae set Witton Bluff apart from the other study sites. This was likely to be attributable to the sites low-lying status and topography, which encouraged water retention at low tide. Such characteristics are expected to result in animal assemblages that are, in many ways, more typical of permanent rock pools and shallow, sublittoral zones than they are of the mid-eulittoral zone.

The dominant animal in the sampled region at Witton Bluff was *Turbo undulatus*. This species is a large herbivorous gastropod common on reefs and platforms in the lower littoral and sublittoral zones on medium to high-energy coasts, occurring at depths to 10m (Shepherd and Thomas 1989). The density of *T. undulatus* varied during preliminary monitoring, ranging from an average of 10-15 animals per quadrat until November 1995 after which numbers fell to between 5-7 per quadrat (Fig. 4.24). The contagious distribution of the species was reflected by the large standard error associated with sampling which was particularly evident until October 1995. The low overall abundance of *T. undulatus* and the high variability within sampling times meant that consideration of the size distribution of this animal was not likely to accurately represent the 'true' size composition at Witton Bluff. Therefore, graphs representing the size distribution of *T. undulatus* have been omitted.

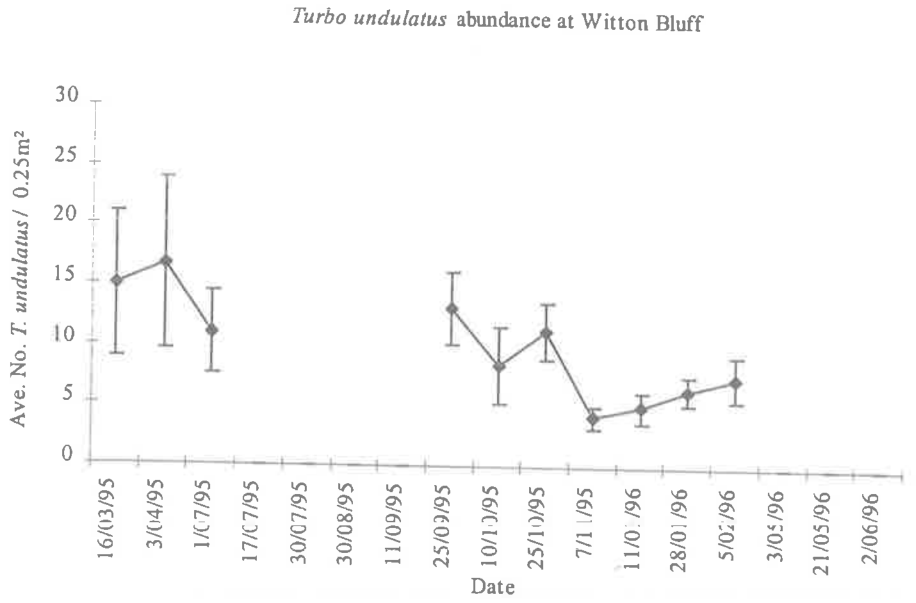


Fig. 4.24 The density of *T. undulatus* has been shown for the preliminary sampling period at Witton Bluff. Density has been calculated as the average number of *T. undulatus* (combined across 'small', 'medium' and 'large' size classes) per $0.25m^2$ quadrat in the 'upper' zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

4.4.3.3 The Abundances and Size Distribution of 'Secondary' Species at Study Sites

A number of animal species were seen co-existing with *B. nanum* at study sites but were typically present at low densities. Details of the life history and characteristics (including feeding behaviour and reproduction) of the most common of these 'secondary' species have been briefly reviewed in Chapter 6 of this thesis.

Three 'secondary' species found at the majority of sites were the medium sized herbivorous gastropods; *Nerita atramentosa, Austrocochlea constricta* and *Austrocochlea concamerata.* Another herbivorous gastropod, the small limpet-like *Siphonaria diemenensis* was occasionally seen at all sites but occurred at high densities at Port Noarlunga South and lower densities at Robinson Point. The total abundances of the 'secondary' species were only examined for those sites where they were frequently seen and their generally low densities meant a population breakdown was unlikely to be informative. *S. diemenensis* was the only 'secondary' species present at high enough densities at one of the sites (Port Noarlunga South) to make consideration of the size structure of the population useful. The secondary species tended to be more numerous in the 'lower' zones at study sites (although still at low densities) which were less frequently sampled due to access difficulties. Therefore, except where a species was conspicuously more numerous in the 'lower' zones, only graphs pertaining to their abundance in the 'upper' zones at relevant sites have been generated.

A general observation made at study sites in relation to *N. atramentosa, A. constricta*, and *A. concamerata* was the tendency for these species to 'favour' the undersurface of mobile rocks and in some cases to aggregate in rock pools at low tide. During the pilot study it was decided not to overturn rocks to census animals and to avoid sampling in rock pools. Therefore, the method of census used during the preliminary study was likely to underestimate the 'true' abundance of species preferentially aggregating under rocks or in rock pools. This had implications when the total abundance of these secondary species and their recruitment patterns were examined and would raise serious concerns if species adopting these strategies were used as bioindicators of oil pollution (see Chapter 6).

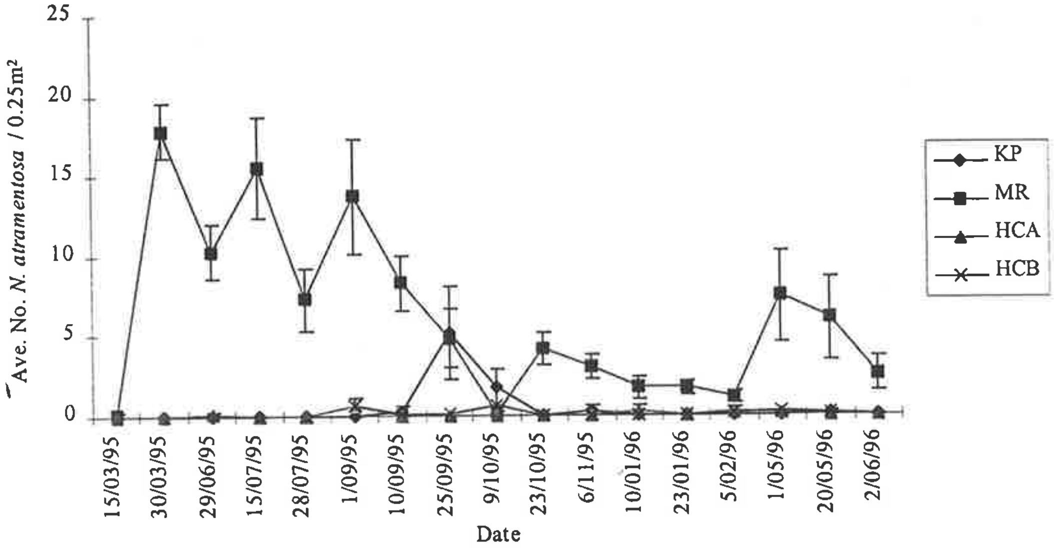
Nerita atramentosa

N. atramentosa was rarely seen in the 'upper' zone at 'Southern' sites but occurred at varying densities at 'Northern' and 'Central' study sites (Fig. 4.25a & b). At 'Northern' sites the species occurred at low densities, often of less than 2 individuals per quadrat (Fig. 4.25a). The exception to this was one occasion at Kingston Park when 5 animals were recorded, and the majority of sampling times at Marino Rocks. At the latter site, densities of *N. atramentosa* ranged from 7 to 17 animals per quadrat until the end of September 1995 after which numbers were generally 5 or less. A secondary abundance peak was noted at this site in May 1996.

The abundance of *N. atramentosa* was highly variable within and between 'Central' sites although PS3 usually supported higher densities than did the other 'Central' sites

4.25b). The general pattern seen in the 'upper' zone at all 'Central' study sites was peak abundances from March to September 1995, followed by declines in dominance until late January 1996 after which numbers again began to increase. The highest recorded abundance of *N. atramentosa* occurred at PS1A in August 1995 when more than 30 animals were counted.

a) 'Northern' Sites



b) 'Central' Sites

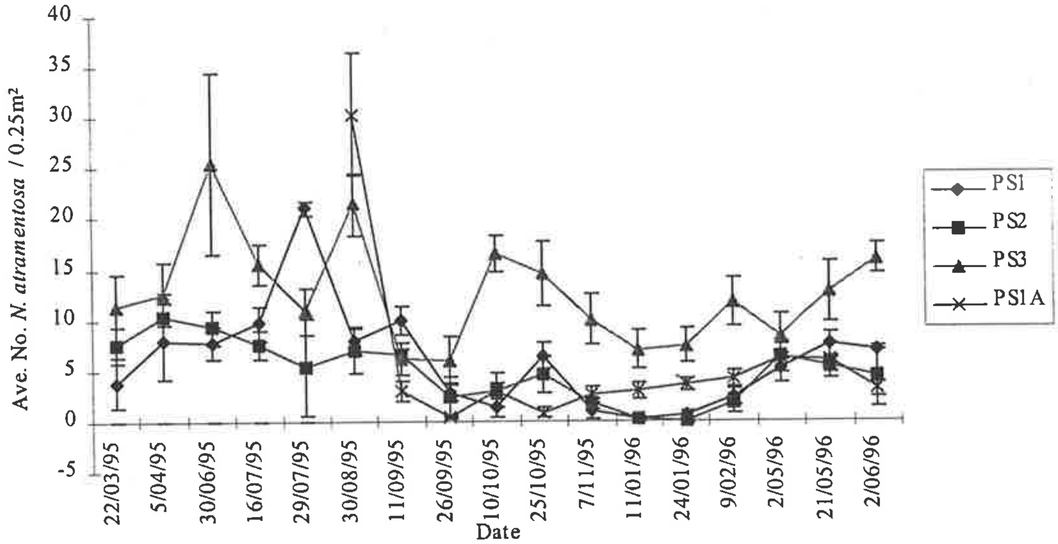


Fig. 4.25 The density of *N. atramentosa* has been shown for the preliminary sampling period in the 'upper' zones at a) 'Northern' and b) 'Central' sites. The sites are shown in the legend and are Kingston Park (KP), Marino Rocks (MR), the two Hallett Cove sites (HCA & HCB), and the Port Stanvac sites (PS1, PS2, PS3 and PS1A). Density has been calculated as the average number of *N. atramentosa* (combined across 'small', 'medium' and 'large' size classes) per 0.25m² quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

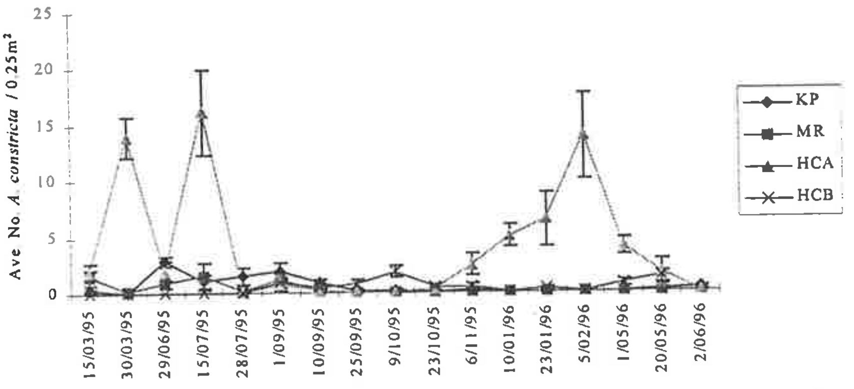
Austrocochlea constricta

A. constricta was present at low densities at the majority of study sites. At 'Northern' sites, apart from HCA, there were generally less than 2 animals per quadrat at all sampling times (Fig. 4.26a). HCA had peak densities of 14-16 *A. constricta* in late March and mid-July 1995, and again in February 1996. Numbers remained low at HCA from late July until October 1995, a trend which was coincident with the sand influx, after which an increase in density was apparent until May 1996. Following this, the density of *A. constricta* again declined at this site.

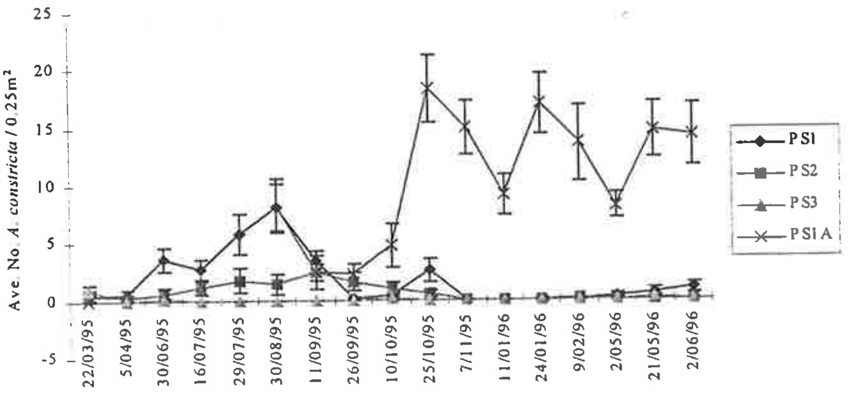
The 'Central' study sites, apart from PS1A and PS1, were also characterised by very low abundances of *A. constricta* (Fig. 4.26b). At PS1A 8-18 animals per quadrat were recorded from late October 1995 until the end of sampling, while at PS1 the highest abundances were found in the winter months of June through to August 1995 with a peak density of approximately 8 animals per quadrat occurring in late August.

The only site where *A. constricta* was consistently found at relatively high densities was Robinson Point where numbers ranged from a peak of around 40 in early October 1995 to a trough of around 12 animals in early January 1996 (Fig. 4.26c). Of the other 'Southern' sites, Witton Bluff supported low densities of *A. constricta* at all times apart from the first two sampling occasions (when 5 or 6 animals per quadrat were recorded), while Port Noarlunga South supported densities ranging from 2-8 animals per quadrat for the duration of sampling.

a) 'Northern' Sites



b) 'Central' Sites



c) 'Southern' Sites

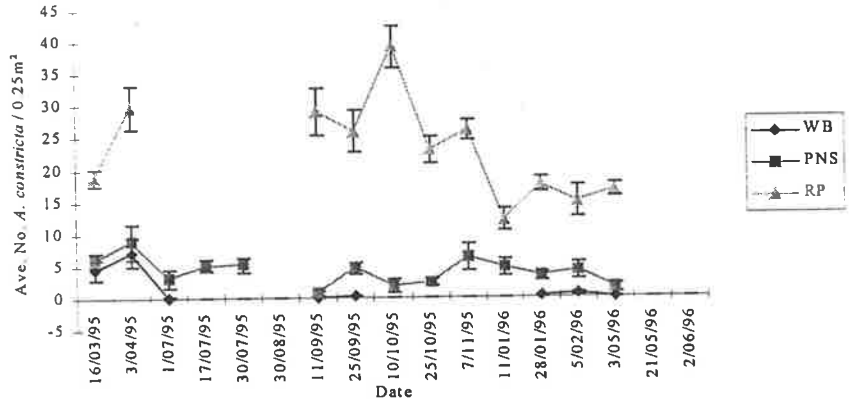


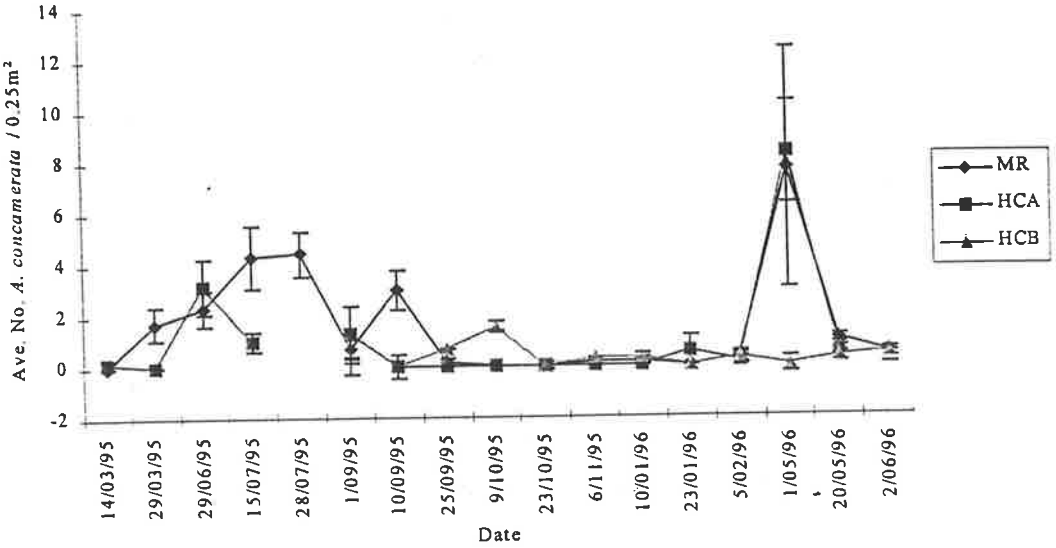
Fig. 4.26 The density of *A. constricta* has been shown for the preliminary sampling period in the 'upper' zones at a) 'Northern' b) 'Central' and c) 'Southern' sites. The sites are shown in the legend and are Kingston Park (KP), Marino Rocks (MR), the two Hallett Cove sites (HCA & HCB), the Port Stanvac sites (PS1, PS2, PS3 and PS1A), Witton Bluff (WB), Port Noarlunga South (PNS) and Robinson Point (RP). Density has been calculated as the average number of *A. constricta* (combined across 'small', 'medium' and 'large' size classes) per 0.25m^2 quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3.1). Error bars represent standard errors.

Austrocochlea concamerata

The abundance of *A. concamerata* was examined at 'Northern' sites (apart from Kingston Park where it was rare), and 'Central' sites. It was also found at very low densities (less than 0.24 animals per quadrat on average) at Port Noarlunga South. In the 'upper' zones at Marino Rocks and the two Hallett Cove sites (HCA & HCB) *A. concamerata* occurred at densities of less than 9 animals per quadrat (Fig. 4.27a & b). Peak abundances of *A. concamerata* were recorded at Marino Rocks and HCA in early May 1996 (Fig. 4.27a). The spatial patchiness of this species was illustrated at Marino Rocks by the large standard error associated with sampling. The Hallett Cove sites generally had densities of 3 or less *A. concamerata* per quadrat, and HCA exhibited greater spatial variability than HCB.

A. concamerata were never recorded at densities greater than 6 animals per quadrat at 'Central' sites (Fig. 4.27b). Peak abundances occurred at the end of July 1995 at PS1, in early October 1995 at PS2 and PS3, and in June 1996 at PS1A. The latter site exhibited the greatest temporal and spatial variability in terms of *A. concamerata* abundance (Fig. 4.27b).

a) 'Northern' Sites



b) 'Central' Sites

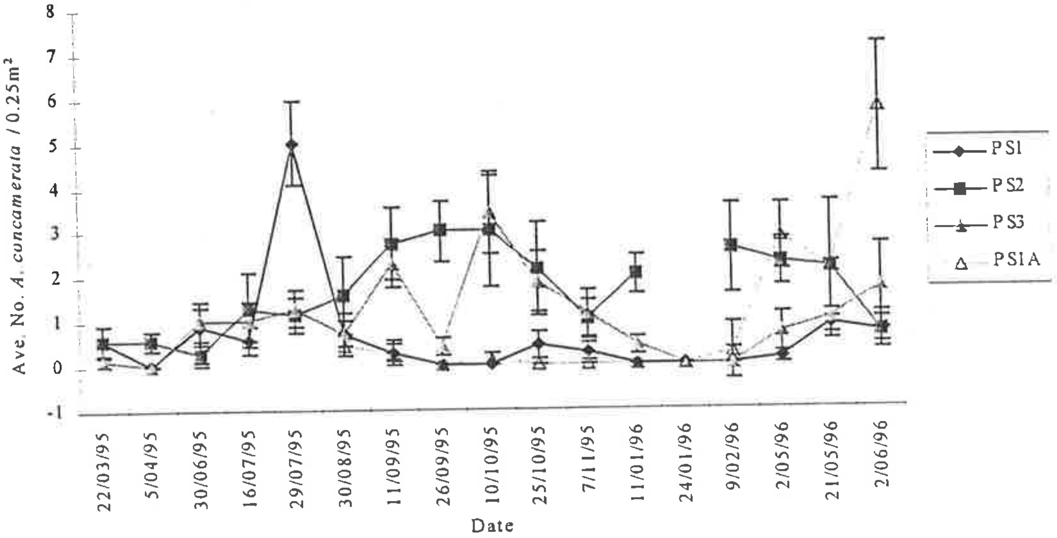


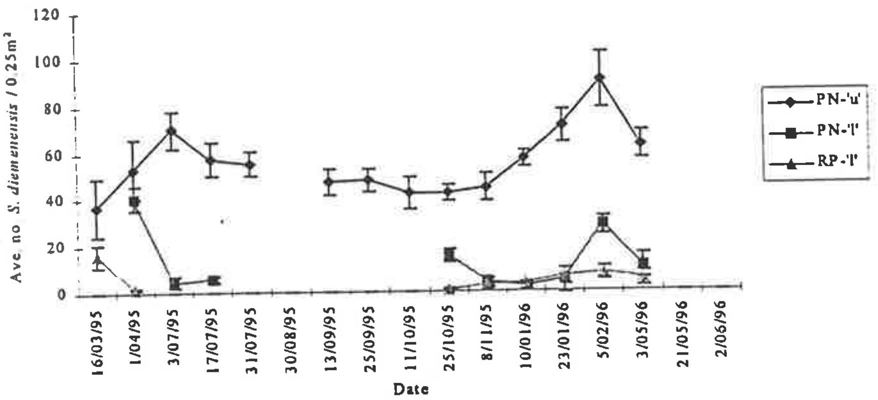
Fig. 4.27 The density of *A. concamerata* has been shown for the preliminary sampling period in the 'upper' zones at a) 'Northern' and b) 'Central' sites. The sites are shown in the legend and are Kingston Park (KP), Marino Rocks (MR), the two Hallett Cove sites (HCA & HCB), and the Port Stanvac sites (PS1, PS2, PS3 and PS1A). Density has been calculated as the average number of *A. concamerata* (combined across 'small', 'medium' and 'large' size classes) per 0.25m^2 quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

Siphonaria diemenensis

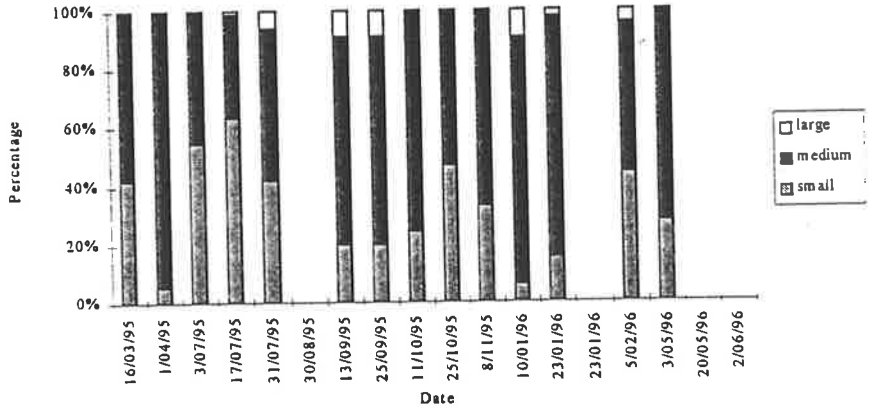
The abundance of *S. diemenensis* in the 'upper' zone at Port Noarlunga South ranged from 37-90 animals for the duration of sampling with densities typically lying between 50-60 animals per quadrat (Fig. 4.28a). The peak abundance occurred in early February 1996 while a smaller secondary peak was noted in early July 1995. Considerable variability between sampling times was observed in the 'lower' zone where densities were below 15 animals per quadrat apart from a peak abundance of around 40 animals in April 1995 and a smaller secondary peak in early February 1996 (Fig. 4.28a). The abundance of *S. diemenensis* in the 'upper' zone at Robinson Point was less than 3 animals per quadrat for the duration of sampling but densities in the 'lower' zone ranged from 5-16 animals per quadrat (Fig. 4.28a).

The population structure of *S. diemenensis* in the 'upper' zone at Port Noarlunga South was dominated by 'small' and 'medium' animals for the duration of preliminary sampling (Fig. 4.28b). Domination by 'small' animals occurred in early and mid-July 1995 when they contributed between 55-65%, while at most other sampling times the 'medium' size class dominated, comprising greater than 80% of the population in April 1995 and January 1996. The number of small *S. diemenensis* recorded at Port Noarlunga South (Fig. 4.28c) will be considered later in this chapter.

a) Total abundance of *S. diemenensis*



b) Population structure of *S. diemenensis* at PNS



c) Abundance of small *S. diemenensis*

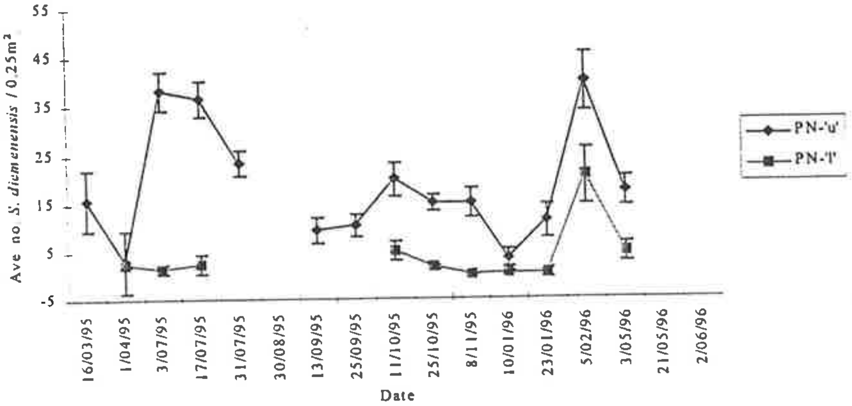


Fig. 4.28 The density of *S. diemenensis* (combined for 'small', 'medium' and 'large' size classes) is shown for the 'upper' zone at Port Noarlunga South (PN-'u'), the 'lower' zone at the same site (PN-'l') and the 'lower' zone at Robinson Point (RP-'l') (a). The population structure of this species is shown for the 'upper' zone at Port Noarlunga South (PNS) and indicates the percentage of all censused *S. diemenensis* belonging to the 'small', 'medium' and 'large' size classes (b). Finally, the abundance of 'small' *S. diemenensis* is presented for the duration of sampling in the 'upper' and 'lower' zones at Port Noarlunga South (designated PN-'u' and PN-'l' respectively) (c). Density has been calculated as the average number of small *S. diemenensis* per 0.25m^2 quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

4.4.3.4 Recruitment and Breeding of Animals at Study Sites

Throughout preliminary sampling any animals less than 2mm in diameter (believed to be new settlers and classed as 'very small') were recorded and, where possible, identified to species in the field. The presence of any eggs or egg capsules was also noted. Information pertaining to these aspects of the life-history strategies of a few of the species seen at study sites will now be detailed.

In early January 1996 what appeared to be the white egg capsules of *Nerita atramentosa* (see Quinn *et al.* 1992, Shepherd and Thomas 1989) were seen at HCA. The yellow egg capsules of *B. nanum* (see Shepherd and Thomas 1989 for a description) were observed at Port Noarlunga South and the Port Stanvac sites in September and October 1995 and in the 'lower' zone at PS3 in May (autumn) of the following year. These capsules were particularly numerous at the Port Noarlunga South site where they averaged approximately 3-4 per 0.25m^2 of horizontal substrata. This site was also characterised by high densities of 'large' adult *B. nanum* (see section 4.4.3.1). Large numbers of 'very small' new settlers of this species were noted at Marino Rocks, Port Noarlunga South and the Port Stanvac sites in January and February 1996.

'Very small' *Chthalamus antennatus* were observed at Kingston Park in October 1995, while 'very small' *Cellana tramoserica* were noted at PS1 and Port Noarlunga South in October 1995 and at Robinson Point in January 1996. Newly settled animals believed to be *Patelloida latistrigata* were also seen at the latter site in January 1996 and at PS1 in November 1995. 'Very small' *S. diemenensis* appeared at Port Noarlunga South, PS3 and Robinson Point in February 1996, and increased abundances of 'very small' *Austrocochlea* spp. were observed at Port Stanvac sites in September 1995.

The minute size of new settlers arriving from the plankton led to identification difficulties which, in conjunction with the large numbers arriving, precluded accurate quantification of animals less than 2mm in diameter. The majority of these new arrivals would not be expected to become a stable part of the population and intertidal assemblage. Therefore, the focus was on animals which had reached a size greater than

2mm. The number of 'small' *B. nanum* referred to in this chapter includes only those animals greater than 2mm and up to 6.7mm in diameter, while the upper limits of the 'small' size classes of 'secondary' species talked about in this section are as defined in Chapter 3. Consideration of the densities of new settlers (ranging up to 2mm in diameter) would have been interesting but was beyond the scope of this thesis.

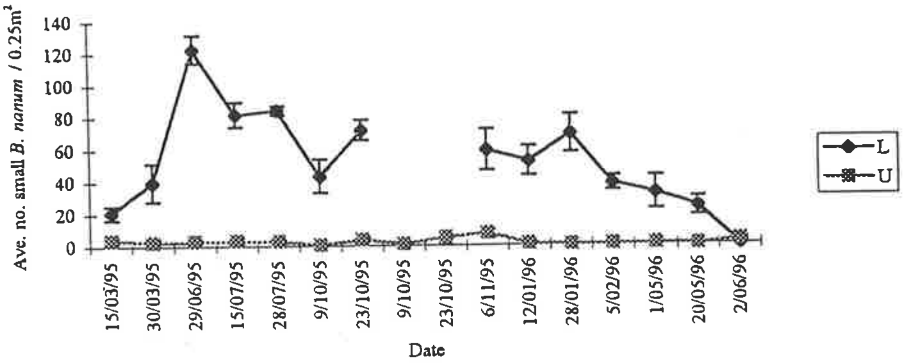
The contribution of 'successful' new recruits to the population structure has been quantified by graphing temporal changes in the abundance of 'small' animals belonging to the most frequently seen species at study sites. The number of 'small' animals present throughout preliminary sampling has been graphed for both 'upper' and 'lower' zones at the sites where they were commonly seen. This was done in the hope of determining the time of the year when some of the main intertidal species recruit even if the level of recruitment was low and the species were relatively rare. The species examined in reference to their recruitment patterns were *B. nanum*, *N. atramentosa*, *A. constricta*, *A. concamerata* and *S. diemenensis*.

Bembicium nanum

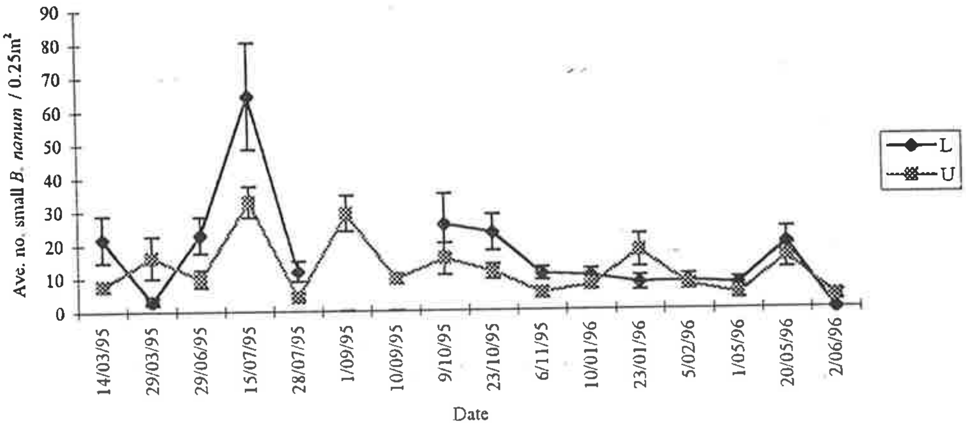
At Kingston Park 'small' *B. nanum* were consistently more numerous in the 'lower' zone, numbering between 20-120 for the duration of sampling, with the peak abundance occurring in June 1995 (Fig. 4.29a). In the 'upper' zone, abundances of less than 10 'small' animals were recorded for the duration of sampling (Fig. 4.29a). The two sampled zones at Marino Rocks supported similar numbers of 'small' *B. nanum* (Fig. 4.29b). 'Small' animals peaked at almost 65 in the 'lower' zone at this site in mid-July 1995 but remained below 30 animals per quadrat at all other times. 'Small' *B. nanum* in the 'upper' zone remained less than 35 animals per quadrat with density peaks occurring in mid-July and the beginning of September 1995.

At the start of preliminary sampling it was evident that no significant difference in the number of 'small' *B. nanum* occurred between the two zones at HCA (Fig. 4.29c). However, by the end of March 1995 access difficulties prevented sampling of the 'lower' zone at this site. Although the effects on biota were not quantified it was noted that the sand inundation which occurred in the 'upper' zone at HCA also occurred in the 'lower' zone and was likely to result in similar biota trends. The abundance of 'small' *B. nanum* in the 'upper' zone at HCA fell from around 90 animals in late March 1995 to less than 20 animals by the end of July 1995 following the sand influx. No 'small' *B. nanum* were then found at HCA until January 1996 when levels appeared to stabilise at around 20 before falling to zero in June when a second sand influx occurred. HCB was sampled from early September 1995 and 'small' *B. nanum* generally ranged from 5-22 animals per quadrat until the end of January 1996 when numbers were below 4 (Fig. 4.29c). As the abundance of 'small' *B. nanum* increased at HCA numbers fell at HCB and as numbers at HCA recovered the reverse trend was noted at HCB (Fig. 4.29c).

a) KP



b) MR



c) Hallett Cove (HCA & HCB)

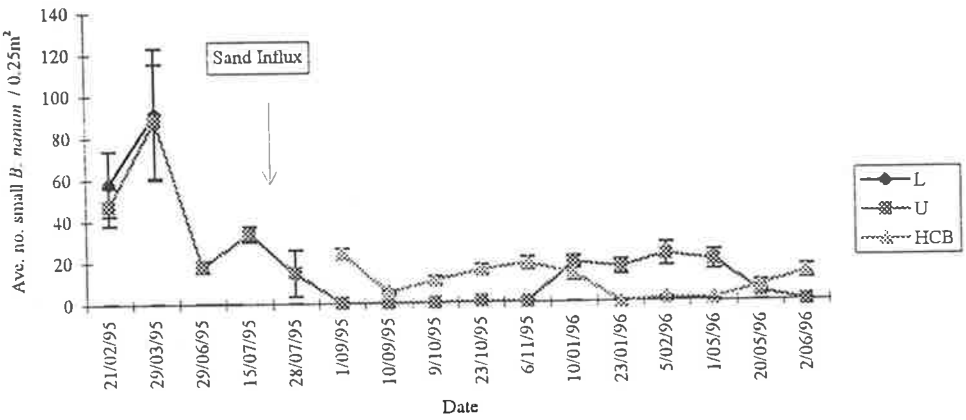


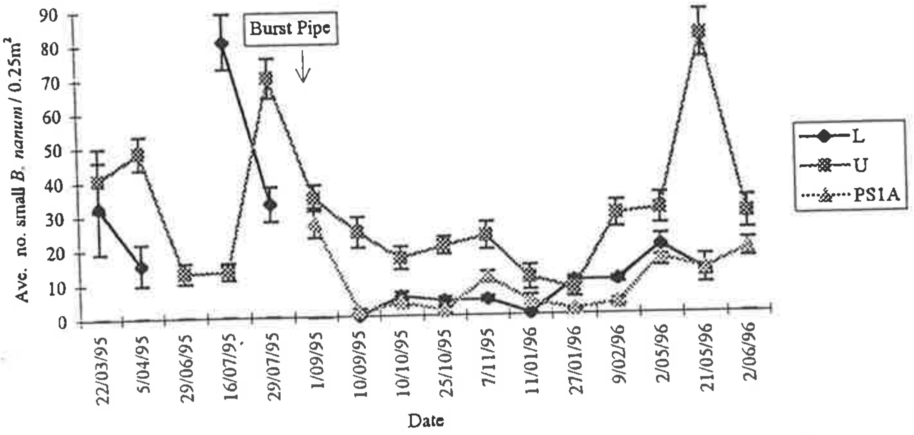
Fig. 4.29 The density of 'small' *B. nanum* is shown in the 'upper' (U) and 'lower' (L) zones at 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (both HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. Density has been calculated as the average number of small *B. nanum* per 0.25m^2 quadrat. The timing of the sand influx is arrowed in c), with small volumes of sand arriving in June and reaching a peak in July, and post-impact sampling beginning in September. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

The abundance of 'small' *B. nanum* in 'Central' study sites varied within and between sites. Peak abundances of 'small' animals occurred in the 'lower' zones at all 'Central' sites in mid or late July 1995 and reduced densities generally occurred in both zones in the middle months of sampling (Fig. 4.30a, b &c). A peak abundance of 80 'small' animals was recorded in the 'lower' zone at PS1, while the 'upper' zone had peak abundances of 70 and 80 'small' animals respectively in late July 1995 and late May 1996 (Fig. 4.30a). The 'upper' zone at PS1 typically supported higher abundances of 'small' *B. nanum* than did the 'lower' zone. PS1A had low densities of between 4-20 'small' animals per quadrat for the duration of sampling apart from a peak of around 26 when the site was first sampled (Fig. 4.30a). The density of 'small' *B. nanum* at PS1A appeared to stabilise at around 20 animals per quadrat from early February 1996.

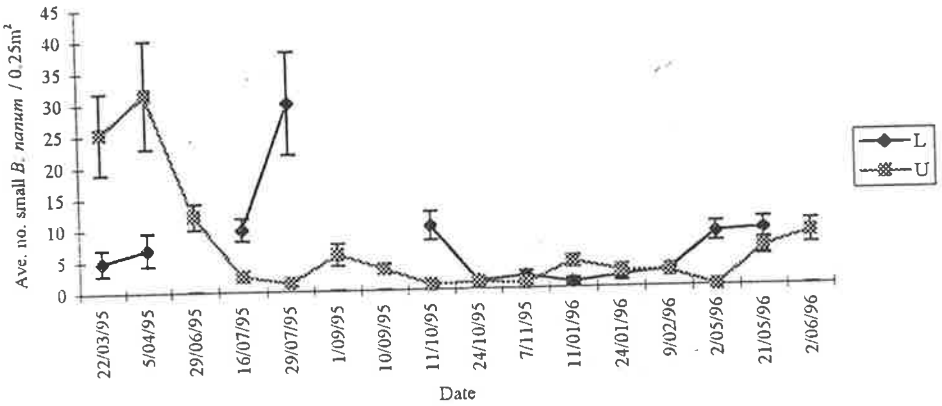
Apart from a peak abundance of 30 'small' *B. nanum* recorded in late July 1995 the 'lower' zone at PS2 supported between 1-11 'small' animals per quadrat for the duration of sampling (Fig. 4.30b). The months between late October 1995 and early February 1996 were typified by a paucity of 'small' *B. nanum* (less than 5 per quadrat), after which densities increased slightly. A similar pattern of low densities in the middle sampling times occurred in the 'upper' zone at PS2 from mid-July 1995 until February 1996. Peak densities of 25-32 'small' *B. nanum* per quadrat occurred in the 'upper' zone at PS2 in March and April 1995, but at all other times the abundance of 'small' animals remained below 12.

At PS3 the abundance of 'small' *B. nanum* in the 'lower' zone peaked at 25-30 in April and late July 1995 with a small secondary peak occurring in February 1996 (Fig. 4.30c). Densities of less than 10 'small' *B. nanum* per quadrat occurred at all other sampling times. The 'upper' zone at PS3 displayed a different temporal pattern of 'small' *B. nanum* abundance with a single peak being recorded in March 1995 after which a steady decline occurred, resulting in abundances of less than 5 from mid-July 1995 until late May 1996.

a) PS1 & PS1A



b) PS2



c) PS3

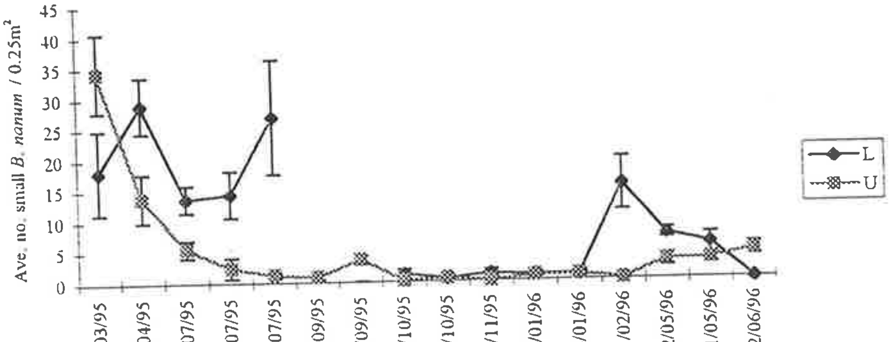
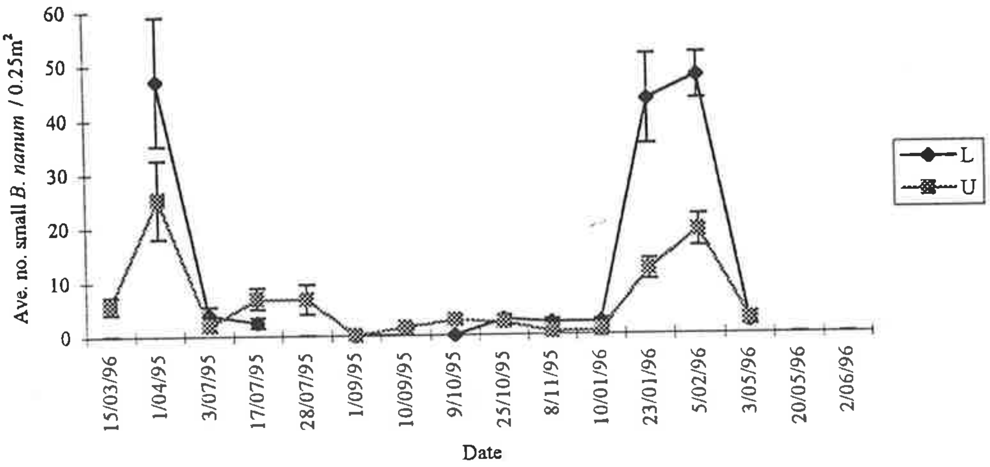


Fig. 4.30 The density of 'small' *B. nanum* is shown in the 'upper' (U) and 'lower' (L) zones at 'Central' (Port Stanvac) sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. The timing of the ruptured effluent pipe at Port Stanvac is arrowed in a). Density has been calculated as the average number of small *B. nanum* per 0.25m^2 quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

The 'Southern' sites where *B. nanum* occurred were typified by a greater contribution of 'large' animals and relatively low numbers of 'small' animals compared to the other study sites (Fig. 4.31a & b). In both zones at Port Noarlunga South 'small' *B. nanum* were found at densities of less than 10 per quadrat for the duration of sampling apart from peak abundances in April 1995 and late January and early February 1996 (Fig. 4.31a). The density of 'small' *B. nanum* in the 'lower' zone at Port Noarlunga South at these 'peak' times was consistently higher than the recorded density in the 'upper' zone; 45-50 animals per quadrat in the former, compared to 10-25 animals per quadrat in the latter. The 'lower' zone at Robinson Point supported abundances of 'small' *B. nanum* which were below 5 at all times apart from early and late March 1995 when numbers ranged from 32-40, and late January and early February 1996 when numbers remained between 15-20 (Fig. 4.31b). The 'upper' zone at Robinson Point supported peak abundances of 8 'small' *B. nanum* in late March 1995, 30 'small' *B. nanum* in late January and 16 'small' *B. nanum* in early February 1996.

a) PNS



b) RP

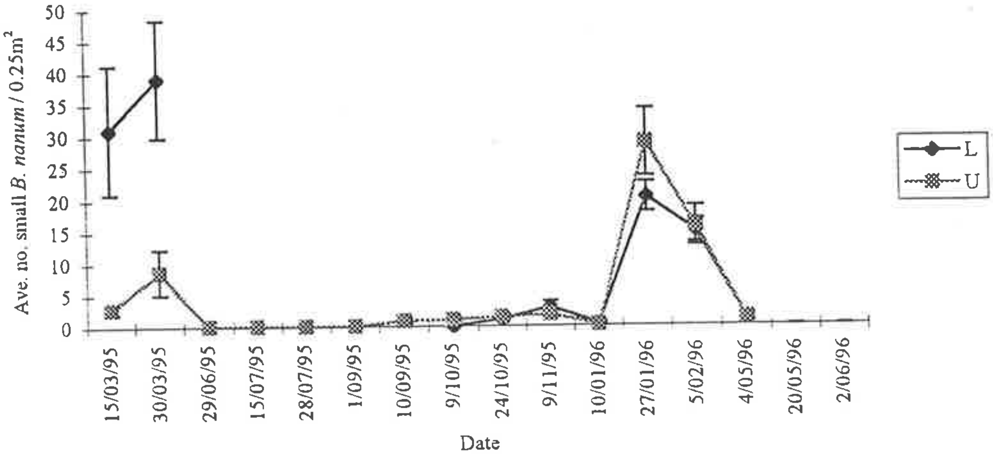


Fig. 4.31 The density of 'small' *B. nanum* is shown in the 'upper' (U) and 'lower' (L) zones at 'Southern' sites; a) Port Noarlunga South (PNS) and b) Robinson Point (RP). Density has been calculated as the average number of small *B. nanum* per 0.25m² quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

Nerita atramentosa

The abundance of 'small' *N. atramentosa* varied considerably, both temporally and spatially, for the duration of sampling, but apart from occasional peak occurrences these animals were generally present at low densities. 'Small' *N. atramentosa* were not recorded in the 'upper' zone at Kingston Park but the 'lower' zone supported between 1-6 'small' animals per quadrat at most times, with peak abundances of around 15 occurring in late June and late July 1995 (Fig. 4.32a). 'Small' *N. atramentosa* occurred at peak densities of around 10 animals per quadrat in the 'upper' zone at Marino Rocks from late March until late July 1995 while less than 5 animals per quadrat were recorded at all other times (Fig. 4.32b). The 'lower' zone supported higher abundances until July 1995, with peak abundances of 22-28 'small' *B. nanum* occurring in late June and early July 1995.

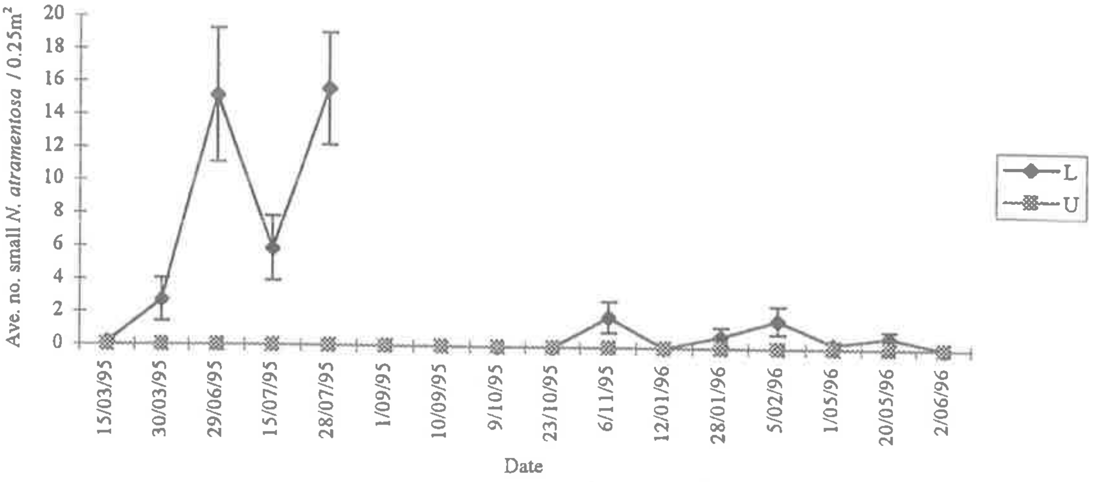
PS1 consistently supported densities of less than 10 'small' animals for the duration of sampling. The abundance of 'small' *N. atramentosa* was generally greater in the 'lower' zone where peaks were detected in July 1995 and February 1996 (Fig. 4.32c). The number of 'small' *N. atramentosa* at PS1A peaked at 20 in late July 1995 (coincident with the start of the 'effluent' perturbation) but at all other times remained below 3. The 'lower' zone at PS2 generally supported higher densities of 'small' *N. atramentosa* than the 'upper' zone. Densities in the latter remaining below 3 while the 'lower' zone had a peak abundance of 23 animals in late July 1995 and abundances of around 10 in mid-July 1995, October 1995 and February 1996 (Fig. 4.32d). The 'lower' zone at PS3 typically supported more 'small' *N. atramentosa* than the 'upper' zone, although the reverse trend was noted in March and April 1995 (Fig. 4.32e). Abundances in the 'upper' zone at PS3 remained below 10 'small' animals but peak abundances of 32 and 24 'small' *N. atramentosa* occurred in the 'lower' zone in early and mid-July 1995 respectively. At Port Noarlunga South and Robinson Point appearances of 'small' *N. atramentosa* were rare in both zones (averaging less than 2 animals per quadrat for the duration of sampling) and have not been presented graphically.

Austrocochlea constricta

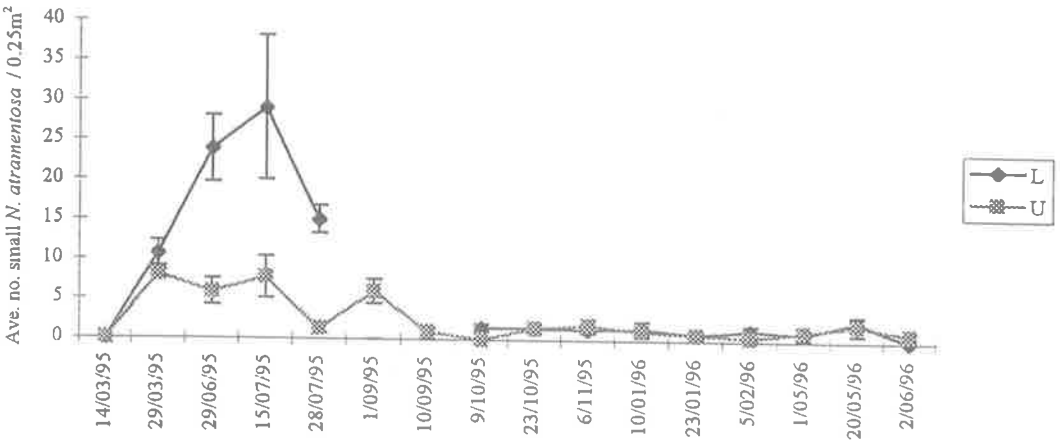
'Small' *A. constricta* were present at low densities at all study sites but were often more abundant in the 'lower' zones. At Kingston Park the average number of 'small' animals in the 'upper' zone was less than one (and often zero) for the duration of sampling but a peak abundance of 9 'small' animals was recorded in November 1995 (Fig. 4.33a). Peak abundances of around 5-6 and 3-4 'small' *A. constricta* were noted in the 'lower' zone at Marino Rocks in mid-March and November 1995 respectively in association with high spatial variability but at all other times 'small' *A. constricta* were rare in both zones (Fig. 4.33b). Peak abundances of 'small' animals were noted in the 'lower' zone at HCA in the first two sampling times and in the 'upper' zone at this site in late March and mid-July 1995, prior to the population crash associated with the sand influx (Fig. 4.33c).

The number of 'small' *A. constricta* were higher at PS1A than at the other study sites with peak abundances of more than 10 occurring in late November 1995 and January 1996 (Fig. 4.33d). At all other times 'small' *A. constricta* remained below 8 at PS1A and in both zones at PS1 (Fig. 4.33d). PS3 was characterised by rare appearances of 'small' *A. constricta* in both zones. 'Small' *A. constricta* were noted at low densities at Port Noarlunga South and Robinson Point and were rarely seen at Witton Bluff. Numbers remained below 4 animals for the duration of sampling at Port Noarlunga South (Fig. 4.33e) but were slightly higher at Robinson Point, peaking in the 'lower' zone in the first two sampling times and in the 'upper' zone in late March and early October 1995 (Fig. 4.33f).

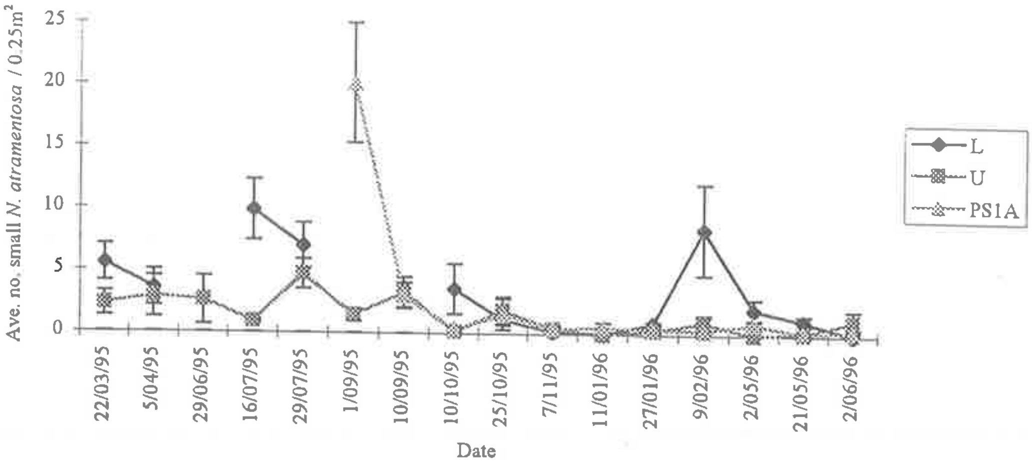
a) KP



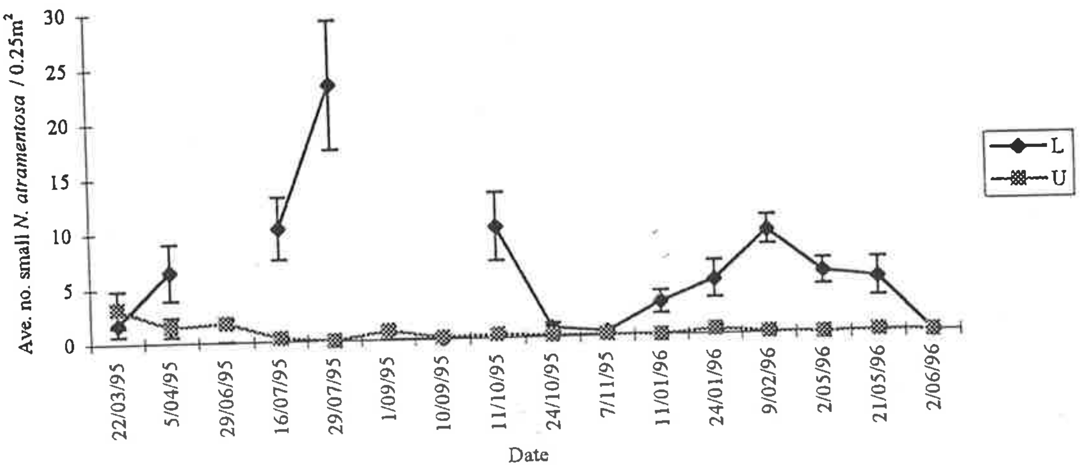
b) MR



c) PS1 & PS1A



d) PS2



e) PS3

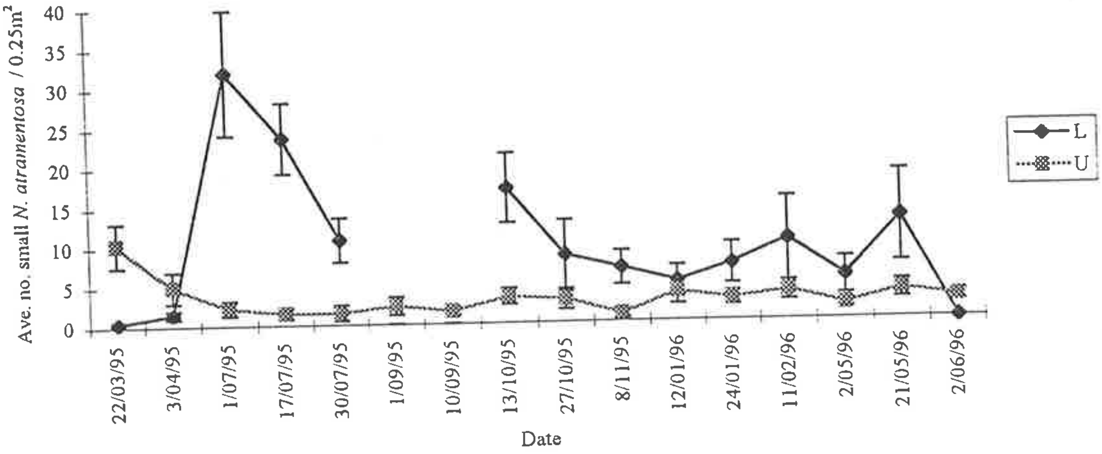
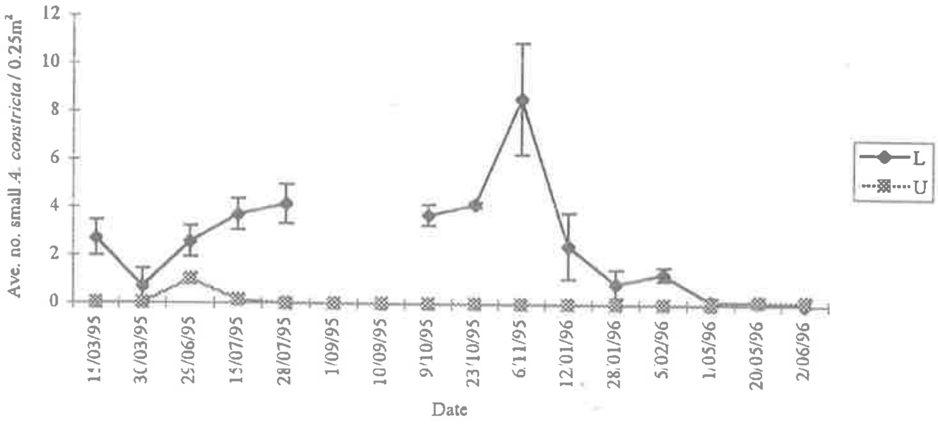
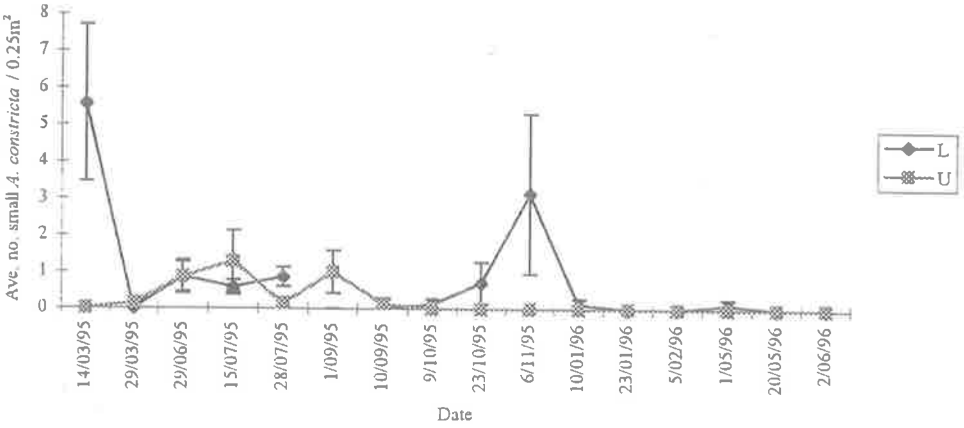


Fig. 4.32 The density of 'small' *N. atramentosa* is shown in the 'upper' (U) and 'lower' (L) zones at; a) Kingston Park (KP), b) Marino Rocks (MR), c) PS1 & PS1A, d) PS2 and e) PS3. The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at PS1. Density has been calculated as the average number of small *N. atramentosa* per 0.25m^2 quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

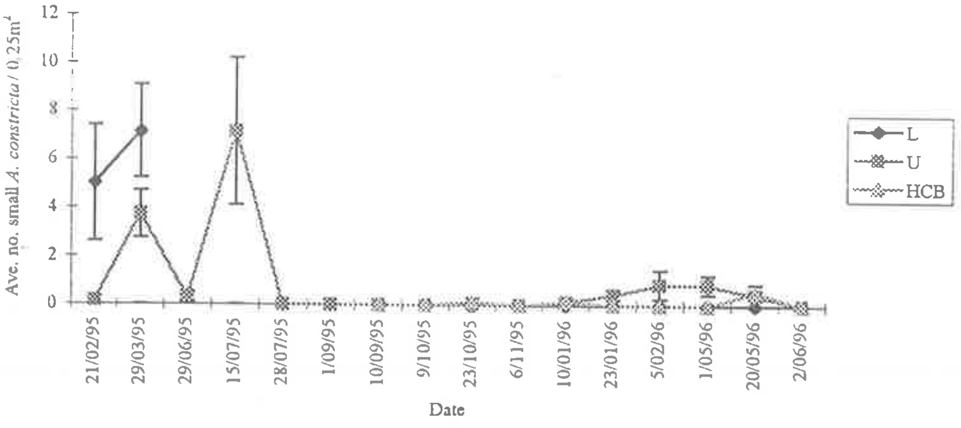
a) KP



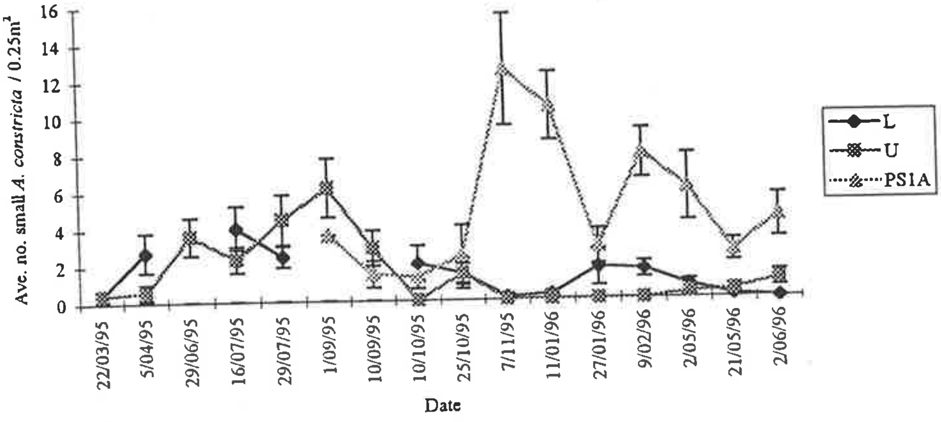
b) MR



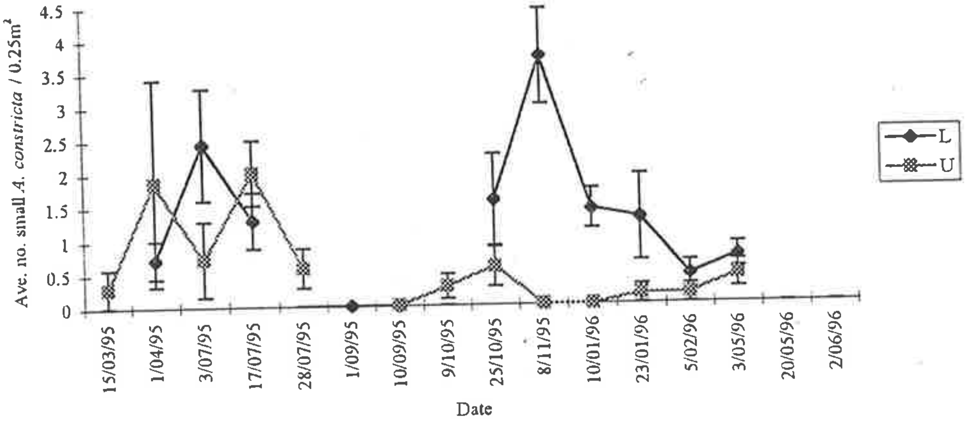
c) Hallett Cove



d) PS1 & PS1A



e) PNS



f) RP

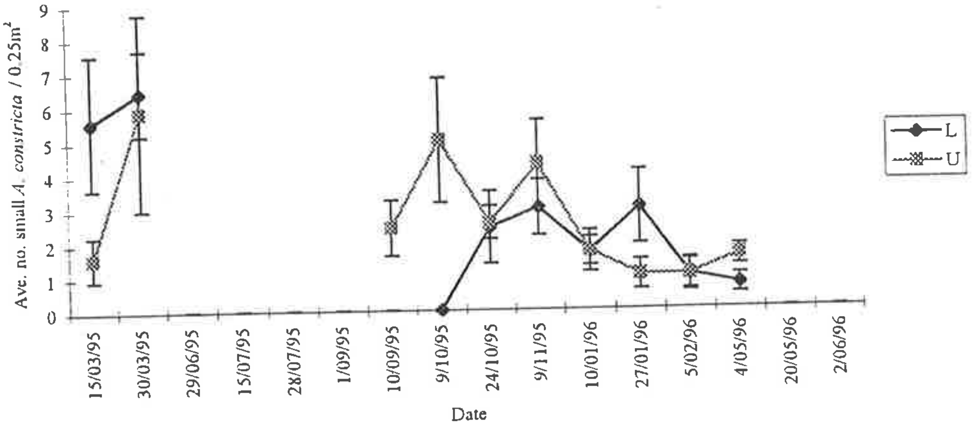


Fig. 4.33 The density of 'small' *A. constricta* is shown in the 'upper' (U) and 'lower' (L) zones at; a) Kingston Park (KP), b) Marino Rocks (MR), c) Hallett Cove (HCA & HCB), d) PS1 & PS1A, e) Port Noarlunga South (PNS) and f) Robinson Point (RP). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA and the equivalent series in d) refer to these zones at PS1. Density has been calculated as the average number of small *A. constricta* per 0.25m^2 quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

Austrocochlea concamerata

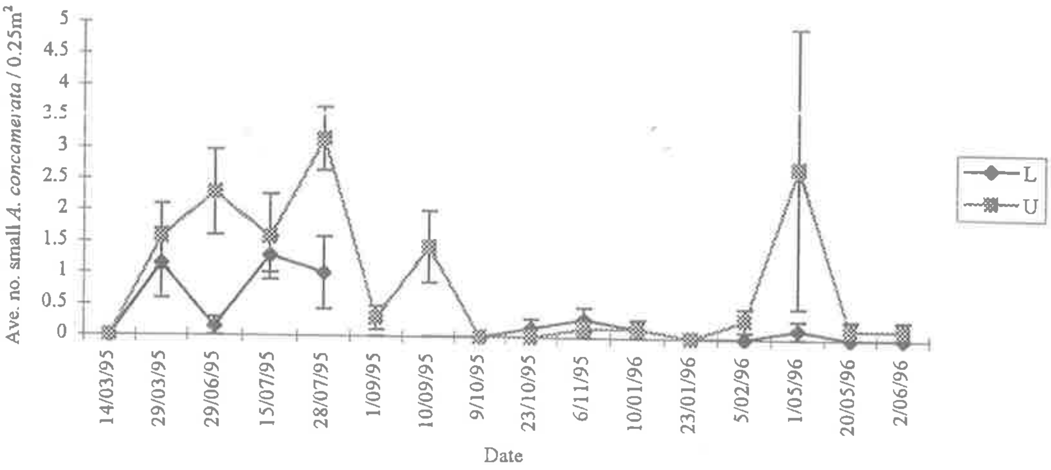
'Small' *A. concamerata* were rarely found at study sites during preliminary sampling. They were never seen in the 'upper' zone at Kingston Park and made few appearances in the 'lower' zone but were slightly more common at Marino Rocks where they were more abundant in the 'upper' zone. At this site 'small' *A. concamerata* never attained average densities of greater than 4 animals per quadrat but were occasionally heavily represented in a single quadrat as indicated by the large standard error associated with the early May 1996 sample (Fig. 4.34a). 'Small' *A. concamerata* were infrequently seen at Hallett Cove.

Low average densities of less than 5 'small' *A. concamerata* per quadrat were noted at all 'Central' study sites (Fig. 4.34b, c & d). Minor peaks in 'small' *A. concamerata* occurred in the 'lower' zone at PS1 in April and July 1995 and February and late May 1996 (Fig. 4.34b) and in the 'lower' zone at PS2 in February 1996 (Fig. 4.34c). Minor peaks in the number of 'small' *A. concamerata* in the 'lower' zone at PS3 were noted in April, May and mid-October 1995 (Fig. 4.34d). A degree of spatial patchiness in the distribution of 'small' *A. concamerata* was seen at many of the study sites. 'Small' *A. concamerata* were rarely seen at 'Southern' study sites.

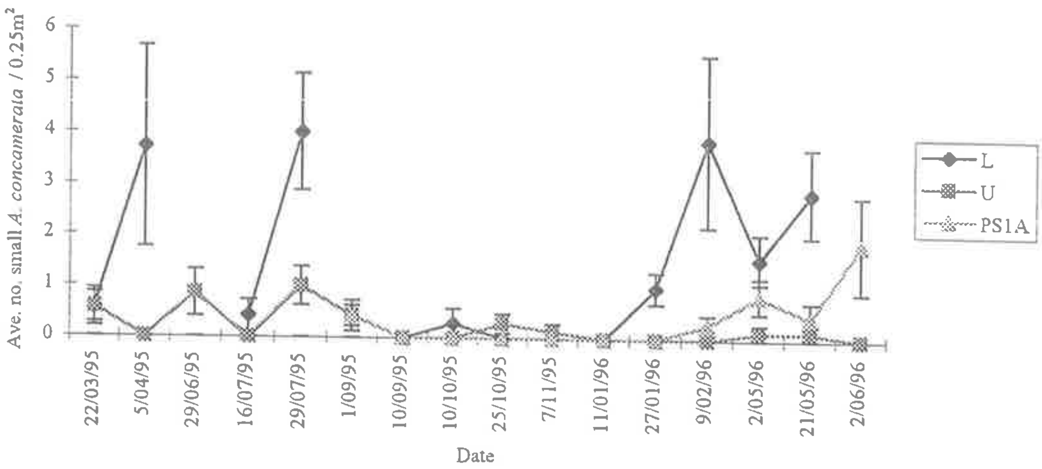
Siphonaria diemenensis

'Small' *S. diemenensis* were rarely seen Robinson Point but were recorded at densities up to an average of 40 per quadrat at Port Noarlunga South (Fig. 4.28c). The 'upper' zone at the latter site supported consistently higher densities of 'small' *S. diemenensis* than the 'lower' zone and exhibited greater temporal variability. Peak occurrences of 'small' animals were noted in the 'upper' zone at Port Noarlunga South in July 1995 and again in February 1996. The latter peak coinciding with a peak average density of 22 'small' animals in the 'lower' zone.

a) MR

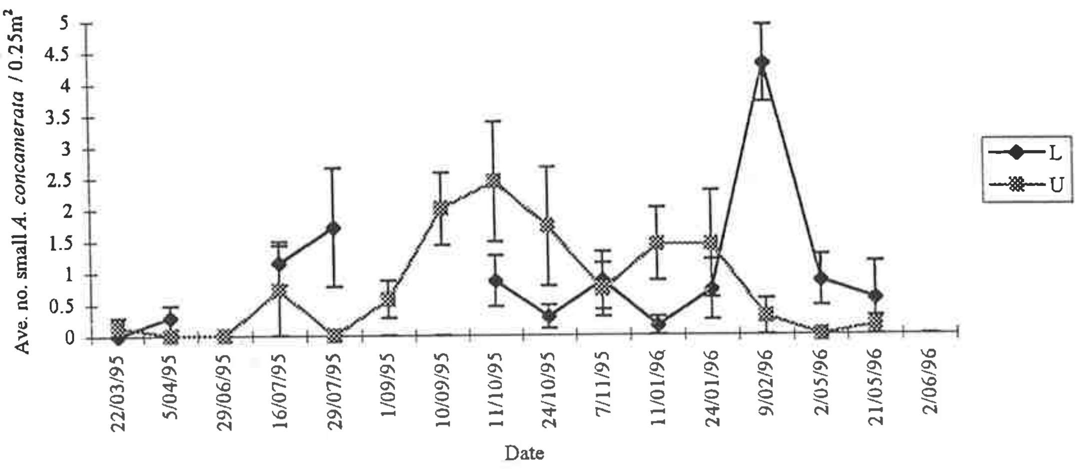


b) PS1 & PS1A



(Caption on next page)

c) PS2



d) PS3

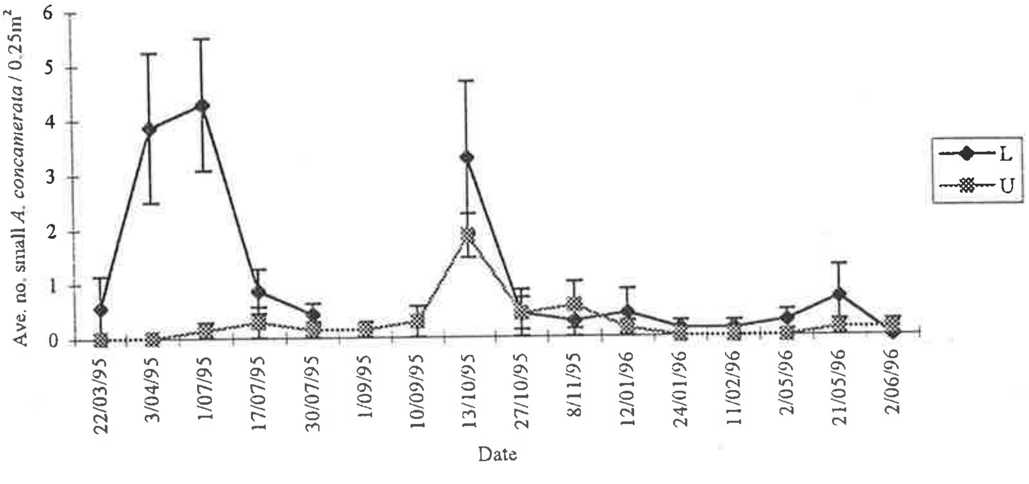


Fig. 4.34 The density of 'small' *A. concamerata* is shown in the 'upper' (U) and 'lower' (L) zones at; a) Marino Rocks (MR), b) PS1 & PS1A, c) PS2, and d) PS3. The 'upper' (U) and 'lower' (L) series shown in b) refer to these zones at PS1. Density has been calculated as the average number of small *A. concamerata* per 0.25m² quadrat. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3). Error bars represent standard errors.

4.4.3.5 Univariate Indices and Associated Variables

Assemblage data were used to generate univariate indices and associated variables using the formulae in Table 4.4 as described in section 4.3.2; "*Univariate Assessment of Temporal Change*".

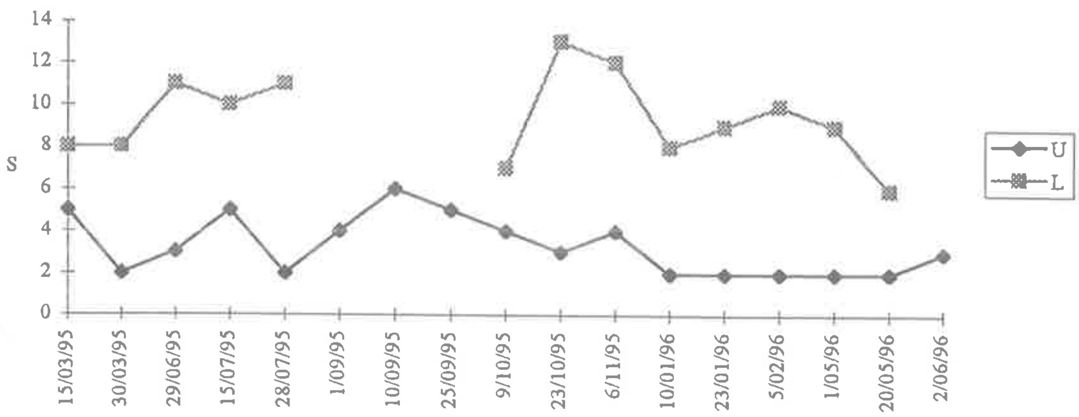
Number of Taxa (S)

The total number of taxa (S) recorded during preliminary sampling were separately plotted for 'Northern' (Fig. 4.35), 'Central' (Fig. 4.36) and 'Southern' sites (Fig. 4.37). Typically, the 'upper' zones at these sites exhibited taxa paucity compared to their respective 'lower' zones. In the 'lower' zones at Kingston Park and Marino Rocks trends in taxa number were comparable, remaining between 6-12 for the duration of sampling, with peak levels occurring in late October 1995 (Fig. 4.35a & b).

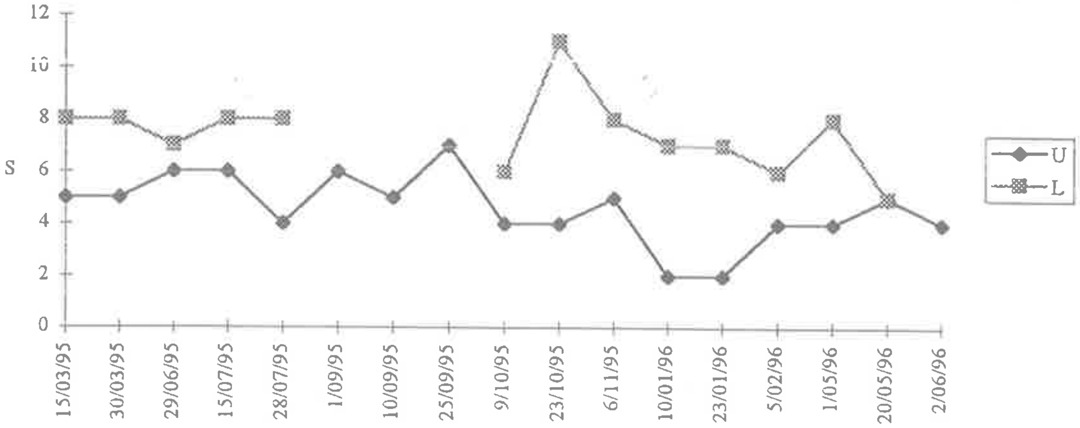
HCA was similar to the other 'Northern' sites in generally supporting a low number of taxa. An interesting trend was the apparent link between the 'upper' zone at HCA and the adjacent HCB site during the sand influx event (Fig. 4.35c). In the 'upper' zone at HCA a reduction in taxa was evident by late September 1995 followed by a recovery in taxa number. These changes were tracked by an increase in the number of recorded taxa at HCB and then a reduction and stabilisation of this parameter. HCB generally supporting more taxa than HCA until November 1995 when the reverse trend was noted (Fig. 4.35c). The 'lower' zones at 'Central' sites typically supported more taxa than their equivalent 'upper' zones (Fig. 4.36a, b & c). An interesting finding relating to the 'Central' sites was the similarity in temporal trends in taxa number at PS1 and PS1A from early October 1995 (Fig. 4.36a).

The 'Southern' sites differed from the other study sites in a general tendency for the 'upper' zones to support more taxa than the 'lower' zones (Fig. 4.37). However, the low-lying status of these sites and the infrequent sampling of their 'lower' zones made determination of any apparent taxa trends difficult. Witton Bluff differed from the other two 'Southern' sites which tended to support similar numbers of taxa and exhibit broadly similar temporal trends (Fig. 4.37b & c). The 'upper' zone at Witton Bluff was dominated by *T. undulatus*, underwent greater temporal variability and often supported slightly less taxa than Port Noarlunga South and Robinson Point (Fig. 4.37a, b & c).

a) KP



b) MR



c) Hallett Cove

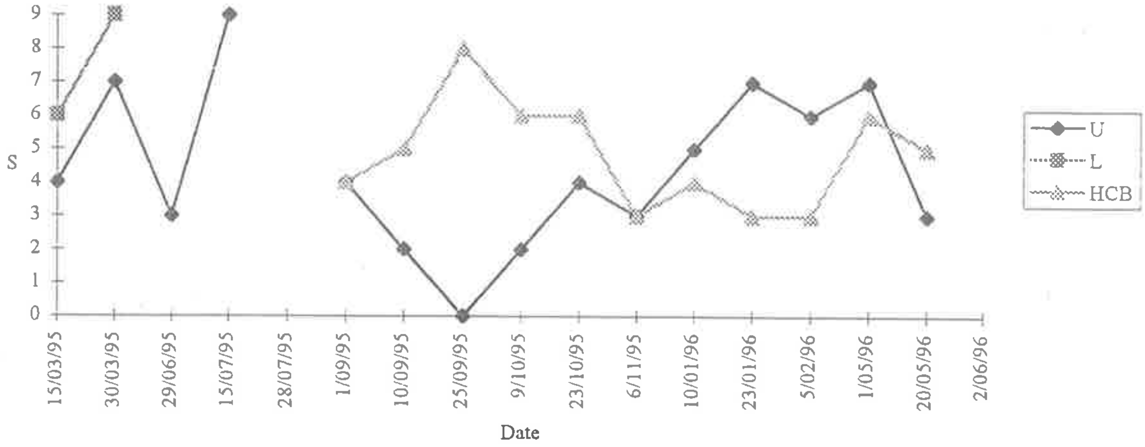
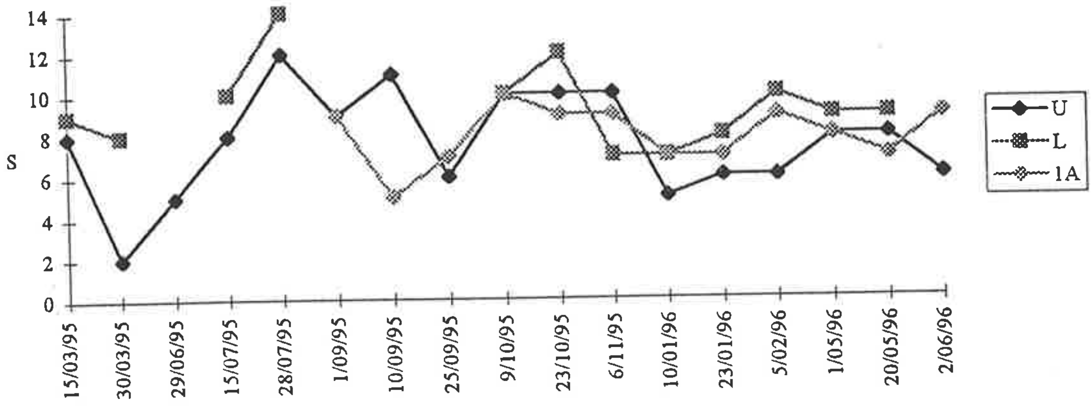
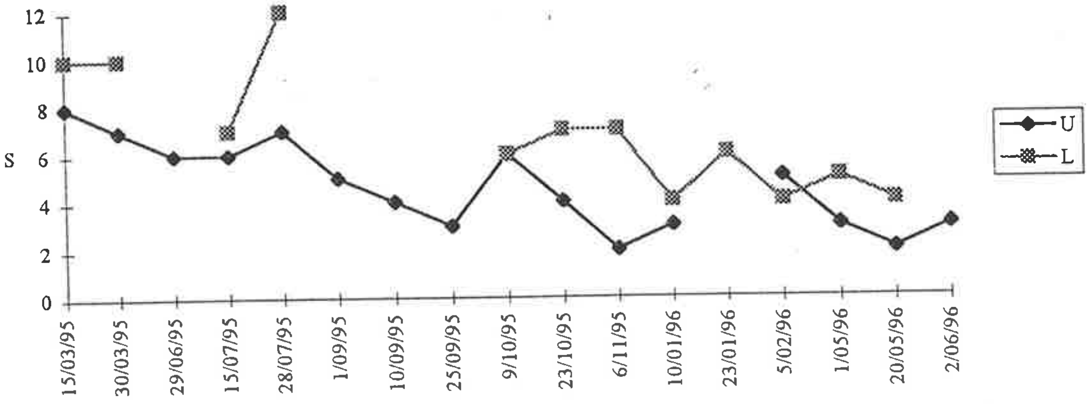


Fig. 4.35 The total number of taxa (S) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. The total number of taxa have been calculated as the summed number of animal taxa (generally species) in seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1 & PS1A



b) PS2



c) PS3

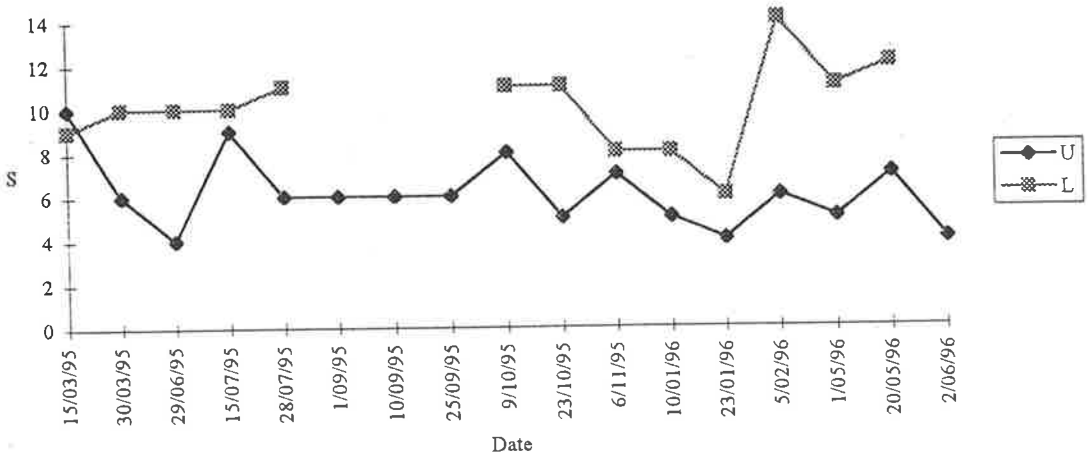
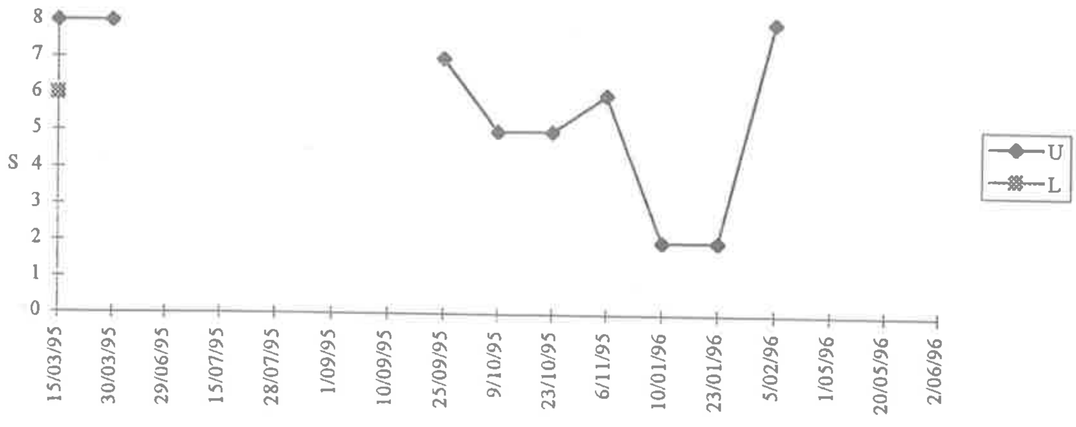
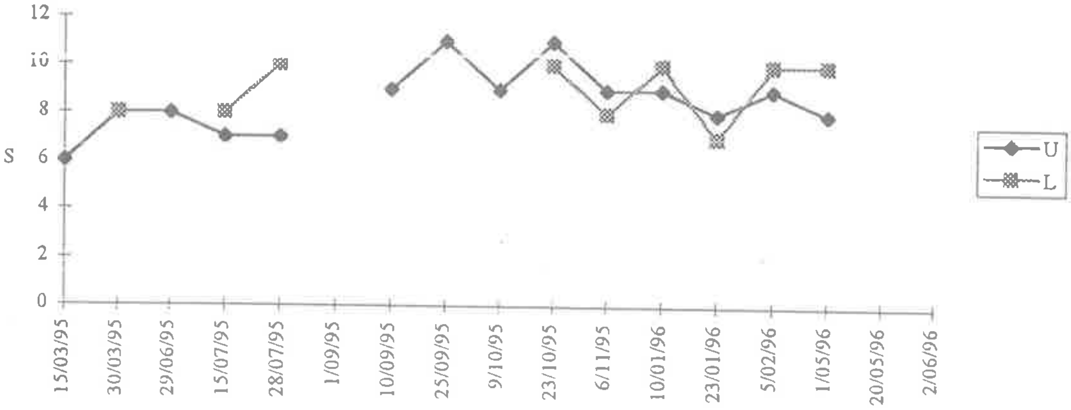


Fig. 4.36 The total number of taxa (S) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Central' sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. The total number of taxa have been calculated as the summed number of animal taxa (generally species) in seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) WB



b) PNS



c) RP

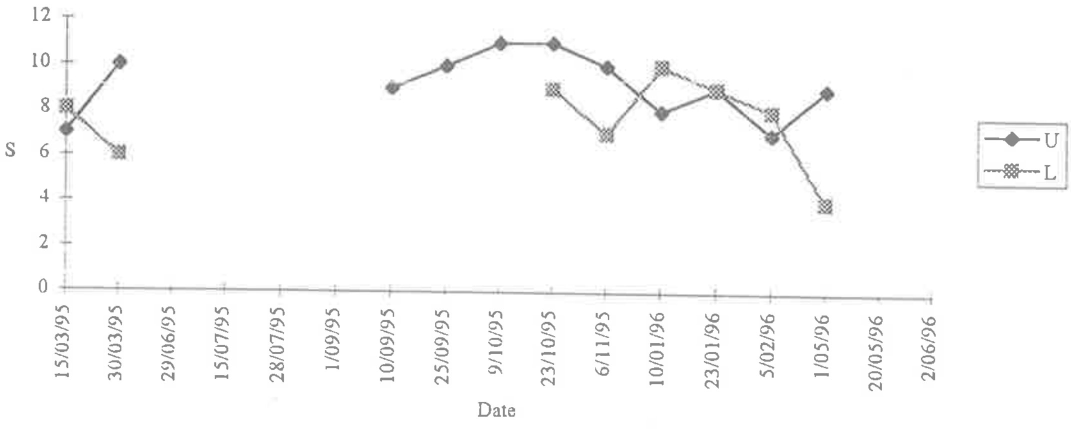


Fig. 4.37 The total number of taxa (S) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Southern' sites; a) Witton Bluff (WB), b) Port Noarlunga South (PNS) and c) Robinson Point (RP). The total number of taxa have been calculated as the summed number of animal taxa (generally species) in seven 0.25m^2 quadrats at each zone. Sampling times shown on the x-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

Number of Individuals (N)

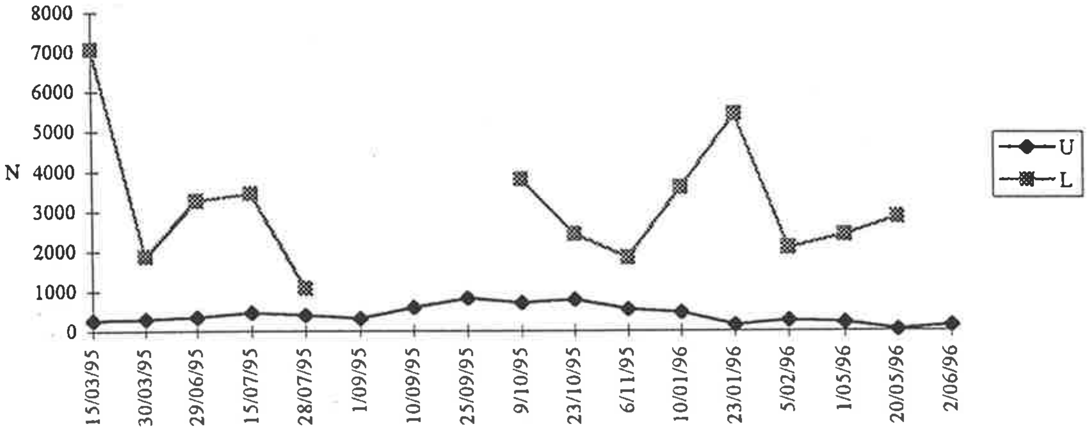
The total number of individuals varied widely between study sites and within zones at a single site but the 'lower' zones typically supported extremely high numbers of individuals especially where mussels and barnacles were common (Figs 4.38, 4.39 & 4.40). This situation was most obvious at Kingston Park (Fig. 4.38a), HCA (Fig. 4.38c) and the 'Southern' sites (Fig. 4.40). The extreme temporal variability in the total number of animals recorded at sites where mussels and barnacles dominated was more likely to reflect the spatial variability and 'patchiness' inherent in the sites than indicate a 'true' temporal trend.

The 'upper' zone at Kingston Park was relatively consistent in the total number of individual animals it supported until a marked reduction following the second sand influx in 1996 (Fig. 4.38a). The 'upper' zone at Marino Rocks generally supported fewer individuals than the other two 'Northern' sites but showed high temporal variability (Fig. 4.38b), while the sand influx at HCA was matched by a sudden and extreme reduction in the number of individuals inhabiting the 'upper' zone (Fig. 4.38c). The relationship between the total number of animals recorded at HCA and HCB was similar to trends identified in terms of the number of taxa these sites supported during and after the sand perturbation.

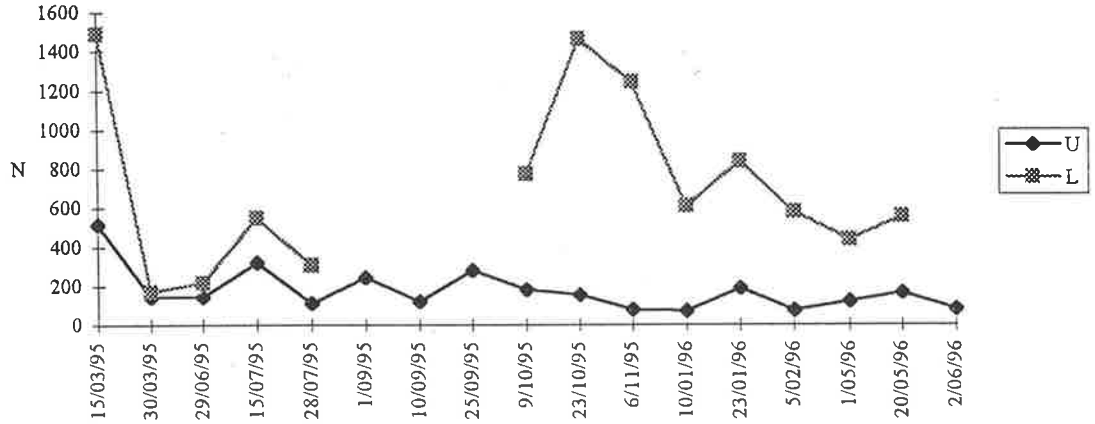
The 'upper' zone at PS1 had a stable substrata for the duration of preliminary sampling ensuring a consistently high number of resident individuals without the large declines coincident with mobilisation of substrata in the equivalent zones at other 'Central' sites (Fig. 4.39a, b & c). The 'upper' zone at PS1 displayed similar trends to PS1A, apart from peak abundances of greater than 500 individuals at the former site in November 1995 and again in late May 1996 (Fig. 4.39a). Changes in the total number of individuals in both zones at PS2 closely tracked each other from October 1995 (Fig. 4.39b). Less concordance was seen in the number of individuals recorded in both zones at PS3 but the 'lower' zone always supported more individuals than the 'upper'. At PS3 both zones displayed high variability but marked reductions in the total number of animals were seen from October 1995, with the exception of a peak in the 'lower' zone in February 1996 (Fig. 4.39c).

The 'Southern' sites were characterised by extremely high numbers of animals in both zones for the duration of sampling, with the 'lower' zones almost always supporting many more individuals than the 'upper' zones (Fig. 4.40a, b & c). The trend to high numbers of individual animals was not seen in the 'upper' zone at Witton Bluff which was characterised by low numbers of individuals (primarily *T. undulatus*) at all times, apart from a single sampling occasion in late March 1995 (Fig. 4.40a). The large number of animals recorded on that occasion was attributed to a pocket of mussels, which had encroached into the 'upper' zone.

a) KP



b) MR



c) Hallett Cove

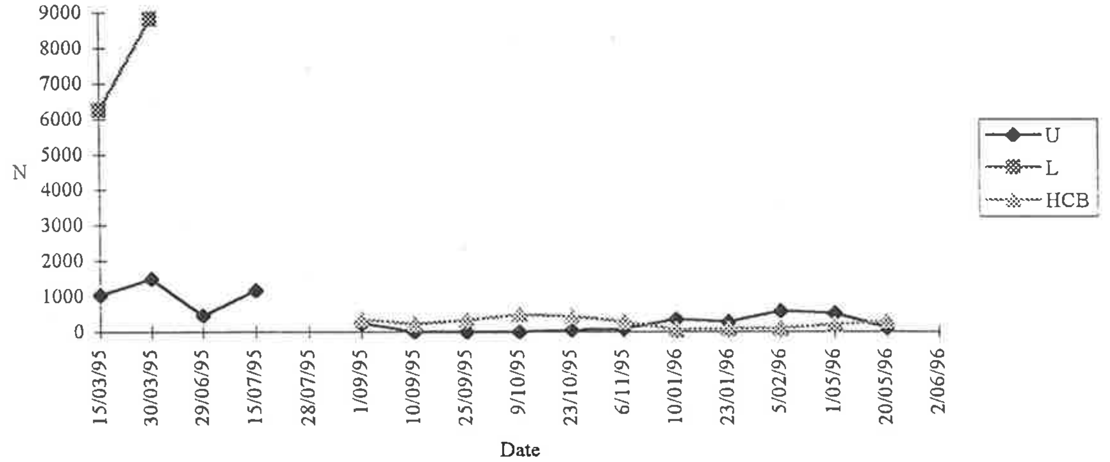
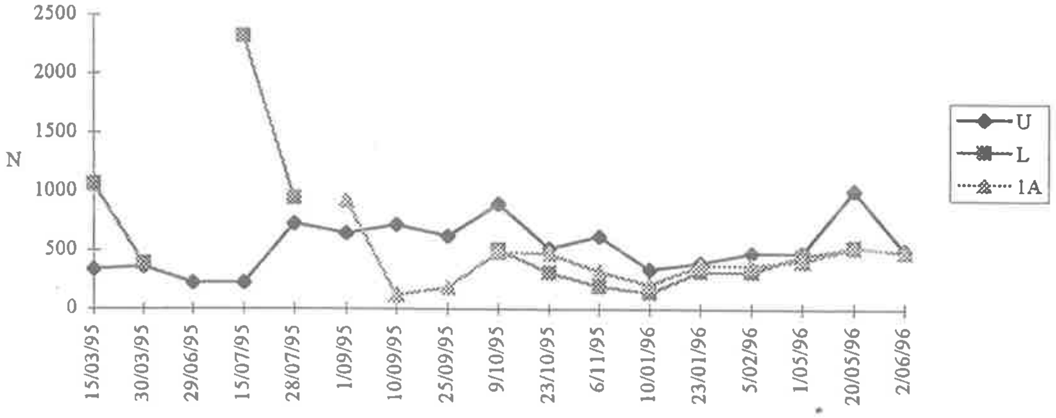
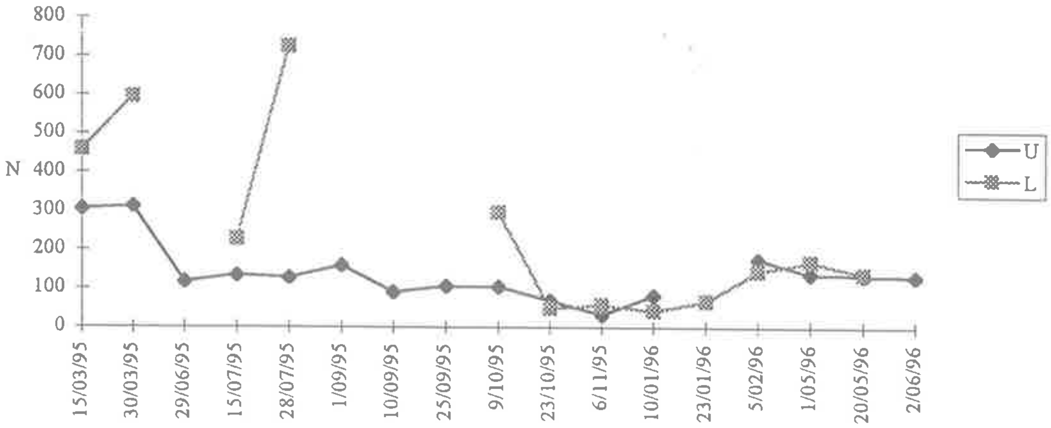


Fig. 4.38 The total number of individuals (N) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. The total number of individuals have been calculated as the summed number of individual animals present in seven $0.25m^2$ quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1 & PS1A



b) PS2



c) PS3

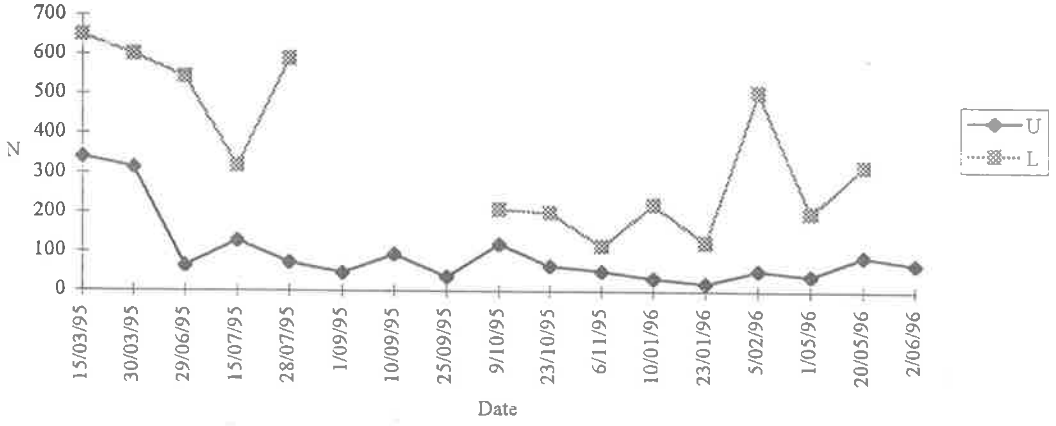
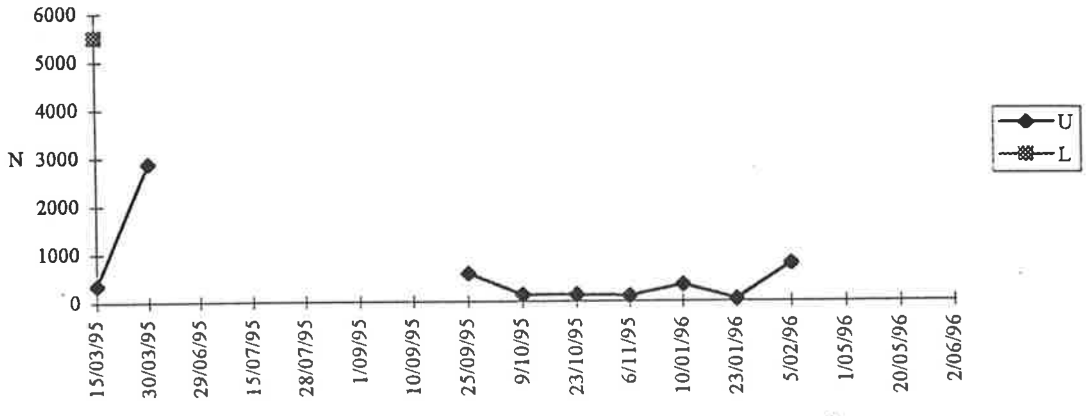
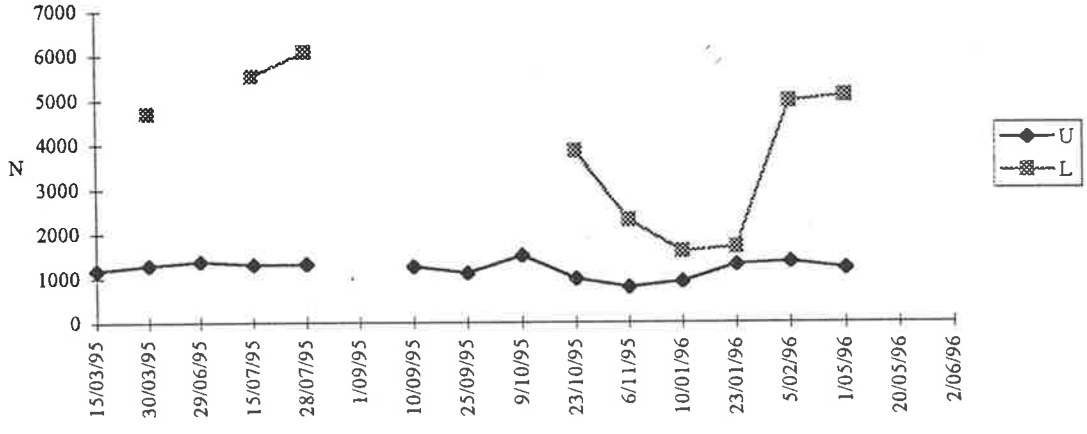


Fig. 4.39 The total number of individuals (N) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Central' sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. The total number of individuals have been calculated as the summed number of individual animals present in seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) WB



b) PNS



c) RP

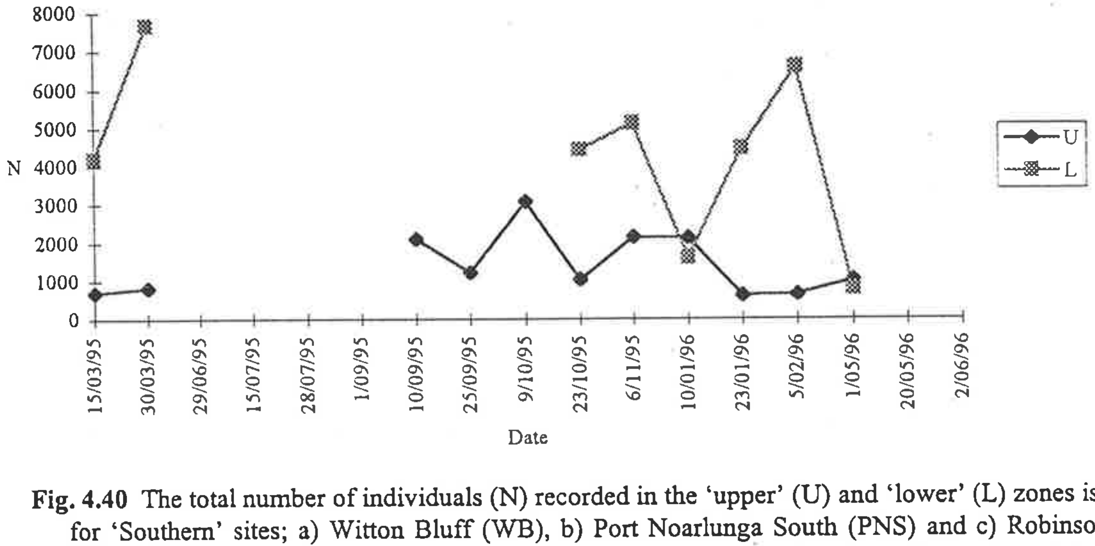


Fig. 4.40 The total number of individuals (N) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Southern' sites; a) Witton Bluff (WB), b) Port Noarlunga South (PNS) and c) Robinson Point (RP). The total number of individuals have been calculated as the summed number of individual animals present in seven 0.25m^2 quadrats at each zone. Sampling times shown on the x-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

Margalef's Species Richness Index

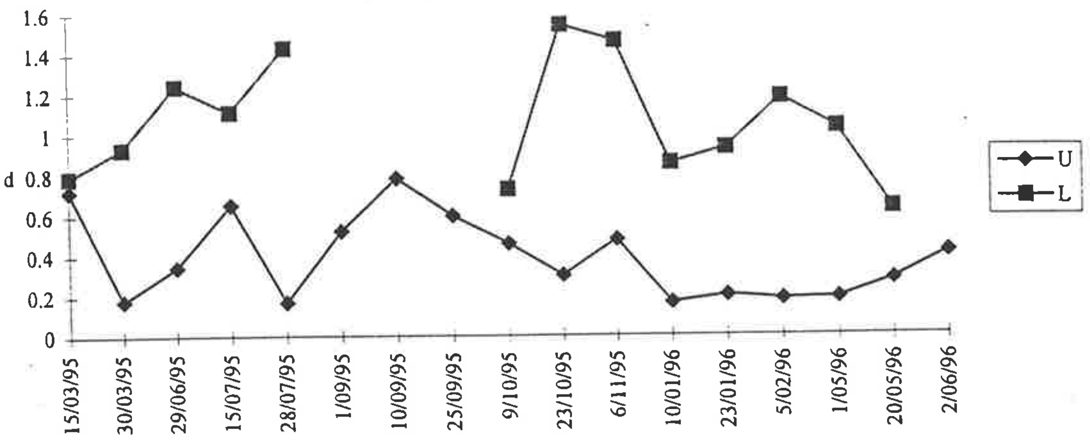
Temporal changes in species richness (quantified using Margalef's Species Richness Index) have been graphed for 'Northern', 'Central' and 'Southern' study sites (Figs 4.41, 4.42 & 4.43 respectively). Species richness tended to be greater in 'lower' zones than in the respective 'upper' zones, but the reverse trend was noted at 'Southern' sites.

Species richness within the 'upper' zones at 'Northern' sites fluctuated widely but was generally below one while the same parameter at 'lower' sites ranged up to 1.5 (Fig. 4.41 a, b & c). The 'upper' zone at Kingston Park generated low species richness scores (of approximately 0.2) on 6 sampling occasions (Fig. 4.41a). HCA and HCB showed a degree of linkage in association with the 1995 sand influx, with a crash in species richness at HCA being matched by an increase in species richness at HCB until late October 1995 when species richness fell at the latter site (Fig. 4.41c).

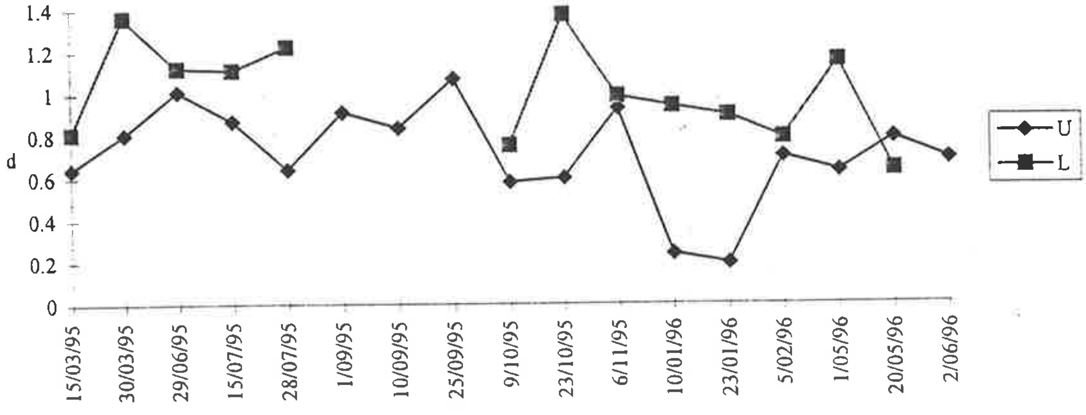
Species richness at 'Central' sites fluctuated but was generally higher than was seen at 'Northern' sites (Fig. 4.42a, b & c). Exceptions to this trend occurred on the second sampling occasion in the 'upper' zone at PS1 when species richness was only 0.2 (Fig. 4.42a), and also in late September 1995 and mid-May 1996 in the 'upper' zone at PS2 when it was 0.3 and 0.2 respectively (Fig. 4.42b). Similar temporal patterns occurred at PS1 and PS1A from October 1995 (Fig. 4.42a), while clear temporal trends were less apparent at the remaining 'Central' sites (Fig. 4.42b & c).

Species richness in the 'upper' zone at Witton Bluff remained between 0.8 and 1.2 until January 1996 when it dipped to around 0.2 before returning to its previous range (Fig. 4.43a). The richness ratings recorded in the 'upper' zones at Port Noarlunga South and Robinson Point tended to fluctuate about unity but were often slightly above this level (Fig. 4.43b & c), while species richness recorded in all 'lower' zones at 'Southern' study sites generally fluctuated about 0.8 (Fig. 4.43a, b & c).

a) KP



b) MR



c) Hallett Cove

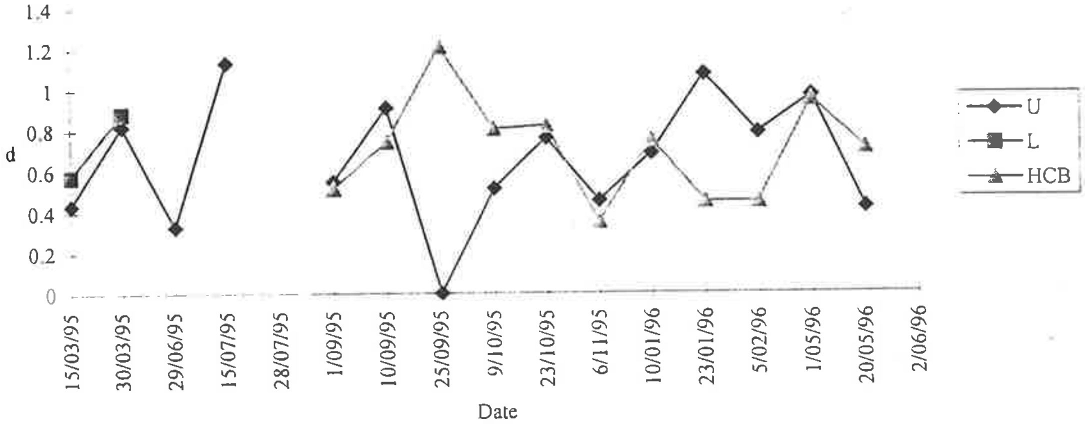
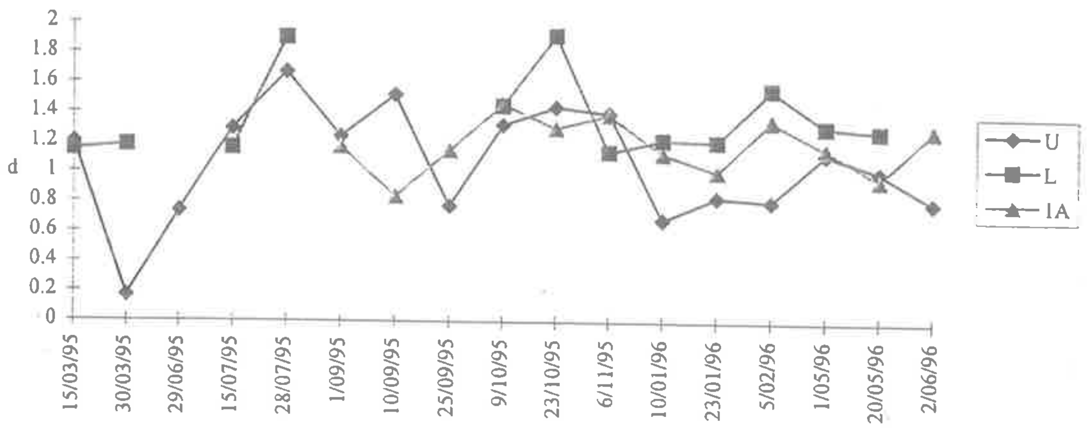
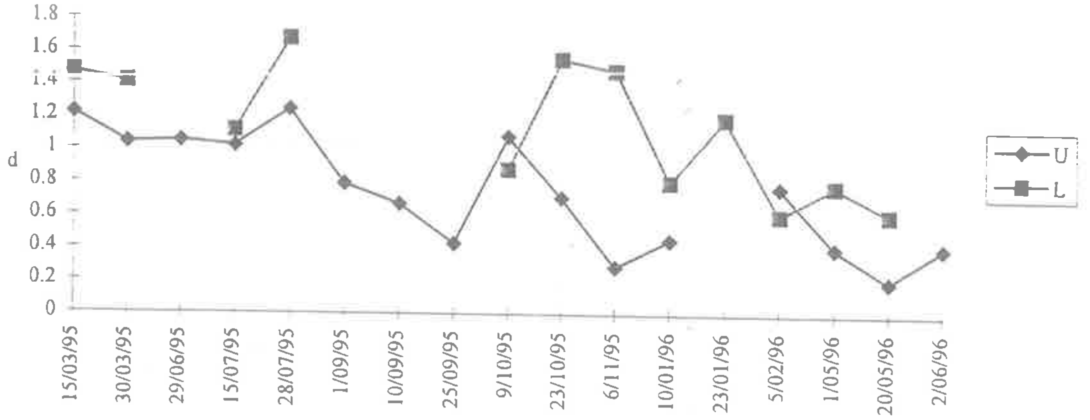


Fig. 4.41 The species richness score (assessed using Margalef's Species Richness Index (d)) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. Species richness has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats deployed in each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1 & PS1A



b) PS2



c) PS3

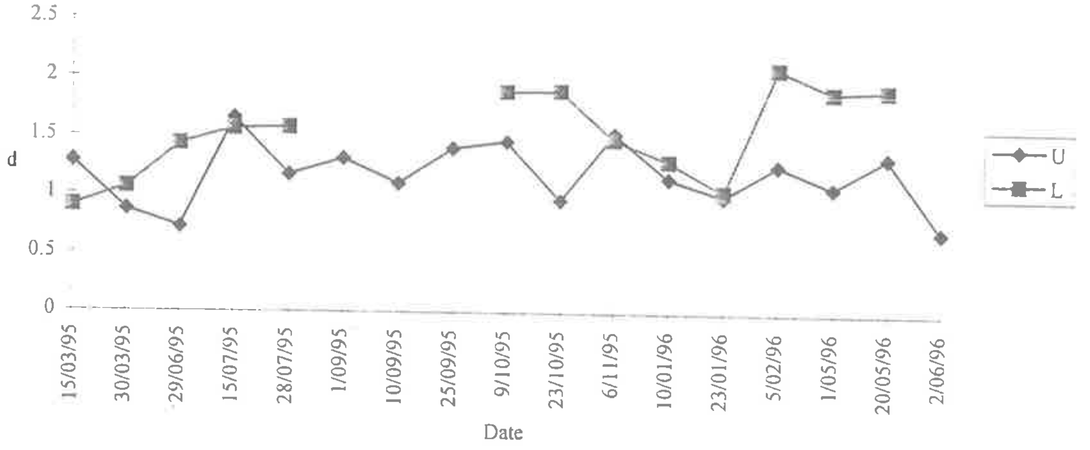
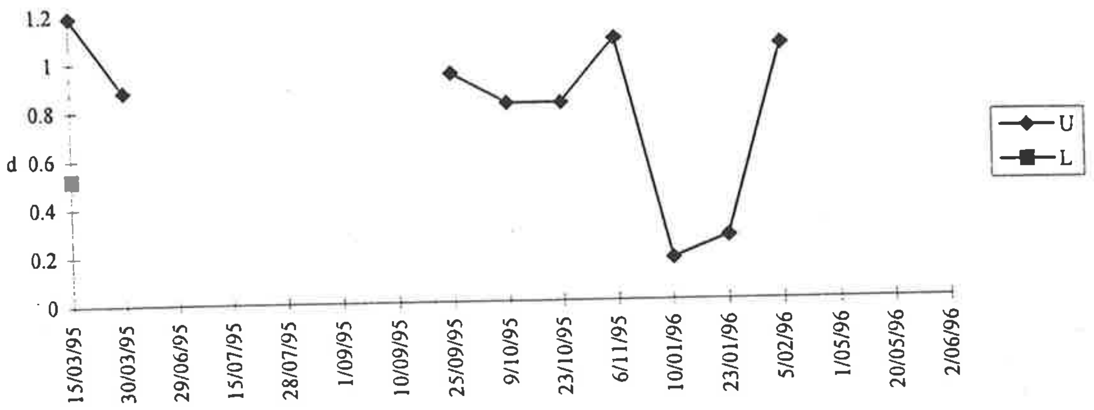
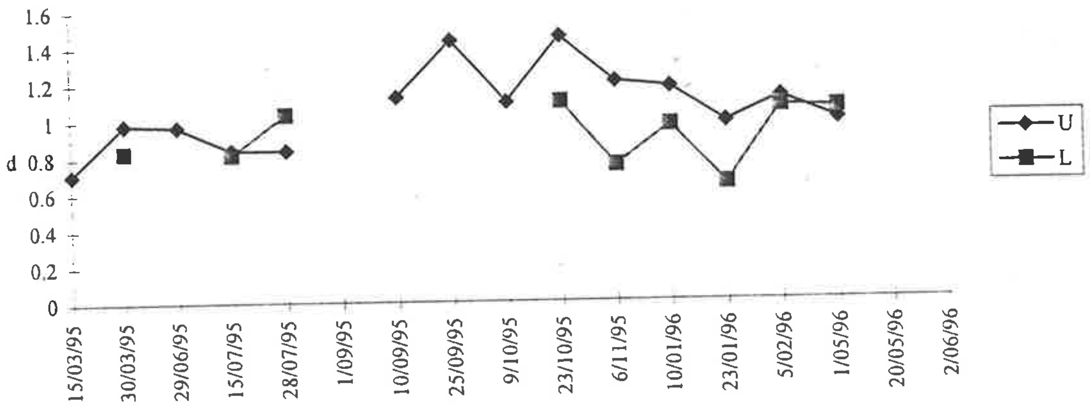


Fig. 4.42 The species richness score (assessed using Margalef's Species Richness Index (d)) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Central' sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. Species richness has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats deployed in each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) WB



b) PNS



c) RP

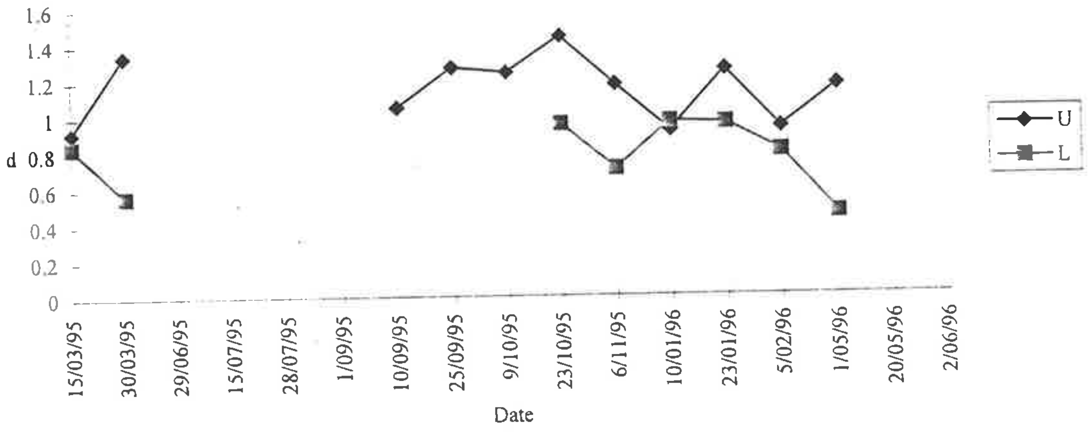


Fig. 4.43 The species richness score (assessed using Margalef's Species Richness Index (d)) recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Southern' sites; a) Witton Bluff (WB), b) Port Noarlunga South (PNS) and c) Robinson Point (RP). Species richness has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats deployed in each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

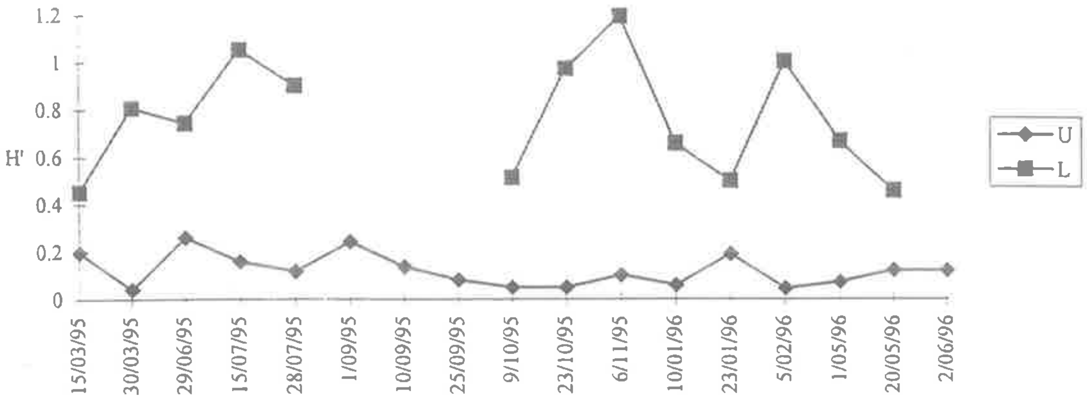
Shannon-Wiener Diversity

Diversity was quantified using the Shannon-Wiener Diversity Index. Use of this index resulted in similar trends to those seen with taxa richness. For example, diversity was generally greater in 'lower' zones at study sites, apart from some occasions at Marino Rocks (Fig. 4.44b), HCA (Fig. 4.44c), and all sampling times at 'Southern' sites (Fig. 4.46a, b & c) where the reverse situation occurred. Diversity within the 'lower' zone at Kingston Park ranged from 0.4 to 1.2 while diversity in the 'upper' zone, heavily dominated by *B. nanum*, generally remained below 0.2 and was relatively consistent for the duration of sampling (Fig. 4.44a). The 'upper' zone at Marino Rocks tended to be more diverse than the equivalent zone at Kingston Park but diversity had fallen to less than 0.1 by early January 1996 (Fig. 4.44b). Diversity in the 'upper' zone at HCA remained above the levels recorded at HCB apart from late September 1995 (when no animals were present) and early May 1996 (Fig. 4.44c). In general, diversity was found to be higher in the 'upper' zone at HCA (compared to both the 'lower' zone and HCB) and remained consistently so from October 1995 to February 1996.

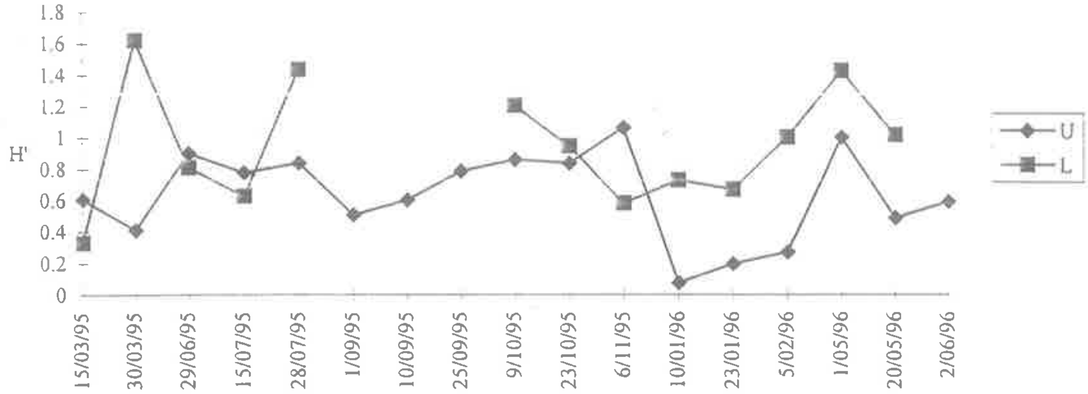
'Central' sites typically registered a higher diversity score than 'Northern' sites and the 'lower' zones were often more diverse than the 'upper' zones (Fig. 4.45a, b & c). In the 'upper' zone at PS1 diversity tended to remain below a maximum of 0.6, while the 'lower' zone had a diversity range of 0.7-1.0. Diversity at PS1A was scored at or above 1.4 on all except one occasion (Fig. 4.45a). The diversity score in the 'upper' zone at PS2 ranged from 0.6 to 1.2, but decreased from October 1995 (Fig. 4.45b). Although less apparent, there was some evidence of the latter trend in the 'lower' zone at this site over the same time interval. The two zones at PS3 were similar in terms of their respective diversity scores although diversity in the 'lower' zone fluctuated over a wider range (Fig. 4.45c).

All 'Southern' sites had more diverse 'upper' zones than their corresponding 'lower' zones (Fig. 4.46a, b & c). Diversity was found to be particularly variable in the 'upper' zone at Witton Bluff where it ranged from 0.1 to greater than 1.2, while the single sampling of the 'lower' zone yielding a diversity score of zero due to the dominance of mussels in the sampled area (Fig. 4.46a). Diversity in the 'upper' zone at Port Noarlunga South ranged between 1.2 and 1.6 (Fig. 4.46b) but fluctuated about a wider range in the 'upper' zone at Robinson Point (Fig. 4.46c). Diversity in the 'lower' zones at 'Southern' sites remained below 0.6 at all times (Fig. 4.46a, b & c).

a) KP



b) MR



c) Hallett Cove

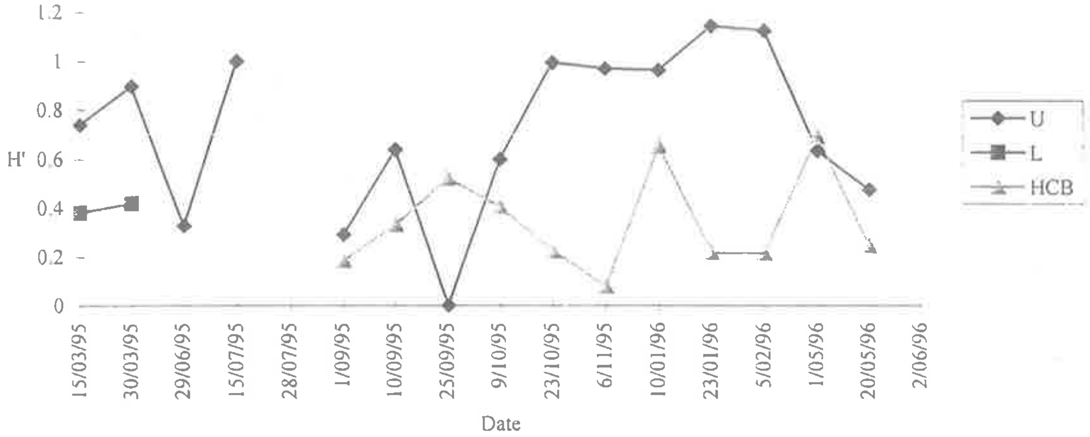
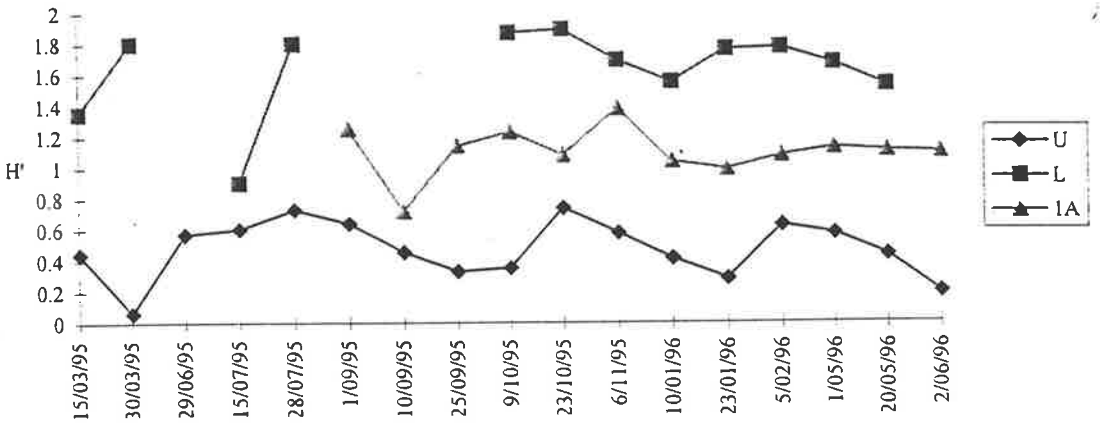
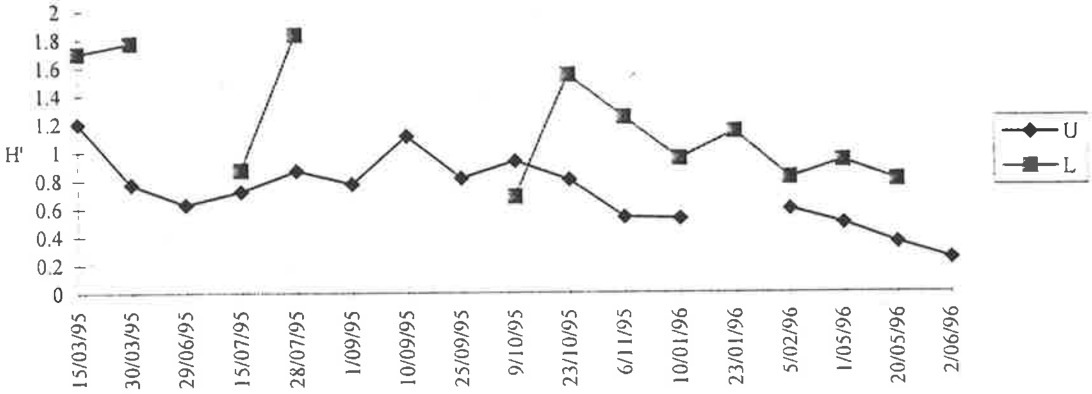


Fig. 4.44 Species diversity, quantified as Shannon-Wiener Diversity (H'), is shown for the 'upper' (U) and 'lower' (L) zones at 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. Species diversity has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats deployed in each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1 & PS1A



b) PS2



c) PS3

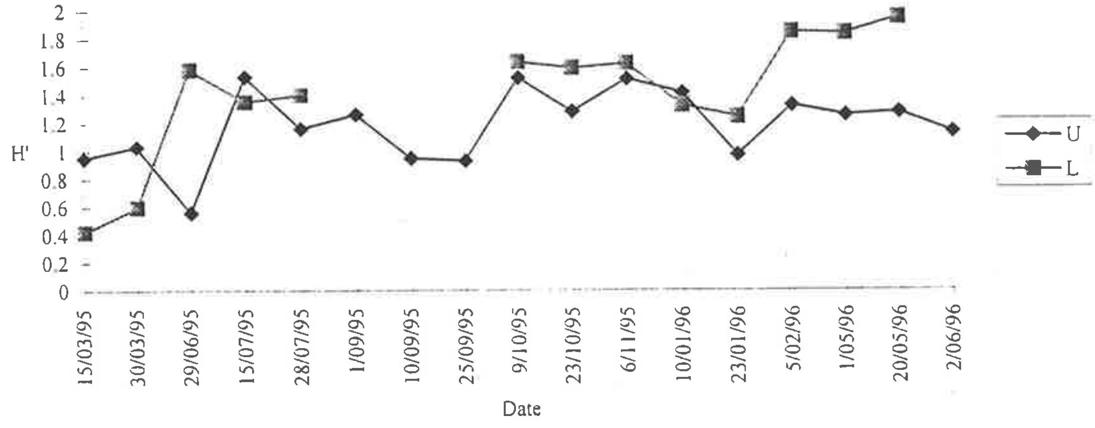


Fig. 4.45 Species diversity, quantified as Shannon-Wiener Diversity (H'), has been shown for the 'upper' (U) and 'lower' (L) zones at 'Central' sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. Species diversity has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

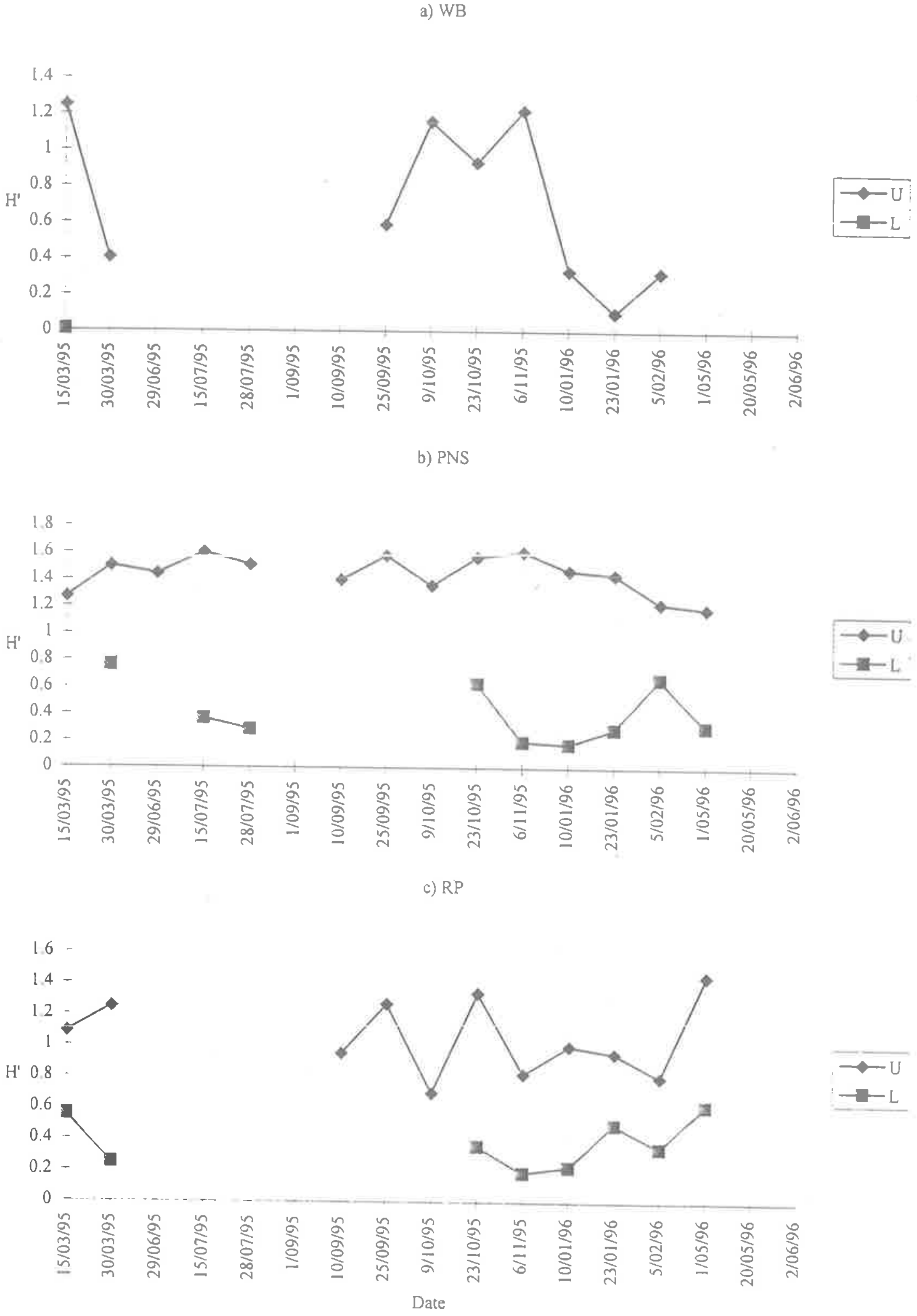


Fig. 4.46 Species diversity, quantified as Shannon-Wiener Diversity (H'), has been shown for the 'upper' (U) and 'lower' (L) zones at 'Southern' sites; a) Witton Bluff (WB), b) Port Noarlunga South (PNS) and c) Robinson Point (RP). Species diversity has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

Equitability: Pielou's Evenness Index

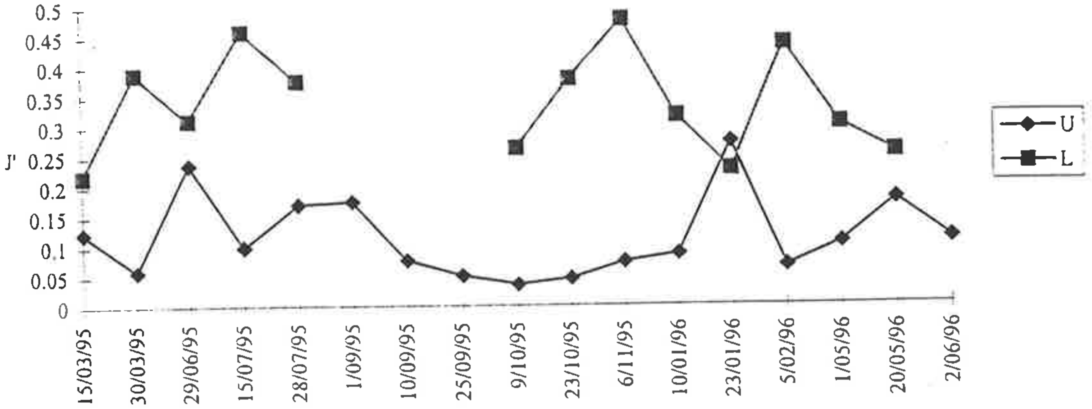
The 'equitability' or 'evenness' of species at study sites was assessed using Pielou's evenness index. This fluctuated widely but was generally higher (and consequently more even) in the 'lower' zones at Kingston Park (Fig. 4.47a) and PS1 (Fig. 4.48a) than in the equivalent 'upper' zones, while the reverse trend was observed at HCA (Fig. 4.47c) and all 'Southern' sites (Fig. 4.49a, b & c). All remaining sites showed a greater degree of evenness overlap between their two zones (Figs 4.47b and 4.48b & c).

Kingston Park recorded low evenness scores (below 0.5) in both zones (Fig. 4.47a). Marino Rocks displayed wider fluctuations in evenness (0.1-0.8), with the highest score being recorded in the 'lower' zone in late March 1995 and the lowest score being noted earlier in the same month (Fig. 4.47b). The 'upper' zone at Marino Rocks registered its lowest evenness score early in 1996 while an evenness peak occurred in early May 1996. HCA was characterised by low evenness in its 'lower' zone while the 'upper' zone had higher evenness scores, ranging from 0.2-0.9 until late September 1995 when they fell to zero before recovering to around 0.8 by the next month (Fig. 4.47c). The recorded evenness at HCB remained at a low but consistent level (between 0.1-0.45) for the duration of sampling (Fig. 4.47c).

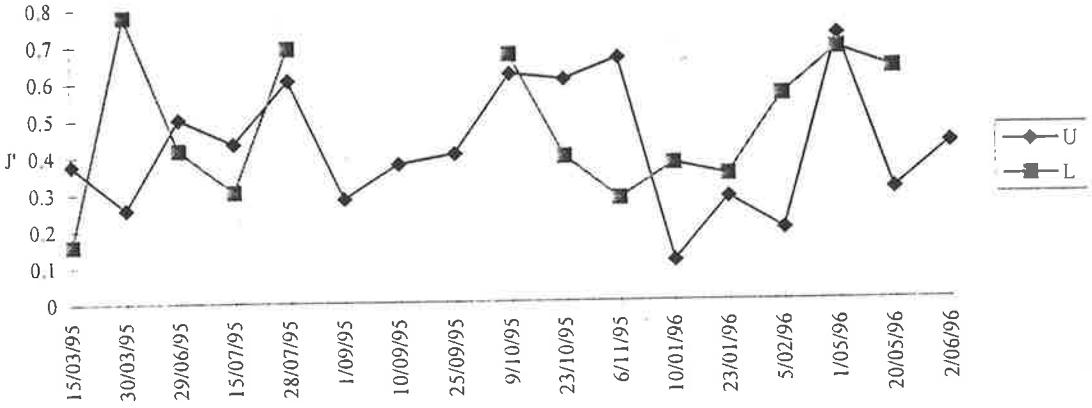
Evenness patterns seen at 'Central' sites were characterised by variability within and between sites (Fig. 4.48a, b & c). Clear trends in evenness were apparent at PS1 and PS1A, with the 'lower' zone at PS1 generally having a higher evenness score (between 0.6 and 0.9 (with one exception)), while the corresponding 'upper' zone registered evenness scores of less than 0.35. The evenness at PS1A was roughly intermediate between the evenness recorded in the two zones at PS1, ranging from 0.4-0.65 (Fig. 4.48a). Considerable overlap in evenness was seen between zones at PS2 although the 'lower' zone tended to plateau at around 0.6 from early January 1996, while evenness in the 'upper' zone remained below 0.6 from this time (Fig. 4.48b). The evenness at PS3 was consistent between zones with both showing a gradual increase to a maximum, relatively stable level of around 0.8 (Fig. 4.48c).

The 'upper' zone at Witton Bluff registered evenness values between 0.15 and 0.6, while an evenness of 0 was recorded in the 'lower' zone at this site (Fig. 4.49a). A relatively stable and narrow evenness range (between 0.55-0.8) was found in the 'upper' zone at Port Noarlunga South, while evenness in the 'lower' zone remained below 0.4 (Fig. 4.49b). In contrast, the evenness at Robinson Point ranged from 0.3-0.65 in the 'upper' zone but generally remained below 0.3 in the 'lower' zone apart from a peak of 0.5 in early May 1996 which matched the timing of the evenness peak in the 'upper' zone (Fig. 4.49c).

a) KP



b) MR



c) Hallett Cove

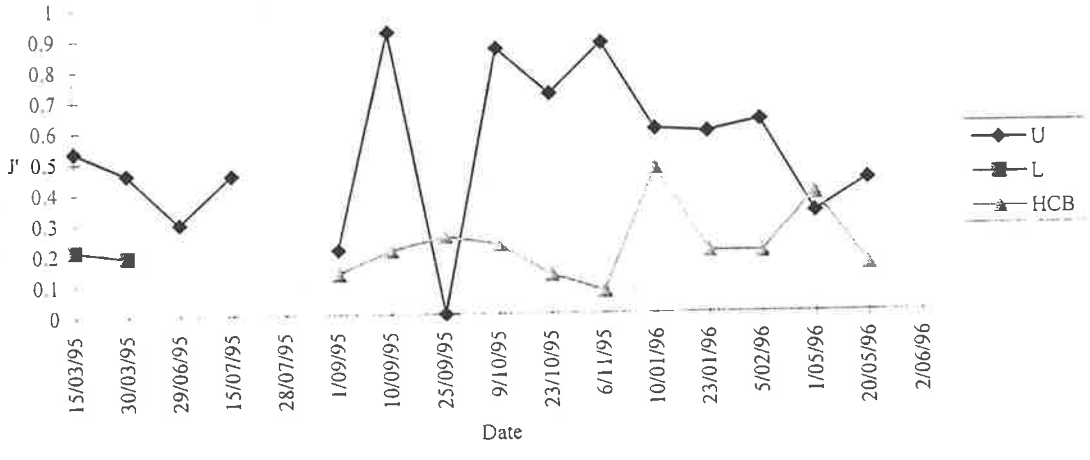
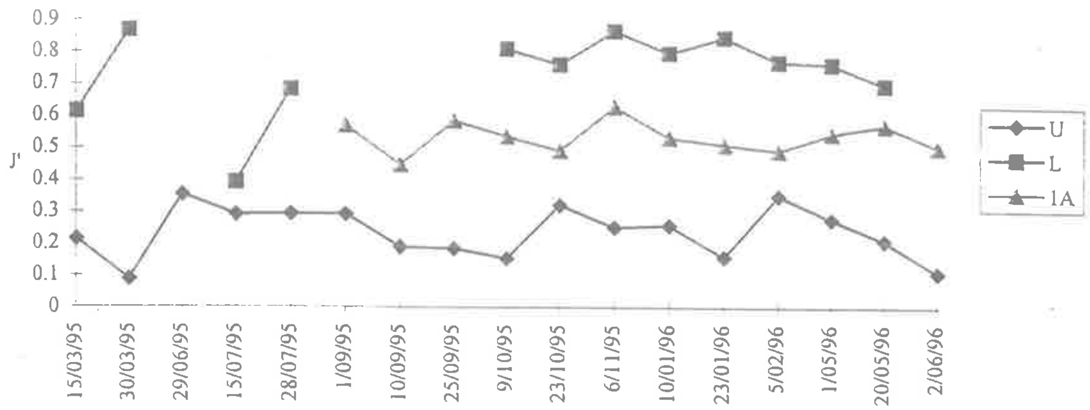
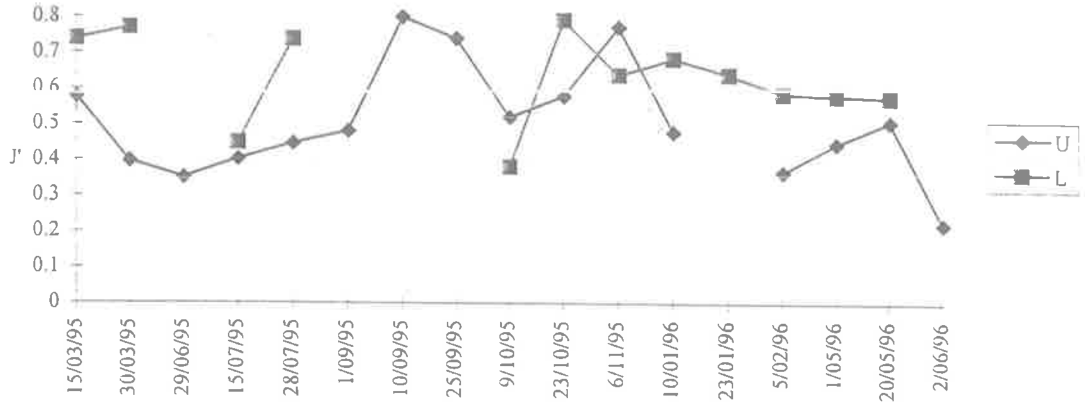


Fig. 4.47 Species evenness, quantified as Pielou's Evenness (J'), recorded in the 'upper' (U) and 'lower' (L) zones at 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. Species evenness has been calculated from raw 'preliminary' data summed across the seven $0.25m^2$ quadrats deployed in each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1 & PS1A



b) PS2



c) PS3

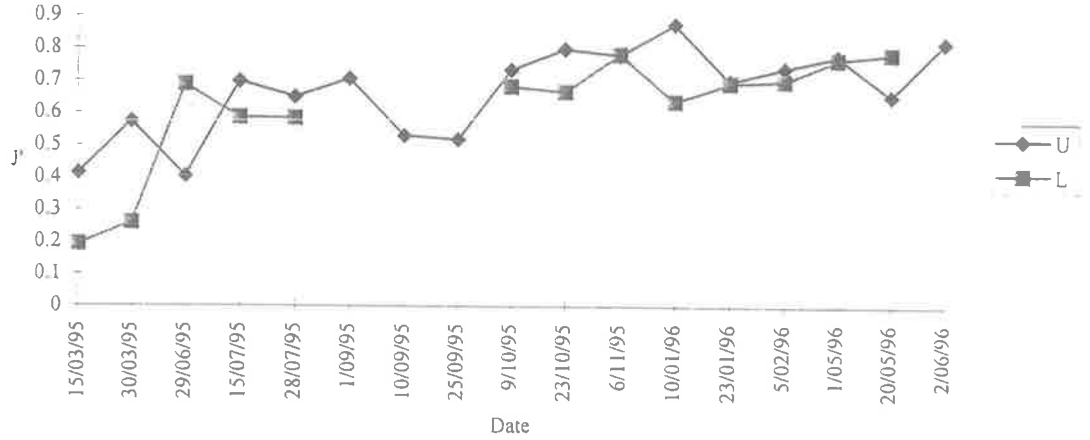
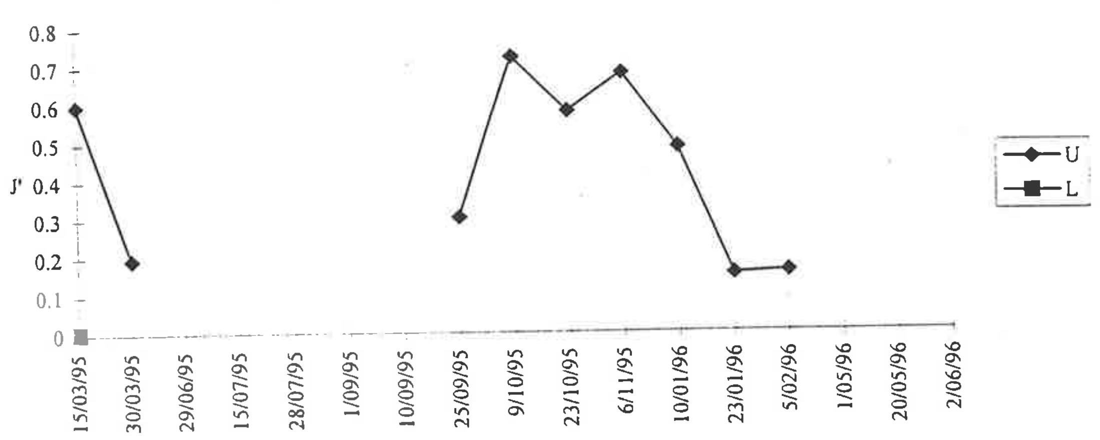
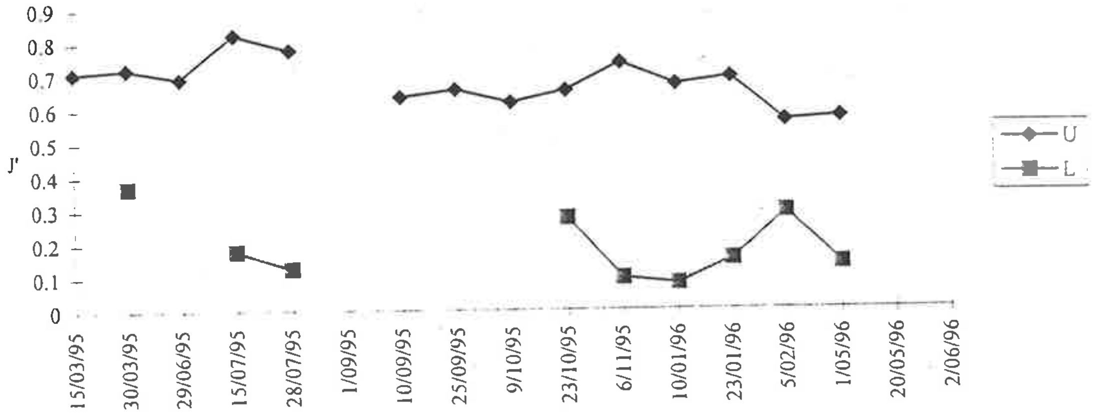


Fig. 4.48 Species evenness, quantified as Pielou's Evenness (J'), recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Central' sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. Species evenness has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) WB



b) PNS



c) RP

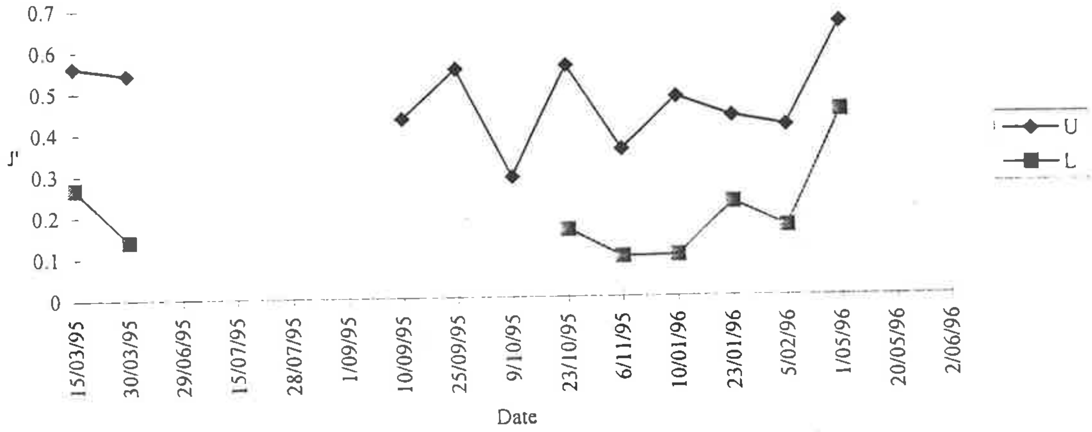


Fig. 4.49 Species evenness, quantified as Pielou's Evenness (J'), recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Southern' sites; a) Witton Bluff (WB), b) Port Noarlunga South (PNS) and c) Robinson Point (RP). Species evenness has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

Simpson's Dominance Index

Simpson's Dominance Index (SI), essentially the inverse of Pielou's Evenness Index, was used as an adjunct to the evenness index to assess temporal patterns at study sites. This index revealed that all study sites with low evenness values had high dominance values and vice versa (Figs 4.50, 4.51 & 4.52). Sites where a single species dominated were characterised by a high dominance score (approaching 1) and included the 'upper' zone at PS1 (dominated by *B. nanum*), and the 'lower' zones at 'Southern' sites (which were heavily dominated by mussels, particularly *X. pulex*).

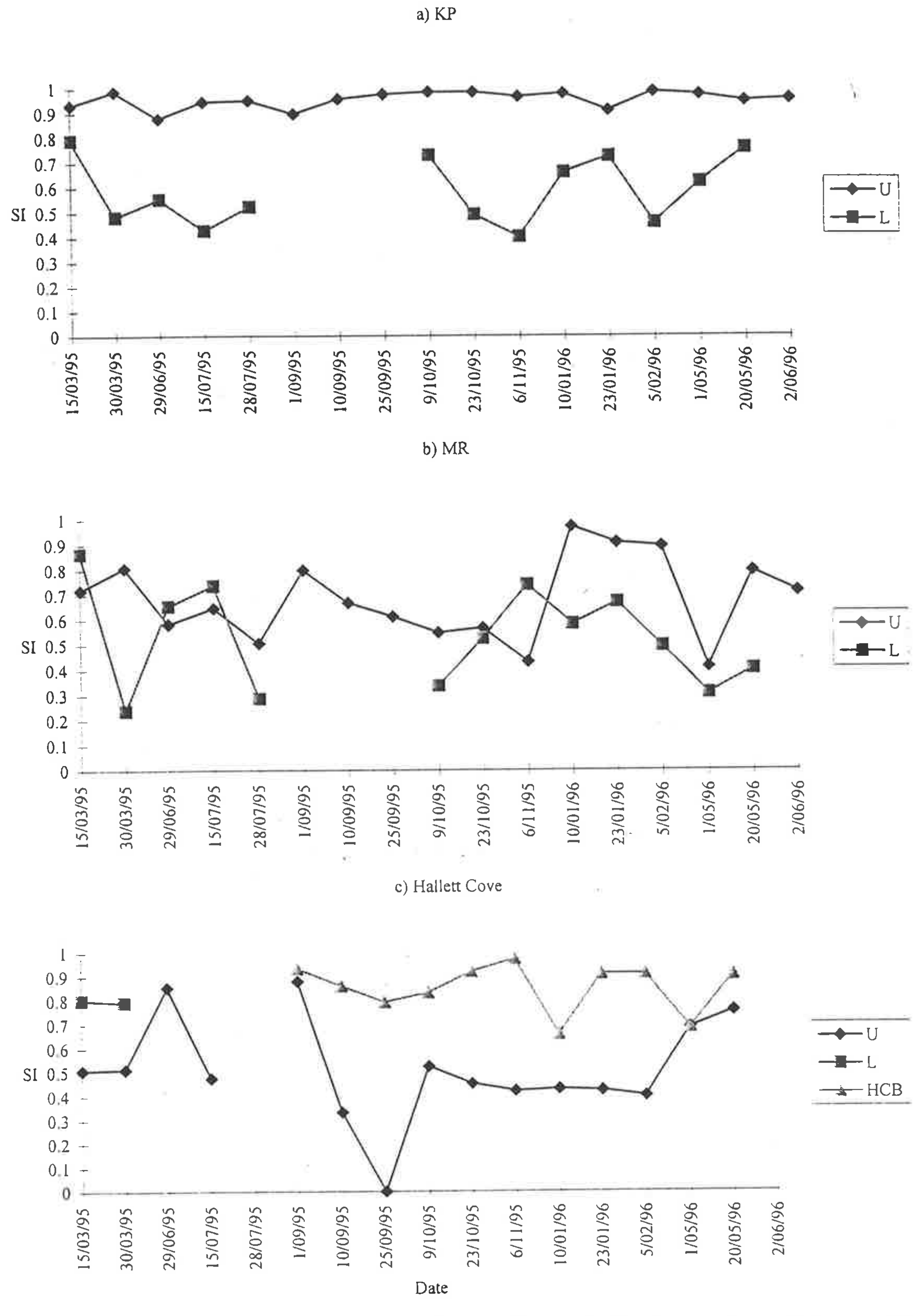
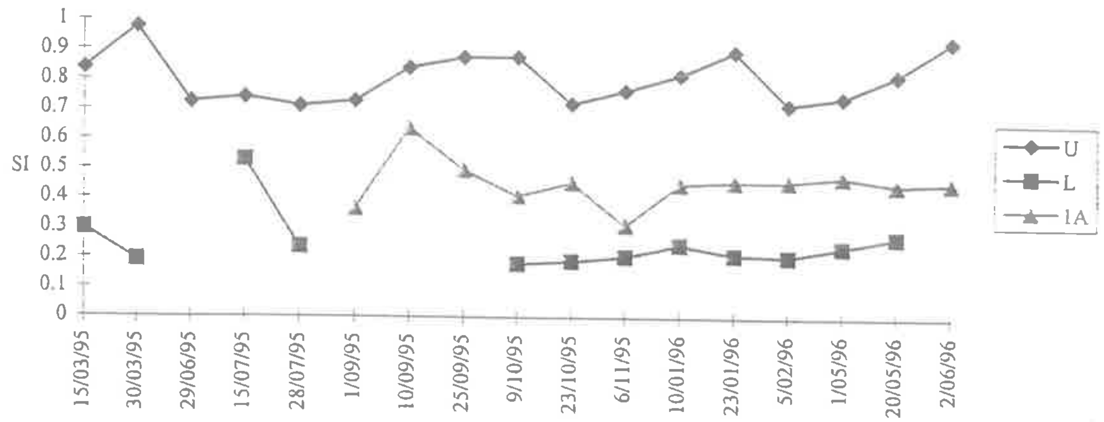
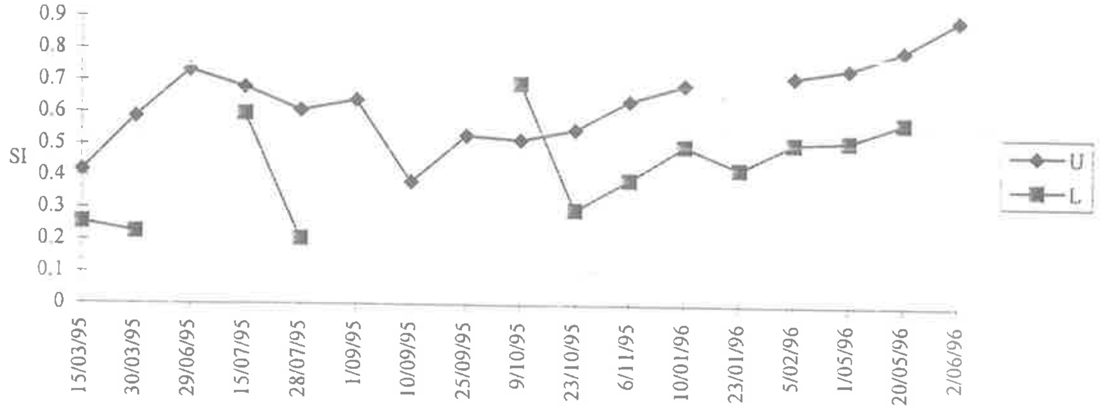


Fig. 4.50 Species dominance, quantified by the Simpson's Dominance Index (SI), recorded in the 'upper' (U) and 'lower' (L) zones at 'Northern' sites; a) Kingston Park (KP), b) Marino Rocks (MR) and c) Hallett Cove (HCA & HCB). The 'upper' (U) and 'lower' (L) series shown in c) refer to these zones at HCA. Species dominance has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats deployed in each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

a) PS1



b) PS2



c) PS3

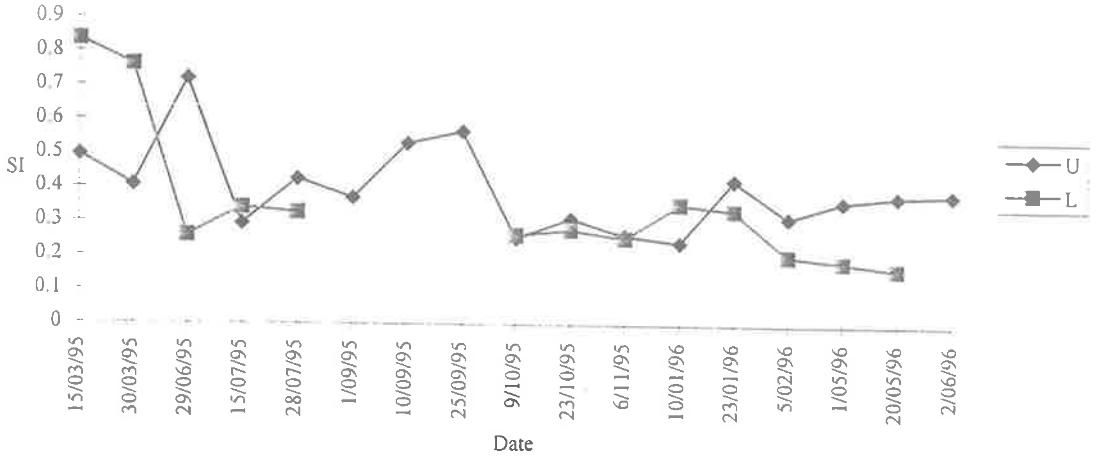


Fig. 4.51 Species dominance, quantified by the Simpson's Dominance Index (SI), recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Central' sites; a) PS1 & PS1A, b) PS2 and c) PS3. The 'upper' (U) and 'lower' (L) series shown in a) refer to these zones at PS1. Species dominance has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats at each zone. Sampling times shown on the x-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

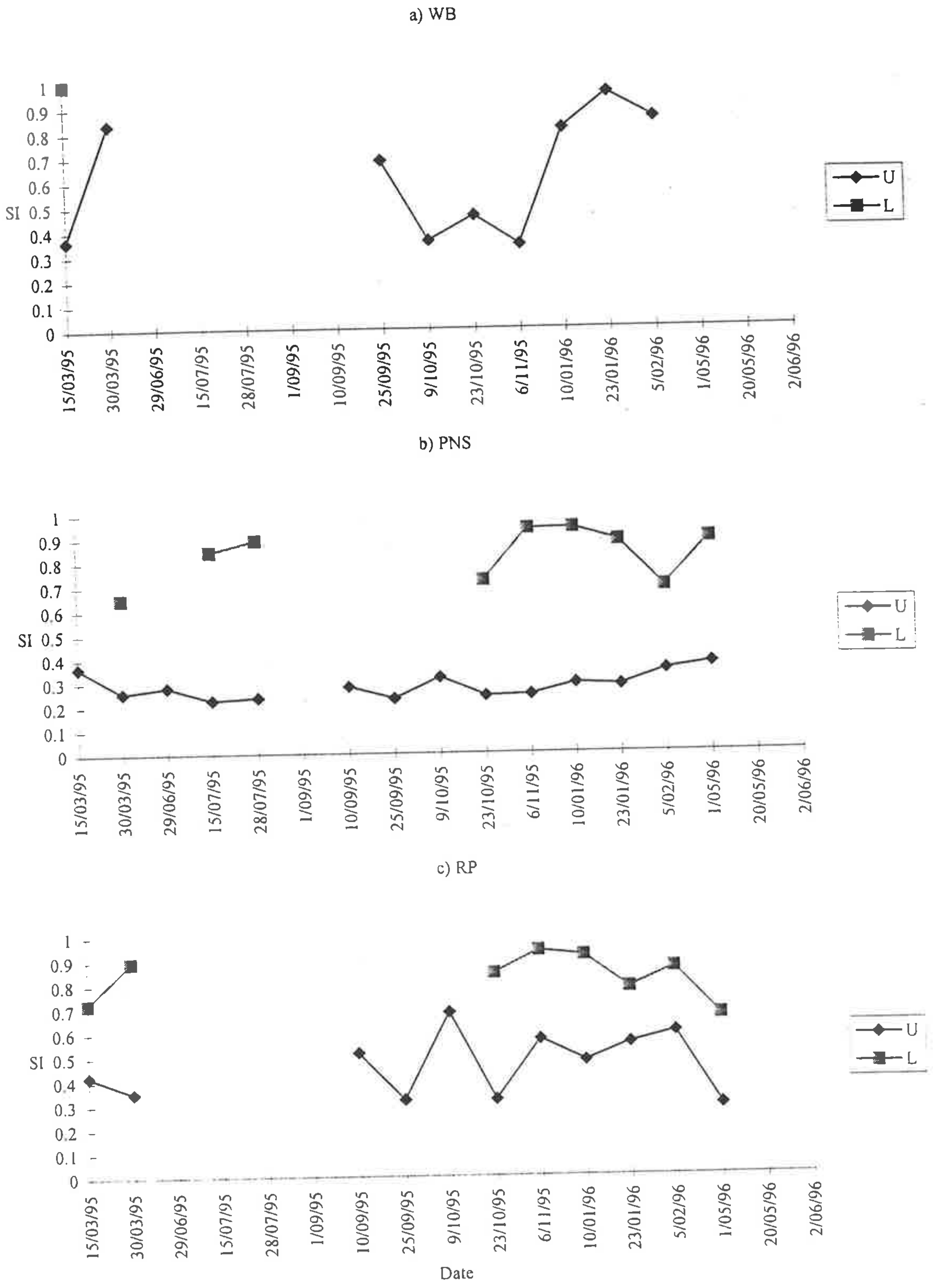


Fig. 4.52 Species dominance, quantified by the Simpson's Dominance Index (SI), recorded in the 'upper' (U) and 'lower' (L) zones is shown for 'Southern' sites; a) Witton Bluff (WB), b) Port Noarlunga South (PNS) and c) Robinson Point (RP). Species dominance has been calculated from raw 'preliminary' data summed across the seven 0.25m^2 quadrats at each zone. Sampling times shown on the *x*-axis have been regularly spaced for ease of interpretation but actual sampling intervals were irregular (refer to section 4.3).

4.4.3.6 The 'Sand-Drift' Perturbation and the Beyond-BACI Analysis

The initial analysis of changes in *B. nanum* abundance at selected study sites (using "GMAV5") revealed that variances were heterogeneous even after a number of transformations were tried (Cochran's C= 0.0991 $P<0.05$). Data were, in general, normally distributed (tested using the Anderson-Darling (AD) and Student-Newman-Keuls test) but after a $\log_{10}(x+1)$ transformation 6 groupings remaining above the critical (0.05) AD stat level of 0.652. Despite the fact that two assumptions of ANOVA were violated it was decided to proceed with the analysis using $\log_{10}(x+1)$ transformed data. This was advocated as sample sizes were equal, extreme heterogeneity of variances were not displayed (Zar 1984), the majority of factors were normally distributed, and the primary aim of the exercise was to test the effectiveness of a Beyond-BACI design and analysis.

The Beyond-BACI ANOVA using the 'sand' perturbation data set was carried out as described by Underwood (1993a). Using "GMAV5" (Appendix N) four intermediate ANOVA results were generated (Table 4.9) and these variances were used to calculate the final ANOVA variances (Table 4.10). A full description of methodology was given in section 4.3.2, "Analysis": *Beyond-BACI Analysis of 1995 Impacts.*

Table 4.9 Calculation of analyses of impact in an asymmetrical Beyond-BACI design using the 'sand' perturbation data set. Four separate ANOVAs were performed using various subsets of the full 'sand-impact' data set as described by Underwood (1993a). SS= sum of squares, df= degrees of freedom (After Underwood 1993a).

Analysis	**a (all data)**		**b (controls)**		**c (before)**		**d (before controls only)**	
Source of Variation	SS	df	SS	df	SS	df	SS	df
Before *vs* After = B	40.53	1	0.73	1	-	-	-	-
Periods = P(B)	7.41	2	7.10	2	6.19	1	7.09	1
Times = T(P*B)	4.01	4	3.96	4	2.03	2	2.76	2
Locations = L	166.30	5	153.71	4	62.65	3	25.76	4
B x L	178.76	5	31.44	4	-	-	-	-
P(B) x L	16.87	10	14.23	8	11.00	5	10.58	4
T(P*B) x L	36.88	20	20.78	16	14.12	10	10.64	8
Residual	97.14	288	73.24	240	44.41	144	37.45	120
Total	547.89	335	305.18	279	141.11	167	94.28	139

Table 4.10 Calculation of final variances following the 'sand' perturbation at HCA. A Beyond-BACI design and ANOVA were used and the tabled values were calculated using the preliminary analyses shown in Table 4.9. The methodology was discussed in section 4.3.2, "Analysis": *Beyond-BACI Analysis of 1995 Impacts*, and is shown in Tables 4.6 and 4.7. SS= sum of squares, df= degrees of freedom (After Underwood 1993a).

Source of variation	SS	df	MS	Calculated from
Before *vs* After = B	40.53	1	40.53	a
Periods (P) = P(B)	7.41	2	3.71	a
Times (B) = T(B)	4.01	4	1.00	a
Locations = L	166.30	5	33.26	a1
Impact *vs* Controls = I	12.59	1	12.59	a1-b1
Among Controls = C	153.71	4	38.43	b1
B x L	178.76	5	35.75	a2
B x I	147.32	1	147.32	a2-b2
B x C	31.44	4	7.86	b2
P(B) x L	16.87	10	1.69	a3
P(Bef) x L	11.00	5	2.20	c1
P(Bef) x I	0.42	1	0.42	c1-d1
P(Bef) x C	10.58	4	2.65	d1
P(Aft) x L	5.88	5	1.18	a3-c1
P(aft) x I	2.23	1	2.23	a3-c1-b3+d1
P(Aft) x C	3.65	4	0.91	b3-d1
T(B*P) x L	36.88	20	1.84	a4
T(Bef) x L	14.11	10	1.41	c2
T(Bef) x I	3.47	2	1.74	c2-d2
T(Bef) x C	10.64	8	1.33	d2
T(Aft) x L	22.77	10	2.28	a4-c2
T(Aft) x I	12.63	2	6.32	a4-c2-b4+d2
T(Aft) x C	10.14	8	1.27	b4-d2
Residual	97.14	288	0.34	a
Total	547.89	335		a

The variances in Table 4.10 were used to test whether the 'sand' perturbation had a significant effect on the abundance of *B. nanum* at the impact site (HCA) compared to this parameter, on average, at the set of control sites. A series of tests were performed to calculate the variances of interest as described by Underwood (1993a). The results were presented in the same format as used by Underwood (1993a). A result which was significant at the 0.05 level was given a ** code, while a result which was significant at the 0.01 level was coded as ***.

1. Test for an interaction among 'Times' that differs between impact and control locations:

   T(Aft)xC /Res = 3.76, $F_{crit(1)0.05,8,288}$ = 1.97 (P=0.00)***. Significant short term temporal interaction between controls.

   T(Aft)xI /T(Aft)xC = 4.98, $F_{crit(1)0.05,2,8}$ = 4.46 (P=0.04)**. Significant short term interaction 'After' the perturbation.

   T(Aft)xI /T(Bef)xI = 3.64, $F_{crit(2)0.05,2,2}$ = 39, (P=0.22). Non-significant effect. The effect is not specific to the 'impact' location. <u>No impact detected at the temporal scale of 'Times'</u>.

2. Test for an interaction among 'Periods' that differs between impact and control locations:

   P(Aft)xC /Res = 2.70, $F_{crit(1)0.05,4,288}$ = 2.40 (P=0.03)**. Significant effect detected, indicating a medium-term temporal interaction among control sites.

   P(Aft)xI /P(Aft)xC = 2.44, $F_{crit(1)0.05,1,4}$ = 7.71 (P=0.19). Non-significant difference. <u>No medium-term impact detected at the temporal scale of 'Periods'</u>.

3. Test for a longer term interaction that differs in control and impact locations:

   BxC /Res = 23.30, $F_{crit(1)0.05,4,288}$ = 2.40 (P=0.00)***. Significant impact detected, indicating a 'Before/After' interaction among controls.

   BxI / BxC = 18.74, $F_{crit(1)0.05,1,4}$ = 7.71 (P=0.01)***. Significant effect detected, indicating an effect at the temporal scale of 'Before/After'. <u>Impact detected at the temporal scale of 'Before/After'</u>.

The power of the analysis to detect an impact at the temporal scale of 'Times' and 'Periods' was found to be 0.85 and 0.44 respectively. This was calculated as described in Underwood (1993) using the formula:

$F_{crit}/(1+n\varnothing)$, where $1+n\varnothing$ =MS T(Aft)xI /MS Res (or MS P(Aft)xI /MS Res)

The value obtained was then converted to 'Power' (P) by using the *F distribution* function in "MICROSOFT OFFICE": "Excel", Version 3.0. For further discussion of the theory behind the calculation of power refer to Underwood (1993a). Calculations are shown below:

The power (P) of the analysis to detect an impact at the temporal scale of 'Times';

$F_{crit(1)0.05,2,288}$/(T(Aft)xI /Res) = 3.03/18.73 = 0.16, *Fdist* (0.16,2,288)= P = 0.85.

The power of the analysis to detect an impact at the temporal scale of 'Periods';

$F_{crit(1)0.05,1,288}$/(P(Aft)xI /Res) = 3.87/6.61 = 0.59, *Fdist*(0.59,1,288)= P = 0.44.

4.4.3.7 The 'Effluent' Perturbation and the Beyond-BACI Analysis

The water samples collected from the ruptured pipe within the Port Stanvac Oil Refinery revealed no detectable levels of oil and grease, but sulphide, chromium and phenol were detected at levels within the average 1994 range listed as acceptable for discharge (Tables 4.11 & 4.1). However, the point of rupture of the effluent pipe exposed the intertidal assemblage directly to the refinery effluent and its mixture of contaminants, which are normally discharged subtidally. Two features of the effluent water which had the potential to affect intertidal animals were its temperature, which was 5-13°C higher than adjacent water, and its freshness, indicated by a specific conductivity of 9.47mS compared to 52.57mS in adjacent water. The discharged effluent water was also less alkaline than adjacent water; 7.28 compared with a pH of 8.35.

Table 4.11 Results of the ANALAB analysis of duplicate water samples collected from the Port Stanvac effluent pipe at the rupture point on the 30th of August 1995.

Substance	Water sample 1 (ppm)	Water sample 2 (ppm)
Chromium (Cr)	0.08	0.08
Sulphide (S)	5.40	2.40
Total Phenol	0.45	0.41
Oil & Grease	< 20	< 20

N.B. ppm (parts per million) =mg/L (milligrams per litre)

The discharge of effluent from the ruptured pipe was estimated to be at a rate of $0.009m/s^3$, and was calculated as described by Wetzel and Likens (1991) using the formula; $Q=A\upsilon$, where Q=discharge (m^3/s), A=cross-sectional area (m^2), and υ=mean velocity (m/s). Values requiring measurement (flow rate, wetted perimeter, surface width and water depth) were assessed on the 30th of August 1995 and the remaining values calculated (Table 4.12). The velocity used to calculate discharge was the actual instantaneous velocity (averaged over three readings) recorded on the 30th of August 1995. This was not reassessed on later visits to Port Stanvac and may not accurately represent the true velocity range for the duration of the discharge.

Table 4.12 Parameters measured or calculated in relation to the ruptured refinery effluent pipe. The first four parameters in this table were measured on the 30th of August 1995. The remaining two parameters were then calculated according to Wetzel and Likens (1991).

Parameter Assessed	Resultant Value
Flow rate	0.2m/s
Wetted perimeter	1m
Surface width	0.8m
Water depths	3,8,3,8,7cm
Cross-sectional area	$0.047m^2$
Discharge	$0.009m^3/s$

N.B. m=metres, s=seconds

The Beyond-BACI analyses to assess the impact of the effluent discharge on the abundance of *B. nanum* were performed in the same way as for the 'sand' perturbation data. The preliminary analysis using "GMAV5" revealed the data to have heterogeneous variances (Cochran's C= 0.1185, $P<0.01$) and non-normality even after transformation (assessed using the AD statistic). Despite this the analyses were completed using $\log_{10}(n+1)$ transformed data for the reasons described previously in reference to the 'sand-impact' data. The raw results of the four analyses (Table 4.13) were used to generate the final ANOVA table (Table 4.14) as previously described.

Table 4.13 Calculation of analyses of impact in an asymmetrical Beyond-BACI design using the 'effluent' perturbation data set. Four separate ANOVAs were performed using various subsets of the full data set (see text and Underwood (1993a) for full details). SS= sum of squares, df= degrees of freedom (After Underwood 1993a).

Analysis	**a (all data)**		**b (controls)**		**c (before)**		**d (before controls)**	
Source of Variation	SS	df	SS	df	SS	df	SS	df
Before *vs* After = B	11.40	1	5.19	1	-	-	-	-
Periods = P(B)	10.35	2	15.22	2	9.20	1	12.49	1
Times = T(P*B)	15.35	8	12.66	8	2.65	4	3.48	4
Locations = L	272.03	5	264.51	4	53.15	5	41.85	4
B x L	56.34	5	52.30	4	-	-	-	-
P(B) x L	34.17	10	27.92	8	25.15	5	21.65	4
T(P*B) x L	51.59	40	36.04	32	27.02	20	21.53	16
Residual	135.36	432	108.37	360	61.29	216	54.76	180
Total	586.59	503	522.13	419	178.46	251	155.77	209

Table 4.14 Calculation of final variances following the 'effluent' perturbation at PS1A. A Beyond-BACI design and ANOVA were used and the tabled values were calculated using the preliminary analyses shown in Table 4.13. Analysis methodology was discussed in section 4.3.2 "Analysis": *Beyond-BACI Analysis of 1995 Impacts* and is shown in Tables 4.6 and 4.7. SS= sum of squares, df= degrees of freedom (After Underwood 1993a).

Source of variation	**SS**	**df**	**MS**	**Calculated from**
Before *vs* After = B	11.40	1	11.4	a
Periods (P) = P(B)	10.35	2	5.18	a
Times (B) = T(B)	15.35	8	1.92	a
Locations = L	272.03	5	54.41	a1
Impact *vs* Controls = I	7.52	1	7.52	a1-b1
Among Controls = C	264.51	4	66.13	b1
B x L	56.34	5	11.27	a2
B x I	4.04	1	4.04	a2-b2
B x C	52.30	4	13.07	b2
P(B) x L	34.17	10	3.42	a3
P(Bef) x L	25.15	5	5.03	c1
P(Bef) x I	3.50	1	3.50	c1-d1
P(Bef) x C	21.65	4	5.41	d1
P(Aft) x L	9.02	5	1.80	a3-c1
P(aft) x I	2.75	1	2.75	a3-c1-b3+d1
P(Aft) x C	6.28	4	1.57	b3-d1
T(B*P) x L	51.59	40	1.29	a4
T(Bef) x L	27.02	20	1.35	c2
T(Bef) x I	5.48	4	1.37	c2-d2
T(Bef) x C	21.53	16	1.35	d2
T(Aft) x L	24.57	20	1.23	a4-c2
T(Aft) x I	10.06	4	2.52	a4-c2-b4+d2
T(Aft) x C	14.50	16	.91	b4-d2
Residual	135.36	432	0.31	a
Total	586.59	503		a

The variances in Table 4.14 were used to test the significance of the effluent discharge on the abundance of *B. nanum* at PS1A compared to the set of control sites. A series of tests were performed to calculate the significance of the variances of interest as described by Underwood (1993a). The results have been presented in the format used by Underwood (1993a). A result which is significant at the 0.05 level was scored **, and a result which is significant at the 0.01 probability level (*P*) was scored ***.

1 Test for an interaction among 'Times' that differs between impact and control locations:

T(Aft)xC /Res = 2.89, $F_{crit(1)0.05,16,432}$ = 1.67 (*P*=0.00)***. Significant short term temporal interaction between controls, with control locations showing variable short-term trends after the effluent disturbance.

T(Aft)xI /T(Aft)xC = 2.78, $F_{crit(1)0.05,4,16}$ = 3.01 (*P*=0.06). Non-significant difference, no short term interaction detected. No impact detected at the temporal scale of 'Times'.

2. Test for an interaction among 'Periods' that differs between impact and control locations:

P(Aft)xC /Res = 5.01, $F_{crit(1)0.05,4,432}$ = 2.40 (*P*=0.00)***. Significant effect detected, indicating a medium-term temporal interaction among control sites.

P(Aft)xI /P(Aft)xC = 1.75, $F_{crit(1)0.05,1,4}$ = 7.71 (*P*=0.26). Non-significant difference. No medium-term impact detected at the temporal scale of 'Periods'.

3. Test for a longer term interaction that differs in control and impact locations:

BxC /Res = 41.73, $F_{crit(1)0.05,4,432}$ = 2.40 (*P*=0.00)***. Significant impact detected, indicating a 'Before/After' interaction among controls.

BxI /BxC = 0.31, $F_{crit(1)0.05,1,4}$ = 7.71 (*P*=0.61). No significant effect detected. No impact detected at the temporal scale of 'Before/After'.

The power (P) of the analysis to detect an impact at the temporal scale of 'Times' and 'Periods' was found to be 0.88 and 0.51 respectively. This was calculated as shown below and as previously described for the 'sand' perturbation data:

$F_{crit}/(1+n\varnothing)$, where $1+n\varnothing$ = MS T(Aft)xI /MS Res (or MS P(Aft)xI /MS Res)

The power of the analysis to detect an impact at the temporal scale of 'Times';

$F_{crit(1)0.05,4,432}$/(T(Aft)xI /Res) = 2.39/8.03 = 0.29, *Fdist*(0.29,4,432)= P = 0.88.

The power of the analysis to detect an impact at the temporal scale of 'Periods';

$F_{crit(1)0.05,1,432}$ /(P(Aft)xI /Res) = 3.86/8.76 = 0.44, *Fdist*(0.44,1,432)= P = 0.51.

The ANOVA had a very low power to detect an impact at the temporal scale of 'Periods'. The implications of this will be mentioned later in this chapter and discussed in more detail in reference to planning of the ongoing monitoring program (see Chapter 8).

4.4.3.8 An Overview of the Beyond-BACI Analyses and Consideration of Serial Correlation in the 'Sand-Impact' and 'Effluent-Impact' Data Sets

The results of the Beyond-BACI analyses for both the 'sand' and the 'effluent' perturbations are summarised in Table 4.15. The only perturbation which was found to have a significant effect on *B. nanum* abundance during preliminary sampling was the sand influx, and this effect was present only at the longest temporal scale of 'Before/After'. However, due to the early intervention of both perturbations the power to detect an impact at the temporal scale of 'Times' and 'Periods' for both data sets was lower than the optimal level of 0.95 (refer to Chapter 2). The low power was of particular concern in detecting either disturbance at the temporal scale of 'Periods'.

Table 4.15 Summary results pertaining to the Beyond-BACI Analysis of the 'sand' and 'effluent' perturbations which intervened in 1995 during preliminary sampling of study sites. Three temporal scales of interest were examined in reference to the two impacts. Refer to the text for further details.

Impact	Temporal Scale Being Tested		
	Short term ('Times')	Medium term ('Periods')	Longer term ('Before vs After')
Sand drift	0.43 NS	0.19 NS	0.00 ***
Ruptured pipe	0.06 NS	0.26 NS	0.61 NS

NS = Non-significant at 0.05 level, **= significant at 0.05 level, ***= significant at the 0.01 level

Another potential problem associated with the 'sand' and 'effluent' data sets was serial correlation (Stewart-Oaten *et al.* 1986). Such a problem violates a major underlying assumption of most statistical procedures (Underwood 1981a & 1993a) as previously described (Chapter 2). Both data sets were analysed for the existence of serial correlation which was found to be present at insignificant levels (0.011) (see Appendix O).

4.4.3.9 Multivariate Analysis and Assemblage Patterns

Animal taxa recorded in the sampled zones at study sites during 1995 and 1996 have been listed in Appendix P and have been included in multivariate analysis unless precluded on the basis of rarity (see section 4.3.2).

4.4.3.9.1 Cluster Analysis

The dendrogram (Fig. 4.53) was generated from hierarchical polythetic agglomerative clustering and UPGMA performed in "PATN" (Belbin 1992) to separate study sites on the basis of their taxa. The dendrogram revealed 14 groups with varying numbers of members and degrees of dissimilarity. To aid in interpretation of the dendrogram two tables were generated, the first of which shows how sites in each dendrogram group fit important physical categories including; location, zone, season, year, stability and impacted status (Table 4.16a). The second table presents the same data converted to proportions to place the dendrogram groupings within a global context (Table 4.16b).

The various study sites assessed during preliminary sampling did not separate out strongly within the dendrogram groupings although they tended to be most heavily represented by one or a few dendrogram groups. For example, PS1 was more common in groups 5 and 13 and HCB was most common in groups 5 and 7 (Table 4.16b). Apart from group 13, which supported more than twice as many 'upper' zone members as 'lower' zone members, the relative distribution of zones within these two subcategories tended to be roughly evenly distributed between all dendrogram groups. Less equality in distribution was found in dendrogram groups in terms of the proportion of members falling into the three location categories of 'Northern', 'Central' and 'Southern'. For example, 'Southern' sites tended to be concentrated in groups 5 and 6, although these groups also supported high numbers of 'Central' sites.

Dendrogram group members did not appear to be strongly aggregated according to seasonality although a bias towards sites which were sampled in summer was seen in members of group 10 (Table 4.16b). A feature of the dendrogram groups was a tendency for members to be equally divided on the basis of sampling year but a strong yearly bias was seen in groups 2 and 6. A heavy aggregation of 'unstable' sites was seen in group 5 while a tendency for the reverse bias was revealed in group 13. However, little difference in stability was seen between members belonging to the other 12 groups (Table 4.16b). Aggregations of post 'effluent-impact' (PS1A) sites were found in groups 5, 6, 11 and 13, with two of the three group 11 members being in this category (Table 4.16a). 'Post-sand-impact' HCA sites occurred in high proportions in groups 2, 10 and 14 while 'pre-sand-impact' (HCA) sites were concentrated in groups 6, 7, 10, 12 and 13 (Table 4.16b).

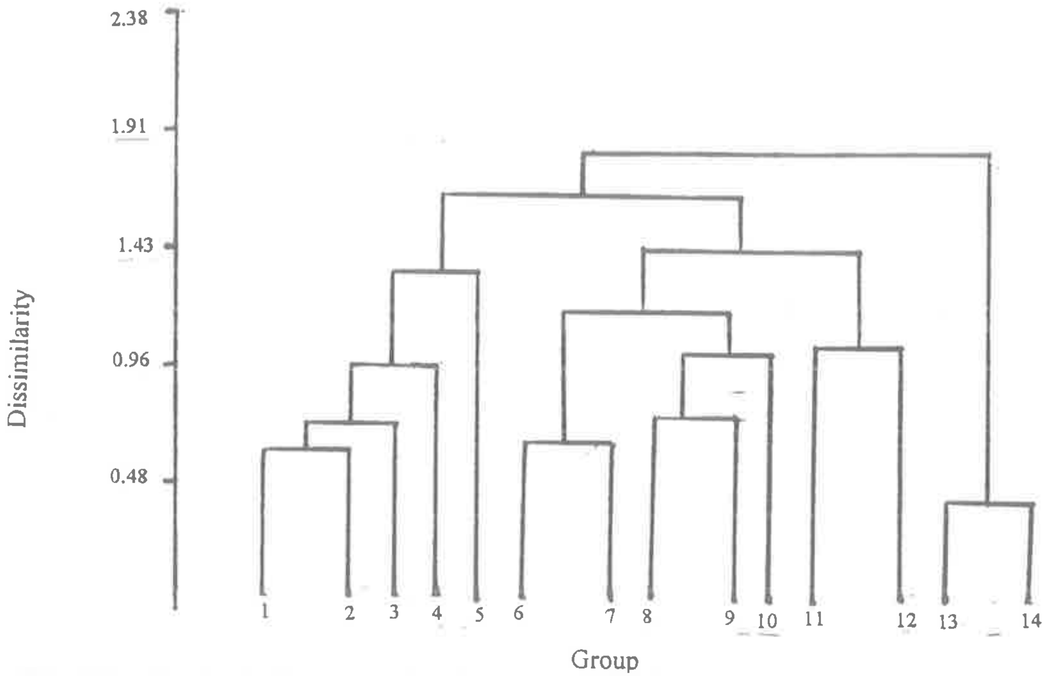


Fig. 4.53 The dendrogram was generated using polythetic agglomerative clustering and UPGMA to attempt to separate (or link) GSV study sites on the basis of the taxa they support. This analysis was performed in "PATN" (Belbin 1992) using the preliminary data collected during 1995 and 1996. The dendrogram shows site dissimilarity, with a low dissimilarity score between dendrogram groups reflecting a high similarity between the groups and the sites they contain. Fourteen groupings (labelled 1-14) have been recognised, the members of which are shown below in Tables 4.16a & b.

(opposite page)

Table 4.16a The fourteen groups identified in the dendrogram (Fig. 4.53) using the GDEF option in "PATN" (Belbin 1992) are presented. The number of members in each group (No.) and the breakdown of each group on the basis of study site, zone, season, substrata stability, impact status, location and year of census are shown. Substrata stability was determined on the basis of domination by embedded rock, immovable bedrock and the degree of shelter afforded by the structure of each site (see Table 4.2) while location was represented by the three categories of 'Northern' (N), 'Central' (C) and 'Southern' (S). Impact status was scored using three categories in reference to both the 'effluent-impact' and the 'sand-impact'; 0=unimpacted, 1='impact' site pre-impact, 2='impact' site post-impact. Season was represented by; A=Autumn, S=Summer, Sp=Spring, W=Winter, while site abbreviations were; 1=PS1, 2=PS2, 3=PS3, 1A=PS1A, 11=Kingston Park, 12=Marino Rocks, 13=HCA, 14=HCB, 21=Witton Bluff, 22=Port Noarlunga South and 23=Robinson Point. Zone abbreviations were; U='upper' and L='lower', and the year of census was coded as; 1=1995 and 2=1996.

Gp	No.	Sites											Zone		Location			Season				Year		Stable		'Effluent'			'Sand'		
		1	1A	2	3	11	12	13	14	21	22	23	U	L	N	C	S	A	S	Sp	W	1	2	No	Yes	0	1	2	0	1	2
1	15	3	0	1	4	2	2	0	1	0	2	0	8	7	5	8	2	5	3	4	3	12	3	8	7	15	0	0	15	0	0
2	12	2	1	1	0	2	3	2	1	0	0	0	10	2	8	4	0	1	0	7	4	12	0	4	8	11	0	1	10	0	2
3	4	1	0	0	1	0	1	0	1	0	0	0	3	1	2	2	0	0	1	2	1	1	3	3	1	4	0	0	4	0	0
4	15	2	1	2	2	2	2	1	0	1	1	1	11	4	5	7	3	5	3	6	1	10	5	7	8	14	1	0	14	0	1
5	55	6	4	5	10	6	5	1	3	3	7	5	37	18	15	25	15	13	9	21	12	35	20	24	1	51	0	4	54	0	1
6	50	3	2	9	9	5	2	4	1	3	6	6	31	19	12	23	15	10	8	24	8	39	11	21	29	48	0	2	46	3	1
7	17	0	1	0	0	2	6	1	2	1	1	3	13	4	11	1	5	3	4	9	1	12	5	6	11	16	0	1	16	1	0
8	6	1	0	1	0	2	2	0	0	0	0	0	3	3	4	2	0	2	0	1	3	4	2	3	3	6	0	0	6	0	0
9	11	0	0	5	2	2	0	0	0	0	1	1	5	6	2	7	2	2	2	4	3	7	4	7	4	11	0	0	11	0	0
10	20	1	0	2	2	2	3	3	1	1	2	3	11	9	9	5	6	3	10	7	0	8	12	7	13	20	0	0	16	2	2
11	3	0	2	0	1	0	0	0	0	0	0	0	3	0	0	3	0	1	1	1	0	1	2	1	2	1	0	2	3	0	0
12	5	0	0	0	0	3	1	1	0	0	0	0	3	2	5	0	0	0	0	3	2	5	0	1	4	5	0	0	4	1	0
13	27	10	1	3	0	3	2	2	1	1	4	0	21	6	8	14	5	7	3	11	6	17	10	9	18	26	0	1	25	1	1
14	5	1	0	0	0	0	2	2	0	0	0	0	4	1	4	1	0	1	1	3	0	4	1	3	2	5	0	0	3	0	2

(opposite page)

Table 4.16b The groupings shown in the above dendrogram (Fig. 4.53) are again presented but the members of each group within the major defining categories (see Table 4.16a) have been converted to proportions of the total number of samples within each of the categories. Abbreviations for each of the categories are as described for Table 4.16a.

Gp	No.	Sites											Zone		Location			Season				Year		Stable		'Effluent'			'Sand'		
		1	1A	2	3	11	12	13	14	21	22	23	U	L	N	C	S	A	S	Sp	W	1	2	No	Yes	0	1	2	0	1	2
1	0.06	0.10	0.00	0.03	0.13	0.06	0.06	0.00	0.09	0.00	0.08	0.00	0.05	0.08	0.06	0.08	0.04	0.09	0.07	0.04	0.07	0.07	0.04	0.08	0.05	0.06	0.00	0.00	0.07	0.00	0.00
2	0.05	0.07	0.08	0.03	0.00	0.06	0.10	0.12	0.09	0.00	0.00	0.00	0.06	0.02	0.09	0.04	0.00	0.02	0.00	0.07	0.09	0.07	0.00	0.04	0.06	0.05	0.00	0.09	0.04	0.00	0.20
3	0.02	0.03	0.00	0.00	0.03	0.00	0.03	0.00	0.09	0.00	0.00	0.00	0.02	0.01	0.02	0.02	0.00	0.00	0.02	0.02	0.02	0.01	0.04	0.03	0.01	0.02	0.00	0.00	0.02	0.00	0.00
4	0.06	0.07	0.08	0.07	0.06	0.06	0.06	0.06	0.00	0.10	0.04	0.05	0.07	0.05	0.06	0.07	0.06	0.09	0.07	0.06	0.02	0.06	0.06	0.07	0.06	0.06	1.00	0.00	0.06	0.00	0.10
5	0.22	0.20	0.33	0.17	0.32	0.19	0.16	0.06	0.27	0.30	0.29	0.26	0.23	0.22	0.17	0.25	0.28	0.25	0.20	0.20	0.27	0.21	0.26	0.23	0.01	0.22	0.00	0.36	0.24	0.00	0.10
6	0.20	0.10	0.17	0.31	0.29	0.16	0.06	0.24	0.09	0.30	0.25	0.32	0.19	0.23	0.13	0.23	0.28	0.19	0.18	0.23	0.18	0.23	0.14	0.20	0.21	0.21	0.00	0.18	0.20	0.38	0.10
7	0.07	0.00	0.08	0.00	0.00	0.06	0.19	0.06	0.18	0.10	0.04	0.16	0.08	0.05	0.12	0.01	0.09	0.06	0.09	0.09	0.02	0.07	0.06	0.06	0.08	0.07	0.00	0.09	0.07	0.13	0.00
8	0.02	0.03	0.00	0.03	0.00	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.04	0.02	0.00	0.04	0.00	0.01	0.07	0.02	0.03	0.03	0.02	0.03	0.00	0.00	0.03	0.00	0.00
9	0.04	0.00	0.00	0.17	0.06	0.06	0.00	0.00	0.00	0.00	0.04	0.05	0.03	0.07	0.02	0.07	0.04	0.04	0.04	0.04	0.07	0.04	0.05	0.07	0.03	0.05	0.00	0.00	0.05	0.00	0.00
10	0.08	0.03	0.00	0.07	0.06	0.06	0.10	0.18	0.09	0.10	0.08	0.16	0.07	0.11	0.10	0.05	0.11	0.06	0.22	0.07	0.00	0.05	0.15	0.07	0.09	0.09	0.00	0.00	0.07	0.25	0.20
11	0.01	0.00	0.17	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.03	0.00	0.02	0.02	0.01	0.00	0.01	0.03	0.01	0.01	0.00	0.00	0.18	0.01	0.00	0.00
12	0.02	0.00	0.00	0.00	0.00	0.10	0.03	0.06	0.00	0.00	0.00	0.00	0.02	0.02	0.06	0.00	0.00	0.00	0.00	0.03	0.05	0.03	0.00	0.01	0.03	0.02	0.00	0.00	0.02	0.13	0.00
13	0.11	0.33	0.08	0.10	0.00	0.10	0.06	0.12	0.09	0.10	0.17	0.00	0.13	0.07	0.09	0.14	0.09	0.13	0.07	0.11	0.14	0.10	0.13	0.09	0.13	0.11	0.00	0.09	0.11	0.13	0.10
14	0.02	0.03	0.00	0.00	0.00	0.00	0.06	0.12	0.00	0.00	0.00	0.00	0.02	0.01	0.04	0.01	0.00	0.02	0.02	0.03	0.00	0.02	0.01	0.03	0.01	0.02	0.00	0.00	0.01	0.00	0.20

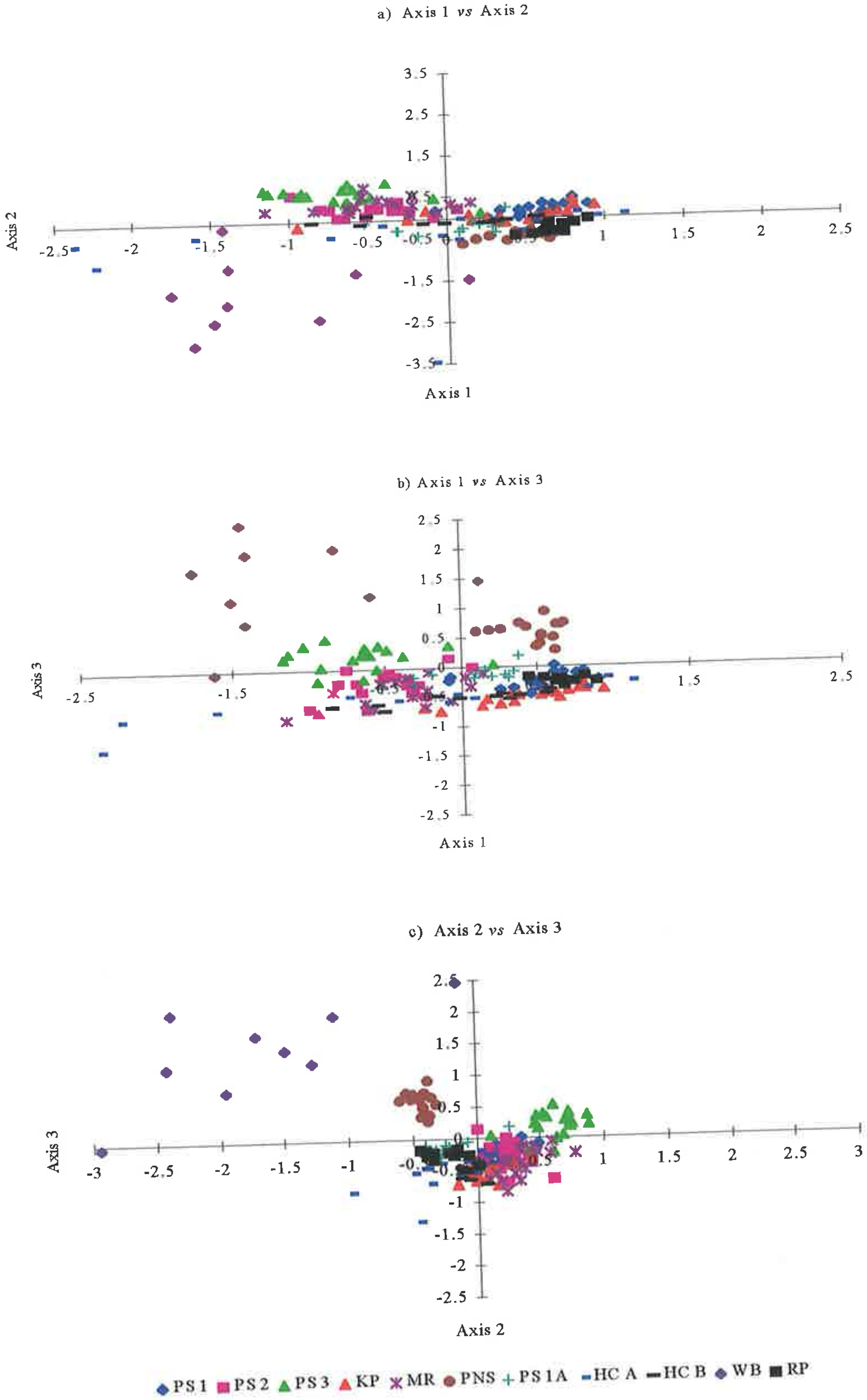
4.4.3.9.2 The Semi-Strong Hybrid (SSH) Multidimensional Scaling (MDS) Ordination

A three-dimensional ordination of all samples censused during 1995 and 1996 gave a satisfactory stress level (S=0.13) and enabled the position of study sites in multidimensional taxa space to be determined. All MDS graphs have been plotted as separate; Axis 1 *vs* Axis 2, Axis 1 *vs* Axis 3, and Axis 2 *vs* Axis 3 plots to facilitate interpretation of patterns. The full MDS Ordination (incorporating all data from all study sites sampled for the duration of preliminary monitoring) revealed that some of the sites grouped closely while others were more unique. The ordination results pertaining to the 'upper' zones (Fig. 4.54a, b & c) have been graphed separately to the 'lower' zones (Fig. 4.55a, b & c), and the results from both zones have been pooled to examine seasonal trends (Fig. 4.56a, b & c).

'Upper' Zones

The 'upper' zones at 'Southern' study sites tended to group out as discrete entities when various combinations of axes were examined. The majority of Witton Bluff data points separate from the other sites, and Port Noarlunga South and Robinson Point (although they show some overlap) tend to be distinguishable when plotted against Axis 1 and Axis 2 (Fig. 4.54a). Witton Bluff and Port Noarlunga South separated strongly when Axis 1 and Axis 3 were used but Robinson Point showed some overlap with PS1 and Kingston Park (Fig. 4.54b). Clear separation of Port Noarlunga South, Witton Bluff and the majority of the PS3 samples were seen when the ordination scores were plotted on Axis 2 and Axis 3 (Fig. 4.54c).

Although the data points representing the separate study sites tended to overlap to varying degrees (particularly when Axis 2 *vs* Axis 3 was used) they were still most heavily represented at slightly different positions on the ordination plots (Fig. 4.54a, b & c). This implies that although sites may share taxa similarities they also have some differences in taxa composition. HCA (the 'sand' perturbed site) exhibited a much higher amount of scatter on Axis 1 than any of the other study sites (Fig. 4.54a & b).


a) Axis 1 *vs* Axis 2

b) Axis 1 *vs* Axis 3

c) Axis 2 *vs* Axis 3

Fig. 4.54 The ordination positions of the 'upper' zones at study sites sampled during preliminary monitoring are shown. A three dimensional solution was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology). The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13) and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3. Site abbreviations are; 'Northern' sites- Kingston Park (KP), Marino Rocks (MR) & Hallett Cove (HCA & HCB), 'Central' sites- PS1, PS2, PS3 & PS1A, and 'Southern' sites- Witton Bluff (WB), Port Noarlunga South (PNS) & Robinson Point (RP).

'Lower' Zones

The 'lower' zones at study sites did not separate out as clearly as the 'upper' zones and the majority showed considerable overlap (Fig. 4.55a, b & c). However, Port Noarlunga South and Robinson Point data points were aggregated between -0.1 and -0.6 on Axis 2, with a wider scatter on Axis 1 which clearly differentiating them from the other study sites (Fig. 4.55a). The 'lower' zone at Witton Bluff was only sampled on one occasion but occupied a unique ordination position (Fig. 4.55a, b & c).

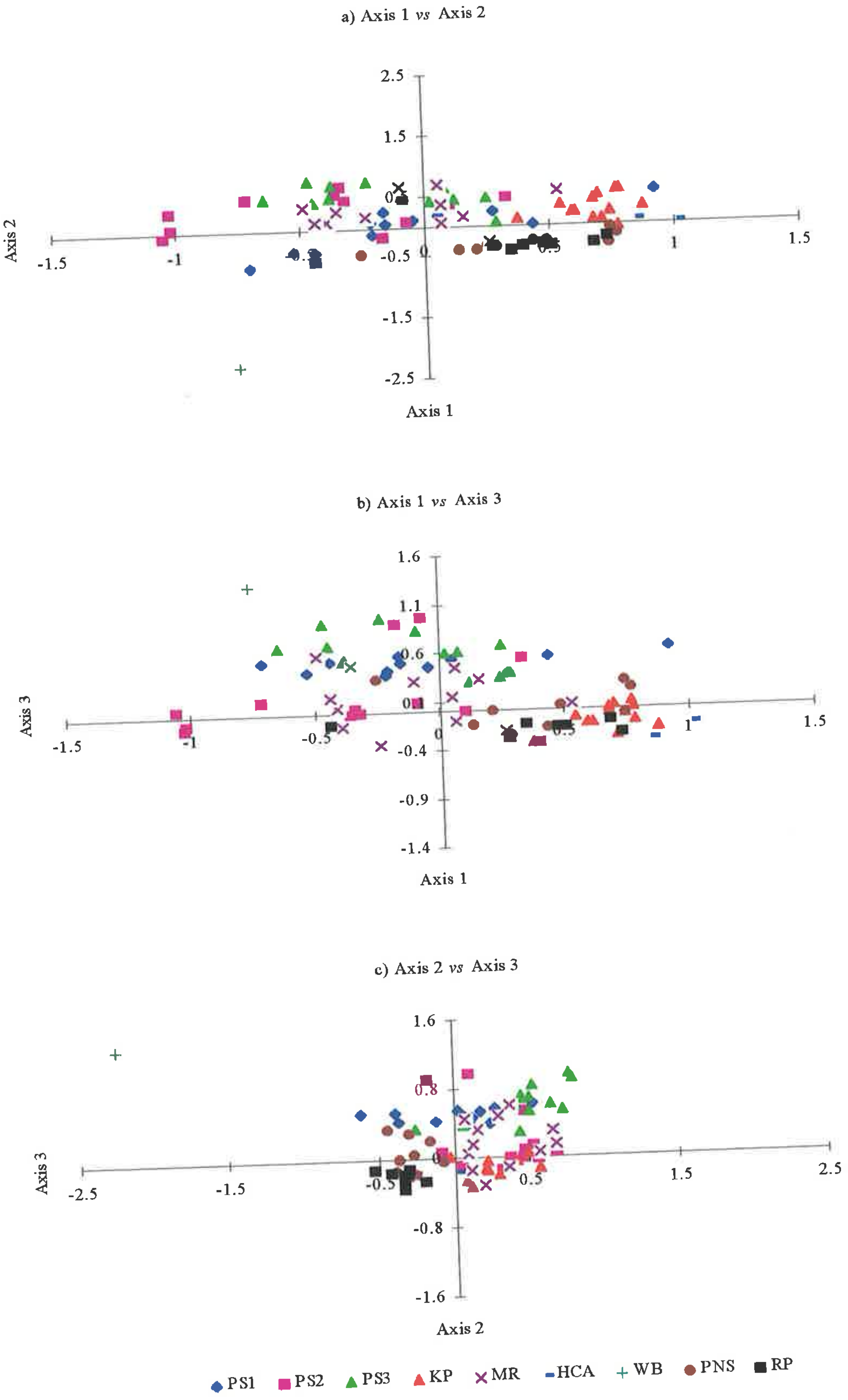
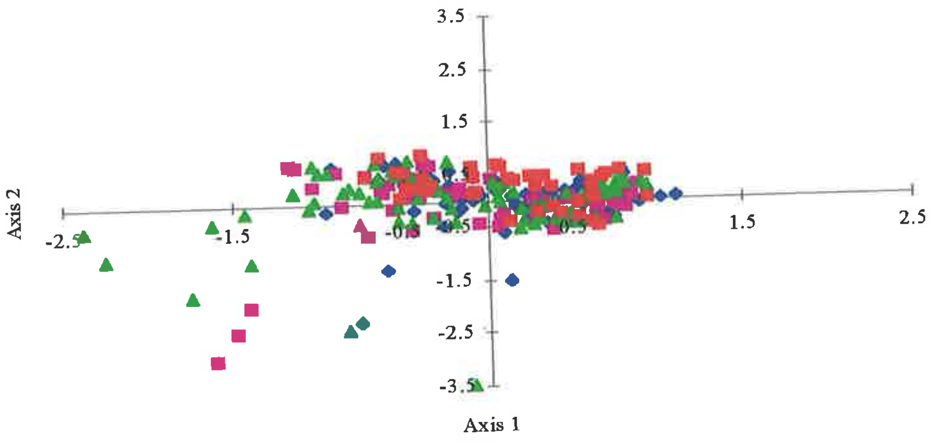


Fig. 4.55 The ordination positions of the 'lower' zones at study sites sampled during preliminary monitoring are shown. A three dimensional solution was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology). The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13) and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3. Site abbreviations are; 'Northern' sites- Kingston Park (KP), Marino Rocks (MR) & Hallett Cove (HCA), 'Central' sites- PS1, PS2 & PS3, and 'Southern' sites- Witton Bluff (WB), Port Noarlunga South (PNS) & Robinson Point (RP).

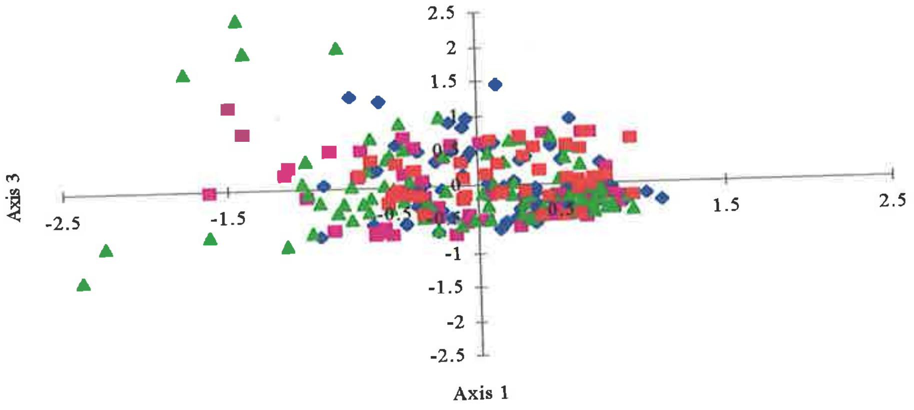
Seasonal Multivariate Patterns

When the location of data points on the ordination axes were plotted on the basis of season some interesting trends were evident (Fig. 4.56a, b & c). The most apparent was the degree of overlap between the seasonal position of data points. Another feature of the data was a wide negative scatter on Axis 1 and Axis 2 in spring and a large spread of summer data points, while winter data tended to occupy a narrower range on both of these axes (Fig. 4.56a). Spring data points showed a marked degree of seasonal scatter when Axis 3 was considered (Fig. 4.56b & c).

a) Axis 1 *vs* Axis 2



b) Axis 1 *vs* Axis 3



c) Axis 2 *vs* Axis 3

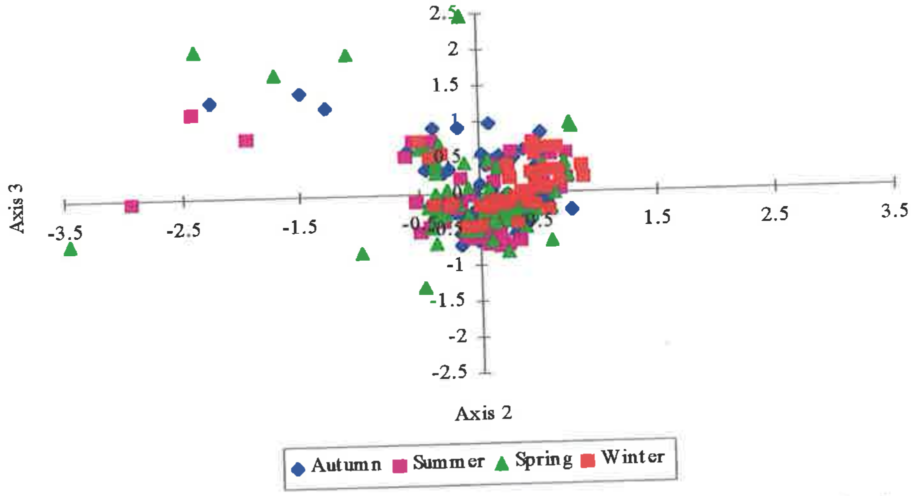


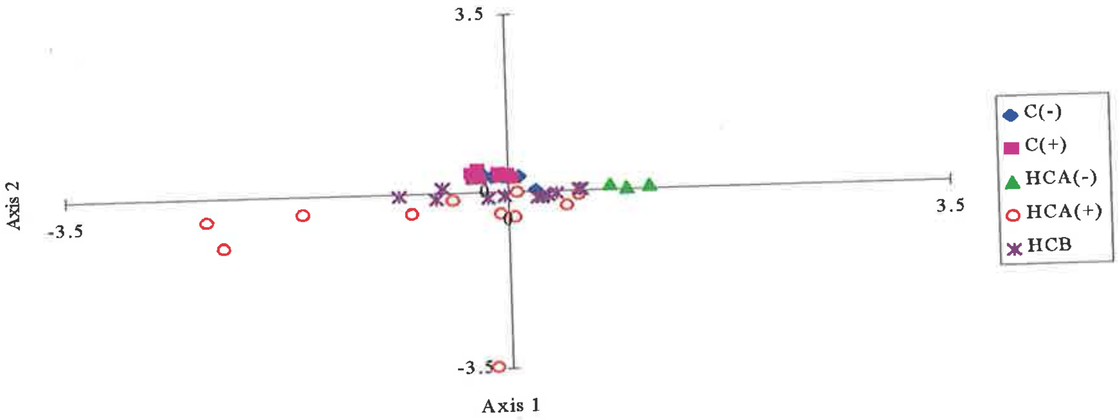
Fig. 4.56 The ordination positions of study sites were differentiated on the basis of season. A three dimensional solution was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology). The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13) and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3. Seasonal coding is shown in the legend.

The 'Sand' Perturbation and Assemblage Patterns

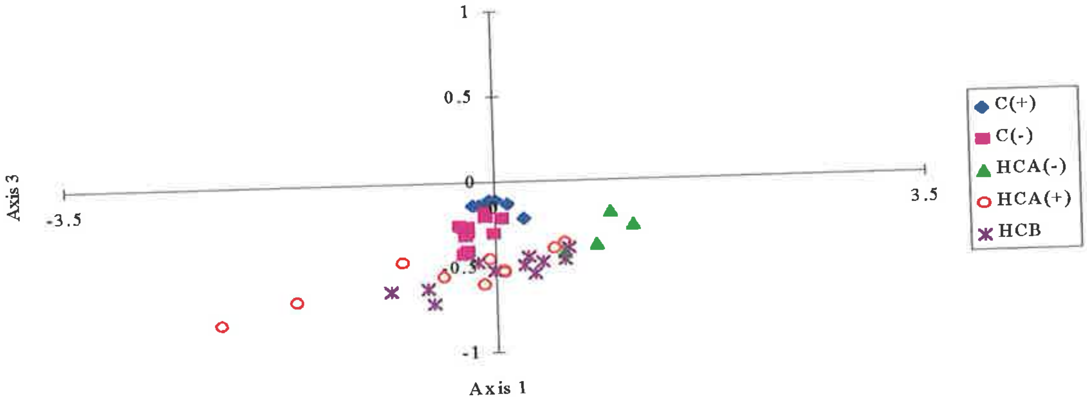
To clarify the effect of the 'sand' perturbation on assemblage patterns the ordination positions of data included in the 'sand' Beyond-BACI analysis were manipulated. The data points representing the control sites were averaged (for each sampling time) and compared to the ordination locations of the 'impact' site (HCA) and the adjacent less sand affected site (HCB). HCB was only sampled after the sand influx but the data for the control sites and HCA were separated into pre-impact (-) and post-impact (+) points and plotted against various combinations of the three ordination axes (Fig. 4.57a, b & c).

There was little evidence of separation of control points pre and post-impact but some evidence of a post-impact negative shift of HCA points on Axis 2 and a more strongly negative post-impact shift along Axis 1 (Fig. 4.57a). Some scatter was seen in HCB data points along Axis 1 but this scatter did not extend as far negatively as the most negative post-impact HCA points (Fig. 4.57a). The greatest scatter was seen with HCA post-impact and this was especially evident when Axis 1 *vs* Axis 2 and Axis 1 *vs* Axis 3 were used (Fig. 4.57a & b). The majority of the HCB data points appeared to be situated approximately midway between the pre-impact HCA and post-impact HCA data points on both Axis 1 and Axis 2 (Fig. 4.57a). No further clarification of sand associated changes in the ordination positions were seen when they were plotted on Axis 2 and Axis 3 (Fig. 4.57c).

a) Axis 1 vs Axis 2



b) Axis 1 *vs* Axis 3



c) Axis 2 *vs* Axis 3

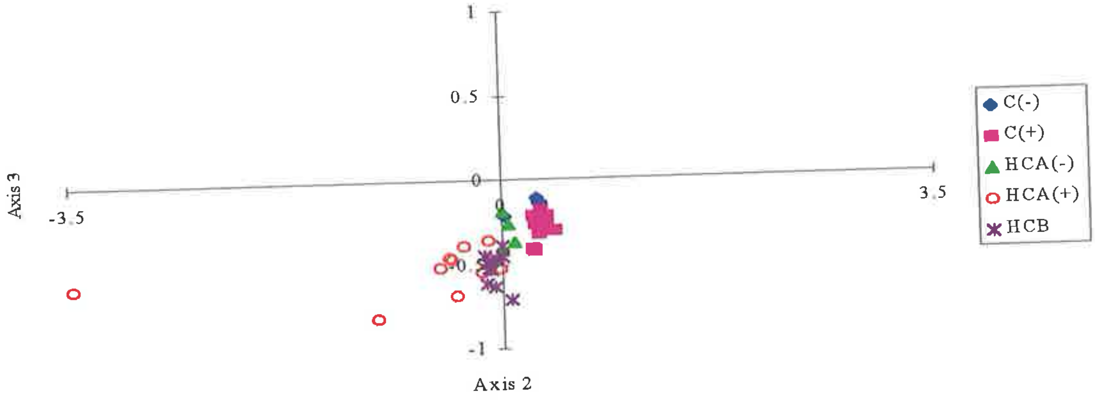
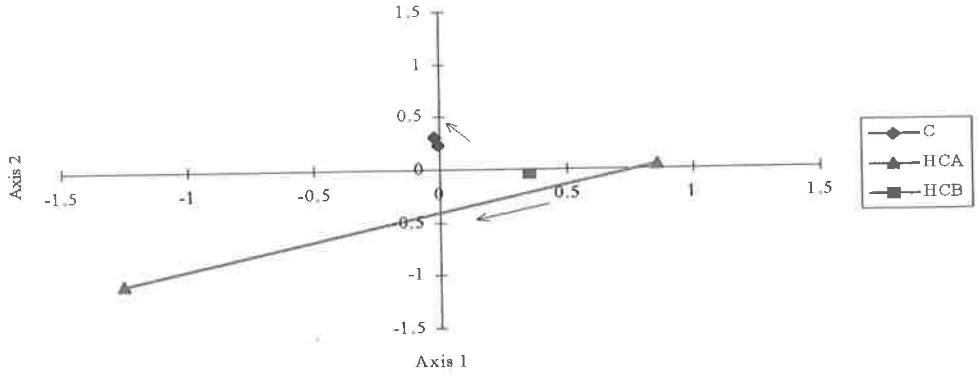


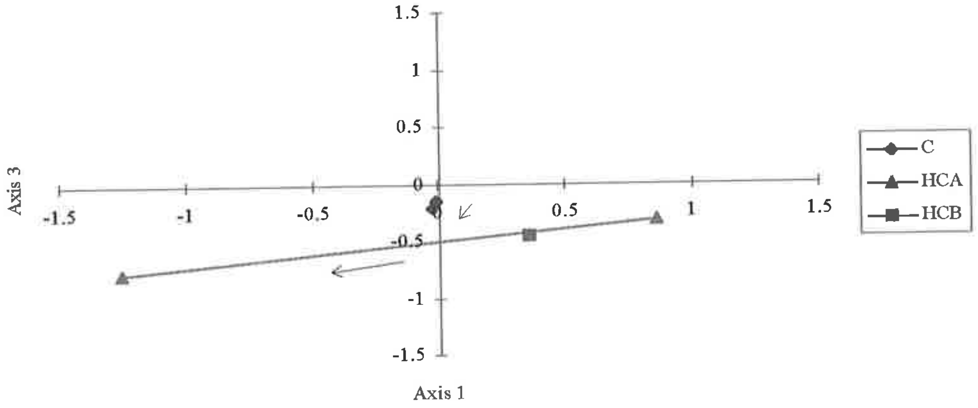
Fig. 4.57 The ordination positions of the 'sand' perturbed site (HCA), the adjacent HCB site and the average position of the set of controls (C) used in the Beyond-BACI analysis of the 'sand' perturbation are shown. Data points represent the temporal positions of the three 'treatments' which have been further separated into pre-impact (-) and post-impact (+) sub-treatments. A three dimensional solution was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology) and the appropriate points were graphed to generate this figure. The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13) and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3.

The assessment of assemblage trends associated with the sand influx was simplified by examining the trajectory of change occurring at control and HCA sites pre and post 'sand-impact' with the average post-impact position of HCB (Fig. 4.58a, b & c). Following the 'sand' perturbation a very small magnitude change occurred in the control sites while a large magnitude change occurred at HCA (Fig. 4.58a, b & c). HCB was not sampled prior to the sand influx but its location on the ordination plot was closer to the pre-impact position of HCA than it was to the post-impact position of this site. The direction of change observed at HCA was strongly negative on Axis 1 (2.12 units) but only slightly negative on this axis at the control sites (0.01). When Axis 2 was considered, HCA recorded a negative change (1.11), while a small positive change was detected at the control sites (0.06). The changes associated with Axis 3 were negative for both sites; -1.09 and -0.05 respectively (Fig. 4.58a, b & c). The direction and magnitude of change at HCA differed most to the vector of change seen at control sites when Axis 1 and Axis 2 were considered (Fig. 4.58a).

a) Axis 1 *vs* Axis 2



b) Axis 1 *vs* Axis 3



c) Axis 2 *vs* Axis 3

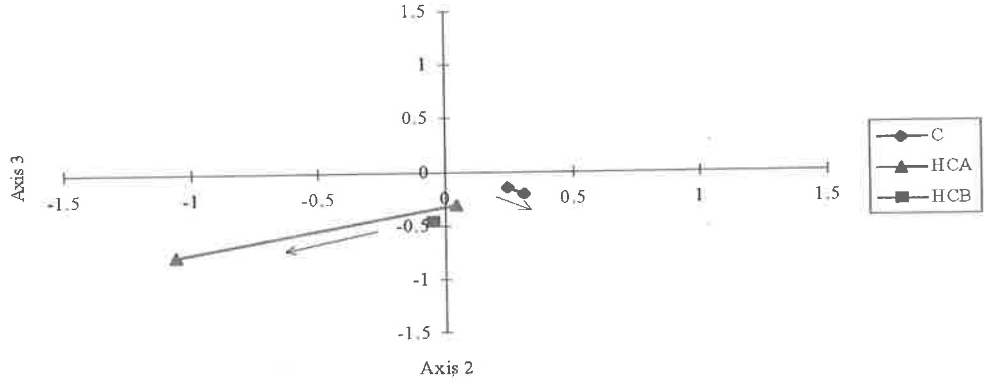


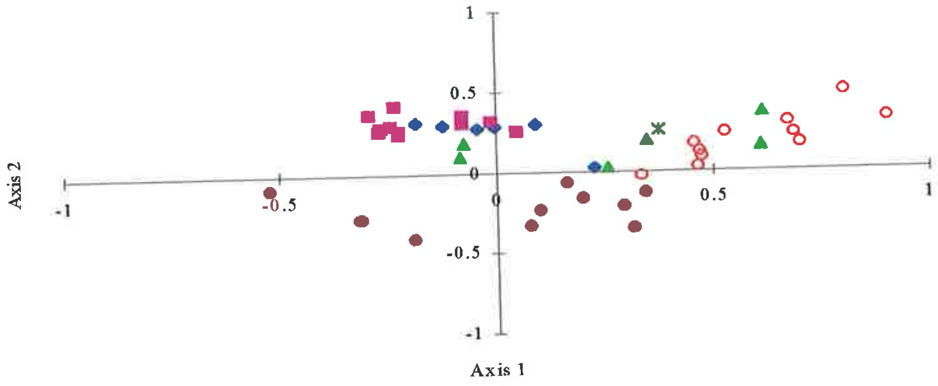
Fig. 4.58 The vector of change coincident with the 'sand' perturbation at HCA (the 'sand' perturbed site) and the set of controls (C) used in the Beyond-BACI analysis are shown. The average position of HCB which was adjacent to HCA is also graphed. The average pre-impact and post-impact positions of the respective temporal ordination series presented in Fig. 4.57 have been calculated for the set of controls (C) and HCA and these have been joined to determine the direction (indicated by the arrows) and magnitude of change associated with the sand influx. The average post-impact position of HCB is also shown. A three dimensional ordination was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology) and the appropriate subset was graphed to generate this figure. The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13), and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3.

The 'Effluent' Perturbation and Assemblage Patterns

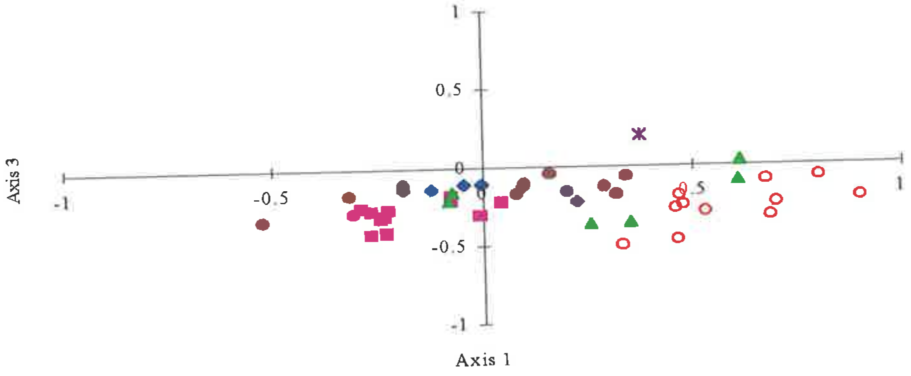
To look for clear trends associated with the 'effluent' perturbation the relevant ordination values pertaining to the Beyond-BACI sampling period were treated as described for the 'sand' perturbation data. The average ordination position of the control sites (at each sampling time) was compared to the positions of the 'effluent-impact' site (PS1A) and the adjacent non-affected site (PS1) pre-impact (-) and post-impact (+). PS1A was only sampled once prior to the impact at which time effluent was being discharged intertidally but was not yet flowing across the site.

There was some evidence of a slight lateral shift (negative along Axis 1) in the control sites post-impact, while the post-impact position of PS1 points appeared to have shifted in a positive direction along both Axis 1 and Axis 2 (Fig. 4.59a). Although only one pre-impact data point was obtained for PS1A there appeared to be a strong post-impact negative shift in the ordination position of this site along Axis 2 (Fig. 4.59a). A negative shift along Axis 3 was noted in control sites post-impact, a trend which also appeared to occur with PS1A points but was not readily apparent at PS1 (Fig. 4.59b & c).

a) Axis 1 *vs* Axis 2



b) Axis 1 *vs* Axis 3



c) Axis 2 *vs* Axis 3

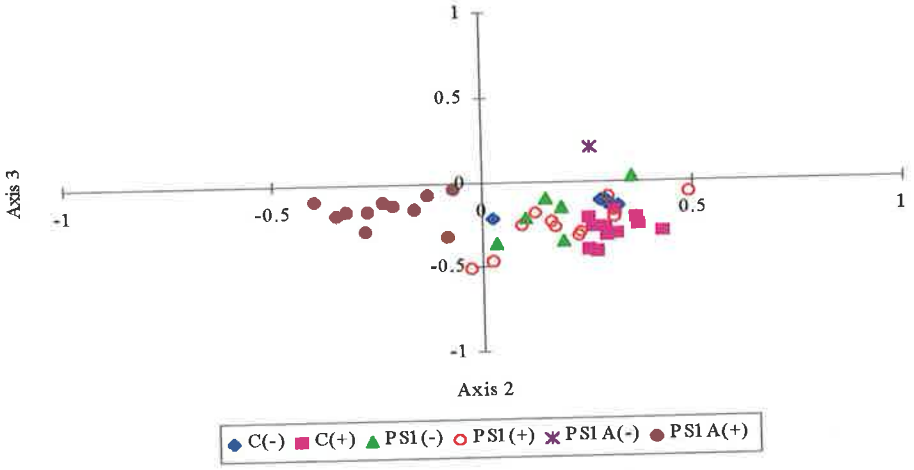


Fig. 4.59 The ordination positions of the 'effluent' perturbed site (PS1A), the adjacent PS1 site and the average position of the set of controls (C) used in the Beyond-BACI analysis of the 'effluent' perturbation are shown. Data points represent the temporal positions of the three 'treatments' which have been further separated into pre-impact (-) and post-impact (+) sub-treatments. A three dimensional solution was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology) and the appropriate subset was graphed to generate this figure. The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13) and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3.

To examine apparent trends, the vectors of change linking the average pre-impact and post-impact positions of the relevant groups were compared (Fig. 4.60a, b & c). A large magnitude negative change (-0.51) was noted at PS1A along Axis 1 compared to a small magnitude negative change (-0.12) along the same axis at the control sites and a positive change of 0.35 at PS1 (Fig. 4.60a). Little change was evident at PS1 along Axis 2 while PS1A registered a negative change of 0.6 and the control sites registered a positive change of 0.06 (Fig. 4.60a). A consideration of Axis 3 revealed a change of -0.40 at PS1A, -0.07 at PS1 and -0.12 at control sites in association with the effluent discharge (Fig. 4.60b & c).

Axis 2 and Axis 3 revealed the clearest difference between PS1A and the control and PS1 'treatments' (Fig. 4.60c). On this plot PS1 and the control treatments showed very similar vectors (including both the direction and the magnitude of change) while PS1A exhibited a large magnitude and different direction of change (particularly influenced by Axis 2). However, care should be used in interpreting any apparent assemblage based trends associated with the 'effluent' impact as the pre-impact position (anchoring the vector of change) was based on a single pre-impact sampling time at PS1A.

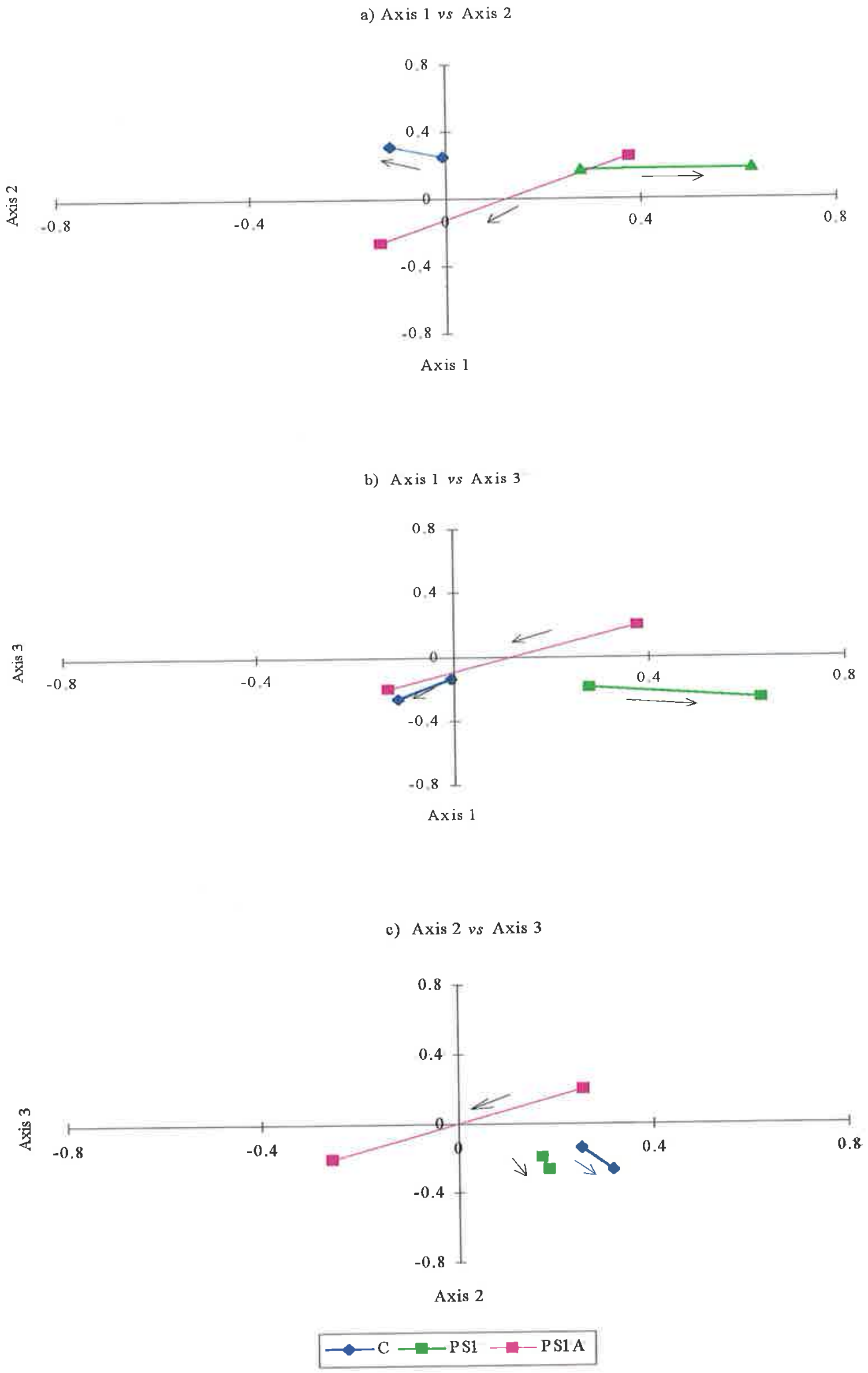


Fig. 4.60 The vector of change coincident with the 'effluent' perturbation at PS1A (the 'effluent' perturbed site), the adjacent site which was not obviously exposed to effluent (PS1) and the set of controls (C) used in the Beyond-BACI analysis. The average pre-impact and post-impact positions of the respective temporal ordination series shown in Fig. 4.59 have been calculated for the set of controls (C), PS1A and PS1 and these have been joined to determine the direction (indicated by the arrows) and magnitude of change associated with the effluent release. A three dimensional ordination was obtained using a SSH MDS Ordination performed in "PATN" (Belbin 1992) on animal taxa recorded at study sites (see section 4.3.2 for a full description of methodology) and the appropriate subset was graphed to generate this figure. The stress level achieved with a three dimensional ordination solution was 0.13 (S=0.13) and graphs have been generated for various axis combinations; a) Axis 1 *vs* Axis 2, b) Axis 1 *vs* Axis 3 and c) Axis 2 *vs* Axis 3.

Taxa Contributing to Assemblage Patterns

A Pearson matrix of Bonferroni probabilities was generated for the dominant animal taxa and the MDS ordination axes. The set of correlations was significant (*P*=0.00) and 4 of the taxa were intercorrelated (see Appendix Q). The PCC analysis was considered a more appropriate method to determine how well animal taxa defined the SSH MDS Ordination space (see Belbin 1992). Vectors which were significant at the 0.05 level (after a correction had been made to account of the use of multiple regressions) have been plotted against combinations of the three ordination axes (Fig. 4.61a, b & c). The r^2 values for each of the tested taxa are presented in Table 4.17.

Table 4.17 The regression values associated with a PCC analysis (Belbin 1992) indicate the importance of different taxa in defining SSH MDS ordination space obtained using the full 'preliminary' data set. The use of multiple regressions in the analysis necessitated a correction of the significant critical probability of 0.05. Only taxa which were found to have regression scores greater than the corrected critical probability have been tabled. Number of samples used (N)=245, number of taxa regressed=20, corrected critical probability=0.0025.

Taxa	Regression Score (r^2)
Austrocochlea concamerata	0.3482**
Austrocochlea constricta	0.1486
Bembicium nanum	0.2714**
Brachidontes erosus	0.7749**
Cellana tramoserica	0.3161**
Chthamalus antennatus	0.2119**
Lepsiella vinosa	0.2711**
Littorina spp.	0.4819**
Nerita atramentosa	0.4957**
Notoacmea spp.	0.3676**
Patelloida alticostata	0.4454**
Patelloida latistrigata	0.4077**
Siphonaria diemenensis	0.7077**
Siphonaria zelandica	0.1353
Turbo undulatus	0.5630**
Xenostrobus pulex	0.2250**

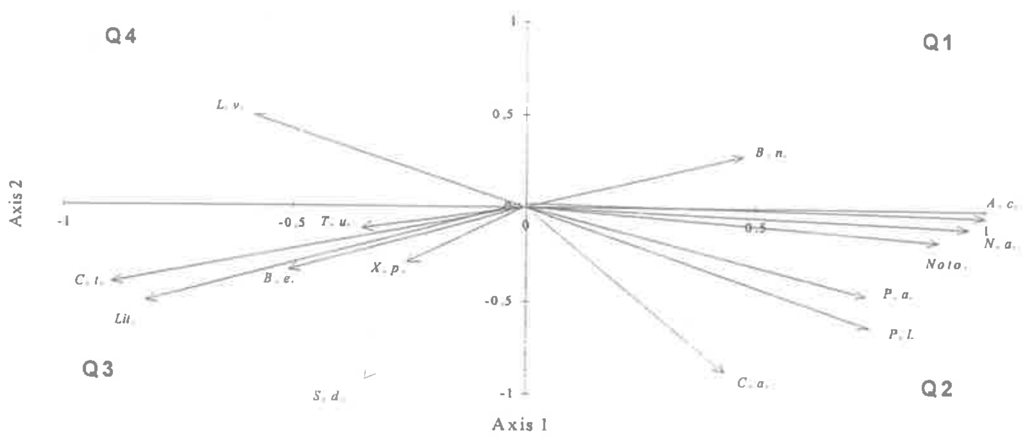
**=Regression scores significant at the corrected probability level.

To simplify interpretation and description of the placement of significant PCC vectors the ordination space on each graph was divided into four quadrats (Q1-4). The taxa correlation vectors within each of these quadrats have been listed against different combinations of the three axes (Table 4.18) and presented graphically (Fig. 4.61a, b & c).

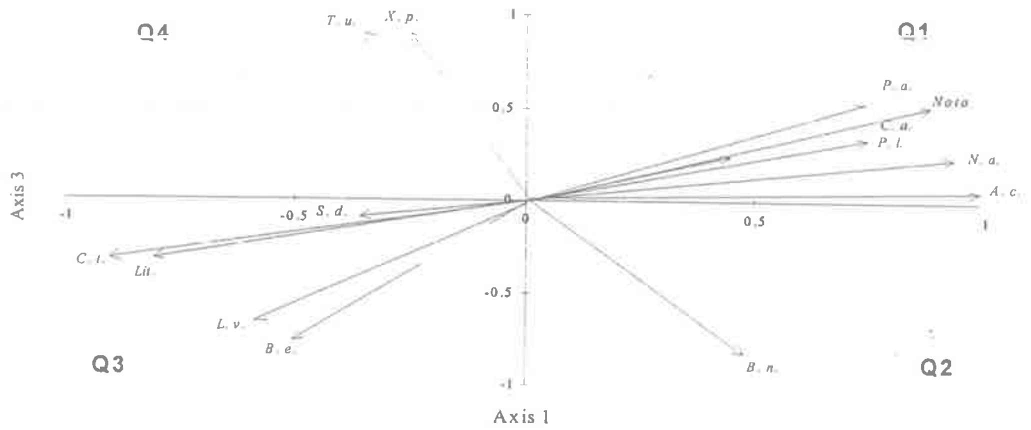
Table 4.18 A Principle Axis Correlation (PCC), essentially a multiple-linear regression program (Belbin 1992), was performed to determine how well animal taxa fitted the ordination space produced by the full 'preliminary' MDS Ordination. Taxa vectors found to be significant (Table 4.17) are shown in relation to their general position in ordination space. To allow a simplified description of the general positions of the vectors, the ordination space has been divided into four quadrats (labelled as Q1-Q4 on Fig. 4.61a, b & c) for each of the three possible combinations of the axes. Significant taxa within each of the quadrats are recorded in the table in clockwise order (refer to Fig. 4.61a, b & c).

Axis Combinations	Quadrat	Significant Taxa
Axis 1 *vs* Axis 2	Q1	*Bembicium nanum*
	Q2	*Austrocochlea concamerata, Nerita atramentosa, Notoacmea* spp., *Patelloida alticostata, Patelloida latistrigata, Chthamalus antennatus*
	Q3	*Siphonaria diemenensis, Xenostrobus pulex, Brachidontes erosus, Littorina* spp., *Cellana tramoserica, Turbo undulatus*
	Q4	*Lepsiella vinosa*
Axis 1 *vs* Axis 3	Q1	*Patelloida alticostata, Notoacmea* spp., *Chthamalus antennatus, Patelloida latistrigata, Nerita atramentosa, Austrocochlea concamerata*
	Q2	*Bembicium nanum*
	Q3	*Brachidontes erosus, Lepsiella vinosa, Littorina* spp., *Cellana tramoserica, Siphonaria diemenensis*
	Q4	*Turbo undulatus, Xenostrobus pulex*
Axis 2 *vs* Axis 3	Q1	-
	Q2	*Lepsiella vinosa, Bembicium nanum*
	Q3	*Brachidontes erosus, Cellana tramoserica, Littorina* spp., *Siphonaria diemenensis*
	Q4	*Chthamalus antennatus, Austrocochlea concamerata, Patelloida latistrigata, Patelloida alticostata, Nerita atramentosa, Xenostrobus pulex, Notoacmea* spp., *Turbo undulatus*

a) Axis 1 vs Axis 2



b) Axis 1 *vs* Axis 3



c) Axis 2 vs Axis 3

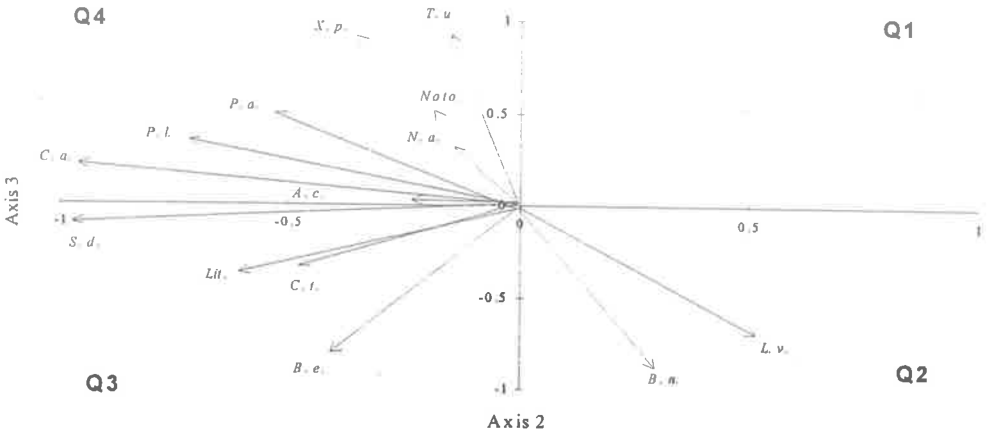


Fig. 4.61 A Principle Axis Correlation (PCC), essentially a multiple-linear regression program (Belbin 1992), was performed to determine how well animal taxa fitted the ordination space produced by the full 'preliminary' MDS Ordination. Taxa vectors found to be significant (Table 4.17) are shown in relation to their general position in ordination space which has been divided into four quadrats (Q1, Q2, Q3 & Q4). The taxa corresponding to the significant PCC vectors are; *A. c.= Austrocochlea concamerata, B. e.= Brachidontes erosus, B. n.= Bembicium nanum, C. a.= Chthalamus antennatus, C. t.= Cellana tramoserica, L. v.= Lepsiella vinosa, Lit.= Littorina* spp., *N. a.= Nerita atramentosa, Noto.= Notoacmea* spp., *P. a.= Patelloida alticostata, P. l.= Patelloida latistrigata, S. d.= Siphonaria diemenensis, T. u.= Turbo undulatus, X. p.= Xenostrobus pulex.*

Fourteen taxa were found to regress significantly with ordination space (Tables 4.17 & 4.18 and Fig. 4.61a, b & c). *B. nanum* was the main species separating PS1 and Kingston Park from the other sites (Fig. 4.54), while a number of species; *T. undulatus*, *S. diemenensis*, *X. pulex* and *C. tramoserica* (predominantly found at lower mid-eulittoral levels) and *Littorina* spp. (predominantly found in the supralittoral zone) were linked with the separation of Witton Bluff from the other sites (Fig. 4.61a). *L. vinosa* was primarily responsible for the positioning of PS2, PS3 and Marino Rocks in ordination space, while 6 taxa significantly regressed with the ordination space which contained Port Noarlunga South, PS1A, Robinson Point and some of the HCA and HCB data points (Fig. 4.61a).

Physical Parameters Contributing to Assemblage Patterns

A Pearson matrix of Bonferroni probabilities was generated for those environmental variables believed to be important in shaping assemblage structure and patterns, and the three MDS ordination axes. The set of correlations was significant and a large number of the attributes tested were intercorrelated (see Appendix R). This was expected and meant that the PCC analysis was a more appropriate way of attempting to link physical factors with ordination space.

To further clarify the relationship between ordination space and the physical parameters assessed at study sites a PCC analysis was performed as described for the taxa data. Once an adjustment had been made to accommodate the multiple regressions used in this procedure none of the r^2 values were found to be significant and hence will not be discussed further (Table 4.19).

Table 4.19 The regression values associated with a Principle Axis Correlation (PCC) to determine the importance of different physical parameters in defining SSH MDS ordination space using the full 'preliminary' data set. All parameters have been assessed as described in section 4.3. The use of multiple regressions in the analysis necessitated a correction of the significant critical probability of 0.05. Number of samples used (N)=245, number of physical parameters regressed=9, corrected critical probability=0.0056. All regression scores were non-significant.

Physical Parameters	Regression Score (r^2)
Stable substrata (bedrock or reef-rock)	0.1004
Boulder	0.1251
Cobble	0.1063
Pebble	0.1005
Sand or grit	0.0556
Retained water	0.0816
Maximum elevation	0.1193
'Chain' measure of topographic complexity	0.0978
Scored presence of oil	0.0725

**=regression scores significant at the corrected probability level

4.5 Discussion

4.5.1 Temporal Changes in Physical Parameters

Preliminary monitoring highlighted the dynamic nature of GSV. Although clear tidal patterns were evident at temporal scales of days, months and seasons, prevailing wind patterns and barometric pressure changes could modify these. Wind patterns were particularly variable on small to large temporal scales and had major effects on tidal patterns and the strength of incident waves.

The study sites found to be most susceptible to natural disturbance from wind, wave or tidal influences (either directly or indirectly) were those with unstable substrata (Table 4.2). These included Marino Rocks and some of the Port Stanvac sites. The 'Southern' sites were most 'stable' due to their domination by bedrock or potentially mobile rock embedded and stabilised by sand and mussel beds. These sites also tended to occupy coastal positions that were relatively sheltered, while the reefs themselves were low-lying in comparison to most of the other study sites. Some of the 'Northern' sites were also dominated by bedrock substrata but were prone to 'northward' sand drift particularly in winter (e.g. HCA).

Sand Drift

Sand drift primarily perturbed 'Northern' sites during June 1995 and again in May and June 1996. The 1995 sand influx affecting both zones at HCA, while the 1996 episode affected the 'lower' zone at Kingston Park and, to a lesser extent, the 'upper' zone at HCA. The sand influxes observed during the 15 months when sites were initially monitored, were suggestive of northward sand drift representing a cyclic perturbation pattern in GSV.

Northward sand drift resulted in decreased abundances of all mid-eulittoral species and an initial increase in variability at the affected site (HCA). Sand affects rocky intertidal animals by covering substrata and any plants (particularly epilithon) which herbivores use as a food source or which shelters them from desiccation on exposed shores. Sand may make it difficult for motile molluscs to clamp onto rocks to avoid desiccation at low tide or to maintain their positions during times of water movement, and may also smother sessile animals such as barnacles and mussels (Littler *et al.* 1983, Brown 1996). If a rocky intertidal habitat is frequently sand-stressed it may act as a refuge for stress-tolerant and opportunistic strategists (Littler *et al.* 1983), which may explain the different assemblage observed at HCA as this site recovered from the perturbation. The PCC analysis used to link taxa with positions in ordination space established that a number of species regressed significantly with the assemblage change seen at HCA in response to the 'sand' perturbation (Tables 4.17 & 4.18 and Figs 4.57 & 4.58). These species were present in adjacent areas but were rare in the sampled zone at HCA prior to the sand influx. Since the majority of the animals were very small it was postulated that they recruited opportunistically into the area as the sand was naturally cleared from HCA and that they formed part of an early successional assemblage.

The 'Effluent' Perturbation

The ruptured effluent pipe at the refinery resulted in an acute but transient increase in the assessed oil score, a 12^0C increase in water temperature, a sharp decline in conductivity and an initial increase in water acidity and increased water retention at PS1A. The oil present in the effluent (although at concentrations below detectable levels) may have been capable of directly inducing changes in the biota or substrata it contacted although it was not considered 'thick' enough to smother biota. The influx of fresh water (indicated by the decline in conductivity) and the non-seasonal increase in water temperature and pH may be capable of inducing acute or longer-term changes in susceptible biota. This is likely to manifest at the organism level if the degree of contact is sufficient to trigger responses in target species (see Underwood 1989) but could induce higher level change.

4.5.2 The Beyond-BACI Analyses

The lack of serial correlation between the sampling times used during preliminary monitoring of GSV sites suggested that the time intervals used were satisfactory in regard to this potential problem (Keough and Mapstone 1995). If this had not been the case it would still have been possible to analyse the data as long as the presence of serial correlation had been taken into account in the analysis (pers. comm. Leppard).

The sand influx at HCA was found to have a significant effect on the abundance of *B. nanum* only at the longest temporal scale of 'Before *vs* After' when a Beyond-BACI analysis was performed. No impact was detected at the two shorter temporal scales of 'Times' and 'Periods' but the power to detect an impact at these scales was only 0.85 and 0.44 respectively. This was well below the *a priori* power of 0.95 which was desired for the analyses and indicated a longer pre-impact monitoring sequence was needed to achieve the desired power given the amount of variability observed at the sites during preliminary monitoring. This means that the results obtained at the shorter temporal scales; particularly at the temporal scale of 'Periods', can only be interpreted with caution (see Toft and Shea 1983, Rotenberry and Wiens 1985, Fairweather 1991a).

The 'effluent' analysis also suffered from a lack of statistical power but did have slightly more power than the 'sand' Beyond-BACI analysis to detect changes at the temporal scales of 'Times' and 'Periods' (0.88 and 0.51 respectively). This was due to the later intervention of the 'effluent' perturbation and the increased number of sampling 'Times' which were nested in 'Periods' (see Table 4.5). The similarities seen between PS1A and PS1 in terms of the post-effluent abundance of *B. nanum* from late October 1995 (apart from the February 1996 sampling time) implies that the assumption that the two sites supported similar pre-impact densities of *B. nanum* was not totally unjustified. On the basis of this assumption (necessary so the analysis could proceed) and the low power of the Beyond-BACI analysis the failure to detect an impact could not be accepted with any degree of statistical confidence.

The relatively early intervention of both the 'sand' and the 'effluent' perturbations coupled with the confounding factors (particularly movement of mobile substrata) acting differentially at study sites reduced the power of the Beyond-BACI analyses to detect the impacts at the relevant temporal scales. The apparently cyclic 'sand' perturbation seen at 'Northern' sites would also be likely to confound an analysis if it coincided with an oil spill. This highlights the need to include a relatively large number of study sites in an ongoing monitoring program and to target sites with stable substrata. It also supports the need to consider substrata changes in association with animal abundance measures in an ongoing monitoring program.

4.5.3 Spatial Patterns at Study Sites

The study sites were characterised by a relatively high degree of intra-site variability in terms of their substrata and the composition of intertidal assemblages. This is typical of rocky intertidal areas (Schoch and Dethier 1996) and of intertidal GSV in the vicinity of Port Stanvac (Womersley 1982 & 1988). For example, although both the 'upper' and 'lower' zones designated for sampling at the majority of study sites were within the mid-eulittoral zone they displayed different assemblage patterns. Typically, the 'lower' zones were characterised by increased abundances of sessile animals, including mussels and barnacles, and/or greater gastropod diversity, while the 'upper' zones tended to support a sparse faunal taxa with domination by one or a few gastropods, frequently including *B. nanum* (Womersley and Thomas 1976). The reduced diversity and species richness associated with *X. pulex* beds could be due to their tendency to retain sand and reduce available primary substrata for epilithon growth or to provision of an anchoring material. However, it has been reported that mussel shells can act as secondary substratum, providing habitat for epilithon growth and other intertidal species, and that survivorship and recruitment of some intertidal taxa may actually be higher on shells of mussels (Lohse 1993). The difference seen between the biota occupying the 'upper' and 'lower' zones was primarily attributed to the longer immersion times experienced by biota in the latter and was locally modified by the topographic complexity of the substrata and the presence of rock pools.

A number of sites were characterised by a complex topography (e.g. crevices or pits) and semi-permanent or permanent rock pools which represented unique and complex habitats within the intertidal area (Astles 1993, Metaxas and Schiebling 1993, Metaxas and Schiebling 1994, Metaxas *et al.* 1994, van Tamelen 1996). This type of terrain provides refuge areas for biota which normally occupy 'lower' shore positions including the sublittoral zone as was evident at Witton Bluff (see Shepherd and Thomas 1989, Quinn *et al.* 1992). Rock pools were occasionally seen within sampled areas at all study sites but were especially prevalent at 'Southern' sites. The low-lying status of the 'Southern' sites was associated with comparatively higher total densities of animals (when all species were pooled) and individuals were, on average, larger than individuals of the same species found at other study sites.

Some intertidal biota favoured rock pools and/or crevices at low tide. An experiment by Chapman and Underwood (1994) found a positive association between *Nodolittorina pyramidalis* (Quoy & Gaimard) and topographically complex rocks during low tide. Small animals of this species were particularly responsive to habitat complexity and tended to aggregate within pits and crevices, although other factors (such as food availability) influenced the time animals remained on the complex habitat. The advantages afforded by this behaviour were not established but were unlikely to be associated with decreased temperature and reduced evaporation rates as the snails within this area were at least as hot and had similar water reserves to those on adjacent, less complex substrata (Chapman and Underwood 1994). A preference for rock pools and cracks/fissures has been identified for *A. constricta* (Underwood 1976a, Underwood 1977, Womersley 1982, Astles 1993), neretid snails, including *N. atramentosa* (Underwood 1976a, Levings and Garrity 1983), and *Nodolittorina pyramidalis* (Chapman and Underwood 1994). In the field *A. constricta, A. concamerata,* and *N. atramentosa* appeared to be more abundant in the 'lower' zones and to preferentially aggregate under large rocks and in rock pools at low tide but *B. nanum* did not adopt these strategies (refer to Chapter 6).

Sampling of rock pools was avoided during preliminary monitoring due to their unique and highly variable assemblages (Dethier 1982 & 1984, Fairweather and Underwood 1991, Metaxas and Scheibling 1992 & 1993, van Tamelen 1996). Sampling pool biota in conjunction with non-pool biota during preliminary monitoring would have increased inherent variability within sites. This would be likely to decrease the power of preliminary monitoring to detect changes associated with a particular perturbation. However, not sampling the animals present in rock pools was likely to underestimate the abundance of species which favour this behaviour and has implications in the choice of bioindicators for ongoing monitoring.

4.5.4 Temporal Patterns at Study Sites

4.5.4.1 The Abundance, Population Structure and Recruitment of *B. nanum*

Abundance

B. nanum were not found at Witton Bluff but occurred at all other study sites and were present at moderate, relatively constant densities at Port Noarlunga South and Robinson Point. Conditions at the latter sites were expected to protect animals from large physical stress (such as high desiccation risk and frequent natural perturbation), as well as allowing increased foraging time and encouraging enhanced epilithon growth, important for herbivores such as *B. nanum* which utilise this food source.

B. nanum abundance was highly variable over time, even in the absence of identified perturbations; such as 'northward' sand drift, the 'effluent' perturbation and movement of mobile substrata. However, these disturbances were clearly linked to decreased *B. nanum* abundances at perturbed sites. Spatial and temporal variability in *B. nanum* abundance was typically more extreme in the 'lower' zones which generally supported higher total abundances of *B. nanum* than the corresponding 'upper' zones (Figs 4.13-4.15). Exceptions to this trend occurred when 'lower' zones were characterised by high densities of mussels (with mussels being the dominant space occupiers), or where the situation was complicated by movement of mobile substrata or heavy sand loads (e.g. Kingston Park in May and June 1996). The 'lower' zones were not as frequently censused as the 'upper' zones at study sites and it was not possible to determine if the differences between 'upper' and 'lower' zones were persistent for the duration of preliminary sampling.

Increased densities of *B. nanum* in the 'lower' zones could be linked to the reduced desiccation risk experienced by animals (and plants) at lower shore levels. However, since the populations under study were not static in time or space it was expected that seasonal changes would be evident between the two zones. For example, in winter (when the risk of desiccation was reduced) it was predicted that the relative abundance of *B. nanum* would increase in the 'upper' zone as animals migrated to this region from lower shore levels, and that the reverse trend would be observed in summer. A slight increase in the abundance of *B. nanum* in the 'upper' zone was seen at Kingston Park in winter, and more notably in spring during preliminary monitoring (Fig. 4.13a). In summer the abundance of *B. nanum* decreased in the 'upper' zone at this site as densities increased in the 'lower' zone, a pattern which persisted until the advent of the second sand influx. A similar trend was seen at Port Noarlunga South during summer 1996 (Fig. 4.15a) but was not identified at the remaining sites. The study by Womersley (1982) found that *B. nanum* did exhibit this type of seasonal behaviour and were more abundant at higher shore levels at Port Stanvac in winter. This could be linked to seasonal changes in the density and composition of epilithon (Nicotri 1977, Underwood 1981b & 1984a, b, & c, MacLulich 1987, Anderson 1995, Kennish *et al.* 1996).

The lack of clear seasonal trends in *B. nanum* abundance at the majority of sites, was likely to be due to the interplay of biotic characteristics (predation, competition for food and space, and the influx of new herbivores, particularly *B. nanum* recruits), and abiotic factors. The latter include the frequency and magnitude of physical disturbance, substrata type and microtopography. This suite of complex characteristics would superimpose extra layers of variability over any patterns associated with the previously postulated seasonal changes, effectively obscuring such trends.

Population Structure

'Small' and 'medium' sized *B. nanum* tended to dominate the population at all study sites apart from Port Noarlunga South and Robinson Point where 'large' animals made a greater contribution (Figs 4.16-4.23). High herbivore densities (including *B. nanum*) and the generally larger size of herbivores at the latter sites implied that competition for epilithon would be greater. However, the 'Southern' sites were also characterised by a higher density of coralline and encrusting algae, and a slippery sheen on the rocks was suggestive of high abundances of epilithon. This suggestion was not directly assessed due to perceived sampling difficulties (see Nagarkar and Williams 1997 for a review). Epilithon was predicted to be less of a limiting resource to herbivores at 'Southern' sites despite the perceived higher grazing pressure per unit area than it would be to herbivores at the other study sites. The sheltered and 'stable' nature of the 'Southern' sites was expected to reduce the risk of storm perturbations and subsequent damage to animal assemblages or epilithon films. Under these conditions it is more likely that epilithon would be a stable late-successional assemblage, largely structured by biotic forces (Farrell 1991), which provides a reliable food source for herbivores such as *B. nanum*.

Larger *B. nanum* may not necessarily equate to older individuals as growth may be stunted at sites where conditions are more stressful and food is limiting (Takada 1995). The height on the shore affects submersion, exposure to desiccation stress, foraging time and food availability and consequently influences the size attained by animals (Garrity 1984, Underwood 1975a & b, Underwood1984b). The predominance of 'large' *B. nanum* at the two 'Southern' sites may also be a response to crab predation. This is supported by the work of Chilton and Bull (1984 & 1986) who found that gastropods exceeding 10mm in height were apparently ignored by common reef crabs on intertidal reefs (including Marino Rocks) in South Australia.

A study by Underwood (1975b) found that *B. nanum* on a shore in Botany Bay, New South Wales, reach adult size within one year of settlement and are capable of reproducing at least ten months after settlement. The same study also predicted a minimum longevity of 4 years and a maximum life span of 7.5-8 years. This suggests that *B. nanum* is likely to survive several consecutive years of sparse larval recruitment and has implications for its use as a bioindicator of oil pollution and in predicting the expected recovery rate of GSV intertidal areas following a medium sized oil spill (see Chapter 6).

Another general trend found during preliminary monitoring was a tendency for sites which were more frequently perturbed by substrata mobilisation to have a population structure dominated by 'small' *B. nanum*. However, consideration of the population structure must also take into account absolute numbers censused at a site. For example, the contribution by 'small' animals peaked in the 'upper' zone at Marino Rocks in the beginning of spring 1995, but the frequent substrata disturbance was matched by low densities of animals which made determination of the population structure unreliable. The domination by 'small' animals at unstable sites may be due to their physical ability to occupy protected positions in substrata fissures and thus avoid destructive forces which may kill, or displace, larger animals (but see Underwood and Chapman 1989). It is also possible that frequent disturbance of the substrata (as seen at Marino Rocks) opens up colonisation opportunities for new recruits and results in increased proportions of 'small' animals.

The absolute numbers of 'small' *B. nanum* were typically greater in the 'lower' zones than they were in the corresponding 'upper' zones. Where clear abundance peaks were apparent this tended to occur in winter in the 'lower' zones and in autumn in the 'upper' zones (Table 4.20). The exception to this trend was seen at Port Noarlunga South and Robinson Point where abundance peaks occurred in both zones in autumn 1995 and summer 1996. This result implies that for the duration of preliminary monitoring study sites fluctuated roughly in phase in terms of the timing of increased densities of 'small' *B. nanum.* Similar but less definitive trends were evident when the relative contribution of 'small' *B. nanum* to the population structure at study sites was considered. The greater contribution by 'small' animals in the 'lower' zones may be linked to increased epilithon growth and the reduced desiccation stress experienced in this region.

Table 4.20 The seasonal timing of peaks in the absolute abundance of 'small' *B. nanum* at sites where trends in this parameter were noted are shown (refer to Figs. 4.29-4.31).

Site	Peak abundance of 'small' *B. nanum*
Kingston Park	'lower' zone- winter 1995
Marino Rocks	'lower' zone- winter 1995
PS1	'lower' zone- winter 1995 'upper' zone- winter 1995 & autumn 1996
PS2	'lower' zone- winter 1995 'upper' zone- autumn 1995
PS3	'lower' zone- autumn & winter 1995 'upper' zone- autumn 1995
Port Noarlunga South	'lower' zone- autumn 1995 & summer 1996 'upper' zone- autumn 1995 & summer 1996
Robinson Point	'lower' zone- autumn 1995 & summer 1996 'upper' zone- autumn 1995 & summer 1996

B. nanum egg capsules were observed at 'Central' and 'Southern' study sites in spring 1995 and early autumn 1996. Underwood (1975b & 1994b) reported that spawning in this species occurs over an extended period (August to March), and that they have a resting period in autumn. The capsules seen in autumn may have been laid in summer since the time until hatching has been reported to be 18-28 days (Shepherd and Thomas 1989). New *B. nanum* settlers were observed in January and February (summer) 1996 and although not seen at high densities at all study sites were noted to arrive simultaneously to at least one 'Northern', 'Southern' and 'Central' site. This implies that the settlement of *B. nanum* would appear to be in phase across study sites during 1996.

The actual settlement rate of marine species utilising planktonic dispersal has been examined and opposing results have been found. The studies of Gaines and Roughgarden (1985), Navarrete and Castilla (1990) and Minchinton and Scheibling (1993) found settlement rates to be proportional to the availability of suitable substrata (see Anderson 1996). However, a number of studies including that of Pineda and Caswell (1997) found that as substrata availability is reduced the settlement rate per unit area intensifies. Which of these relationships exists between the availability of suitable substrata and the settlement rate of *B. nanum* and other intertidal invertebrates found in GSV could have implications to the rate of recovery of an intertidal area decimated by oil exposure, boulder mobilisation or sand influx.

The post-settlement success of new recruits (which has implications to a population based monitoring program) is expected to depend on a range of factors. These include: epilithon abundance and condition (Hawkins and Hartnoll 1983a, Underwood 1984a & b, MacLulich 1987, Anderson 1995, Wieczorek *et al.* 1995); the presence and abundance of conspecifics (Bence and Nisbet 1989); the intensity and interaction of competition, predation, disturbance and physical structuring factors (Dayton 1971, Peterson 1979, Paine 1984); site characteristics including topographic complexity (Emson and Faller-Fritsch 1976, Raffaelli and Hughes 1978, Hughes and Roberts 1980, Connell and Jones 1991, Sanson, Stolk and Downes 1995); the energy reserves available at settlement; the timing of settlement relative to the tidal cycle, and micro-site selection (Minchinton and Scheibling 1993, Moreno *et al.* 1993, Gosselin and Qian 1996). These factors form a suite of characters operating over a range of temporal and spatial scales (Underwood 1985) which tend to interact and covary, and the importance of any one factor may also vary over time (Peters 1991, Likens 1992).

4.5.4.2 Changes Associated With the 'Sand' Perturbation

The 'sand' perturbation at HCA was associated with a massive, rapid reduction in the abundance of *B. nanum* which initially fell by 68% (compared to the average pre-impact abundance at this site) and then plummeted to zero by the next sampling time (Fig. 4.13c). It appeared that the abundance of *B. nanum* was linked at HCA and HCB, with the decrease at HCA being matched by an increase in abundance at HCB. Once sand was naturally cleared from HCA and the number of *B. nanum* increased, a corresponding decline was observed at HCB. This implies that the sand influx drove *B. nanum* individuals from HCA rather than smothering them, and that many were able to find refuge at HCB until conditions at HCA again improved. The sand influx was also associated with an initial increase in variability, apparently arising as slightly elevated sand-free substrata afforded small refuge areas where animals could aggregate until conditions were completely untenable for them (Brown 1996). Increased variability has been identified as a perturbation response in situations where the average abundance of the impacted population does not change and a Beyond-BACI monitoring design is capable of detecting altered variability coincident with a perturbation (Underwood 1991a).

Linkage between HCA and HCB was also found in terms of the total number of taxa, the number of individuals, Margalef's species richness, Shannon-Wiener diversity and Pielou's evenness, but was less apparent with the Simpson's Dominance Index. This implies that the sand influx affected all animal taxa at HCA (although some species appeared to be more tolerant of the changed conditions) but that HCB was able to act as a refuge area for many of the motile animals. Taxa dominance returned fairly rapidly to a normal range at HCA and was not greatly altered at HCB in association with the sand influx.

4.5.4.3 Changes Associated With the 'Effluent' Perturbation

A decrease in the abundance of all *B. nanum* (including those classified as 'small') appeared to occur following the 'effluent' perturbation at PS1A. However, since only one pre-impact sampling was completed and intra-site variability was high (Figs 4.14a & 4.30a) it was difficult to determine if this was a real trend or a sampling artefact. If this was a 'real' response it was postulated to occur as a result of loss of adherence to the substrata when exposed to the effluent water, making them more susceptible to dislodgment by subsequent high tides. Loss of adherence could be a response to increased water retention at PS1A which simulated a false high tide, could be a toxic (or narcotic) effect of pollutant exposure, or may be a response to the sudden unseasonable increase in water temperature. None of these hypotheses were tested and any apparent 'trends' may be unrelated to the perturbation.

Changes coincident with the 'effluent' perturbation were noted when some of the assemblage based univariate and associated measures were considered. The total number of taxa present at PS1A did not change but the total number of individuals declined markedly and then recovered rapidly (Figs. 4.36a & 4.39a). Species richness showed a similar transient decrease at the perturbed site, which was not matched at PS1 (Fig. 4.42a). Diversity declined at both PS1A and the 'upper' zone at PS1, although the decline was more marked at the former (Fig. 4.45a), while evenness did not change markedly (Fig. 4.48a) and Simpson's Dominance showed a transient increase at PS1A (Fig. 4.51a). These apparent changes occurred against a high background variability, which makes them less informative than changes associated with the 'sand' perturbation.

4.5.4.4 Other Animal Taxa

Apart from *B. nanum* other animal taxa were generally present at low densities at study sites particularly in the 'upper' zones. Exceptions to this included *A. constricta* (which was reasonably common at Port Noarlunga South and Robinson Point), and *S. diemenensis*, which was found at high densities at Port Noarlunga South. Due to the generally low densities of these taxa at study sites they were not considered informative in terms of elucidating perturbation patterns arising during ongoing monitoring, nor as potential bioindicators for ongoing monitoring. The 'secondary' taxa found at study sites matched those recorded at four intertidal areas in GSV by Womersley (1982) and generally exhibited a high degree of temporal variability. The contribution of these taxa to assemblage patterns during preliminary monitoring will now be briefly reviewed.

4.5.5 Assemblage Patterns

Univariate indices and associated measures derived from 'community' data (such as species richness, evenness and dominance) did not display any clear temporal patterns although some spatial patterns were evident. These included a tendency for greater taxa richness and diversity in 'lower' zones except at sites where mussels and barnacles dominated.

MDS Patterns: Site Differences and Seasonal Trends

It was difficult to identify clear temporal or seasonal trends derived from assemblage data analysed by clustering and SSH MDS Ordination techniques. Ordination of study sites in taxa defined space was the more useful technique in differentiating study sites. Port Noarlunga South and Robinson Point tended to separate from other study sites (although they showed some overlap between their 'lower' zones) while Witton Bluff was the most uniquely positioned study site in terms of the intertidal assemblage it supported (Figs 4.54 & 4.55). The remaining sites tended to show some overlap but were most heavily represented at slightly different positions (Fig. 4.54a, b & c). This was indicative of slight differences in their assemblage composition.

When seasonal trends in the location of points within ordination space were considered it was apparent that strong seasonal patterns were absent and the most striking feature was the considerable overlap existing between seasonally defined data points (Fig. 4.56). However, when ordination Axes 1 and 2 were considered it was noted that spring data points scattered widely (particularly in a negative direction) on both axes, while winter data points occupied the narrowest range (Fig. 4.56a). The other two seasonal groups also displayed a relatively large amount of scatter on Axis 2, with summer scatter being wider in a negative direction along this axis than autumn scatter.

Comparing seasonal patterns with the temporal location of data points separated on the basis of study site (Figs 4.54 & 4.55) suggested that spatial differences and the temporal changes seen at sites were likely to be obscuring clear seasonal assemblage changes in the data set. This 'noise' was presumably in response to such physically driven factors as substrata disturbance (including sand drift), and biotic driven assemblage changes (e.g. competition, recruitment and predation). Such variability is a characteristic of the intertidal region and its assemblage and is a challenge that requires consideration when monitoring for perturbation based change.

The PCC analysis identified a number of taxa which significantly regressed with the ordination, and these were plotted against combinations of the ordination axes (Fig. 4.61 a, b & c & Table 4.18). Intercorrelations existed between some species, such as the positive correlation between *L. vinosa* and *X. pulex*. The former species targets *X. pulex* as one of its prey items (Appendix Q), and such biotic interactions need to be considered when attempting to identify temporal and seasonal assemblage patterns (Connell 1961a & b, Underwood and Jernakoff 1981, Underwood 1978a & b, 1981b, 1984c & 1985).

A PCC analysis did not find any significant relationships between the regression scores associated with the physical parameters assessed at study sites and ordination space once a correction had been made for the number of regressions (Table 4.19). This was likely to be due to the action of other physical factors which were not assessed and which may be differentially affecting study sites and influencing temporal trends, in combination with a possible non-linear relationship between the assessed physical parameters and the ordination (refer to Zar 1984, Wilkinson 1990).

MDS Ordination Changes Associated with the 'Sand' Perturbation

The 'sand' perturbation appeared to be associated with a clear shift in the average position of pre-impact and post-impact HCA ordination points while very little change occurred in the pre-impact and post-impact ordination positions of the set of control sites used in the Beyond-BACI analyses (Fig. 4.58a, b & c). The PCC analysis established significant correlations between ordination space and a number of taxa (Table 4.17). When Axis 1 and Axis 2 were used to plot the vectors of change associated with the 'sand' perturbation (Fig. 4.58a) it was apparent that the direction of change seen at HCA falls into Quadrat 3 (see Fig. 4.61a). The taxa identified by PCC analysis as corresponding to these changes were likely to be *S. diemenensis, X. pulex, B. erosus, Littorina* spp., *C. tramoserica* and *T. undulatus* (Table 4.18). It must be noted that averaging the post-impact ordination positions of HCA effectively combines sampling times when no animals were recorded with sampling times where recovery of the site was occurring and biota were again present.

The assemblage seen at HCA as sand was naturally cleared from this site was initially very different to that recorded prior to the perturbation. The early assemblage following site recovery was characterised by increased abundances of encrusting red algae, *X. pulex*, *B. erosus*, *S. diemenensis*, *C. tramoserica*, and *S. zelandica*. These species co-occurred with *B. nanum* and *A. constricta*, both of which were numerically dominant at HCA prior to the 'sand' perturbation and which, over time, again began to dominate. The PCC analysis illustrated relationships between many of the taxa observed at HCA post-perturbation and the ordination position of this early successional assemblage. It was not until approximately a year after the 1995 sand-influx at HCA that the assemblage at this site resembled the original pre-impact assemblage, at which time a second sand perturbation intervened. The frequency and magnitude of disturbance and the history of disturbance patterns at a site can influence the ecological successsional status and affect intrinsic assemblage variation within a site (Dean and Connell 1987, Underwood 1989, Berlow 1997).

The composition of the post-impact assemblage is likely to be influenced by the timing of the event in relation to new recruits (and possibly adjacent immigrants) being available to recolonise and 'seed' the vacated substrata (see Sousa 1984a & b). In the event of a complete blanket of thick sand overlying a site it is expected that conditions at any of the intertidal sites will be unacceptable to the main species. Effects could be directly related to scouring or smothering of intertidal biota, or may be indirect (Littler *et al.* 1983, Brown 1996). Sand inundation is likely to result in an assemblage which is at a less mature successsional stage (and is more unstable) than assemblages occurring at sites where this disturbance stressor does not occur (Sousa 1979a & b, 1980 & 1984b, Dean and Connell 1987, Farell 1989 & 1991, Underwood and Anderson 1994, Ha Kim and Dewreede 1996, Pugh and Davenport 1997). However, in the event of 'northward' sand drift cyclically perturbing 'Northern' study sites, the observed successional changes seen at HCA during the 15 months of the preliminary study are likely to be similar from year to year as biota modify the area and conditions continue to change. This is because a cyclic sand perturbation is likely to coincide with the same (or similar) suite of planktonic biota available to recruit to the decimated area once conditions improve. It is possible that more mature biota in adjacent areas may also be able to recolonise the area as it recovers (as was found at HCA) (Connell and Slayter 1977, Connell and Keough 1985, Underwood and Fairweather 1989) before the next sand influx results in a similar pattern of change.

MDS Ordination Changes Associated with the 'Effluent' Perturbation

Changes in the pre-impact and post-impact ordination positions of the 'effluent' perturbed PS1A site did appear to be associated with this event. This was particularly evident when Axis 2 and Axis 3 were used to plot the ordination vectors of change of PS1A, the set of control sites, and PS1 (which was not observed to be exposed to effluent) (Fig. 4.60c). However, apparent changes associated with the effluent perturbation should be accepted with caution as the vector of change at PS1A was based on only one pre-impact data point and thus may be a sampling artefact. Changes seen in the control sites (on average) and PS1 were linked to *B. nanum* and *L. vinosa*, while the changes seen at PS1A would appear to be driven by *Littorina* spp., *C. tramoserica*, *B. erosus* and *S. diemenensis* (Fig. 4.61c). *Littorina* spp. occupied elevated positions on substrata in the 'upper' eulittoral zone, possibly allowing them to avoid maximum exposure to the effluent water. In contrast, *C. tramoserica* and *S. diemenensis* appeared to 'favour' 'lower' positions on the shore and were often found in sheltered areas or in rock pools. This behaviour may make them more tolerant to increased water inundation. The apparent linkage of the ordination position of PS1A following effluent exposure with the presence of *B. erosus* was unclear.

4.5.6 Implications for Ongoing Monitoring

The preliminary study found that all sites fluctuated in terms of the abundance of their dominant animals and their assemblage structure. Minor seasonal patterns in variability were seen with the SSH MDS Ordination (Fig. 4.56a, b & c) but the variability in assemblage structure within and between sites appeared to mask any clear seasonal trends (see Fig. 4.54a, b & c). To detect definitive seasonal patterns against this high background variability a longer-term data set would be needed and temporal trends at study sites would need to be separately examined. It was clear that physical parameters acting at study sites were affecting assemblage patterns although these did not regress significantly with the ordination (Table 4.19). The more 'stable' 'Southern' sites separated strongly from the ordination positions of the other sites, indicating different assemblage patterns. Witton Bluff was markedly different to all other study sites and supported a completely different assemblage, closer to that expected in a subtidal environment, and which regresssed strongly with *T. undulatus* and a range of other species (Table 4.18). In view of its unique assemblage this site would not be recommended for retention as a study site for ongoing monitoring.

Sampling 'lower' zones at many study sites was difficult if tides were particularly high, especially if the site tended to be relatively low-lying. It is therefore recommended that ongoing sampling focus on 'upper' mid-eulittoral zones only. The need to select 'stable' study sites comprised of embedded reef-rock or immobile bedrock was also clearly indicated, with storm movement of mobile substrata resulted in 'unstable' assemblages and low numbers of species and individuals following a perturbation. The advent of the sand influx to 'Northern' sites during 1995 and 1996 indicates that care needs to be exercised in selecting 'Northern' sites for ongoing monitoring. Sites selected for ongoing monitoring should have minimal risk of being exposed to a 'sand' perturbation or storm mobilisation of substrata, either of which could confound an oil spill monitoring program. Therefore, all selected study sites will need to be reassessed and possibly new 'upper' regions chosen for ongoing monitoring (discussed in more detail in Chapter 8).

B. nanum was ubiquitous at all study sites other than Witton Bluff and was the only species which occurred at high enough densities to be of use as a population level bioindicator in a Beyond-BACI monitoring program. *B. nanum* abundance data collected during 1995 did not indicate serial correlation which implies that the sampling intervals ('Times' and 'Periods') used during preliminary monitoring would be appropriate for ongoing monitoring if this species was selected as the bioindicator (Underwood 1989, Osenberg *et al.* 1994). Another benefit to using *B. nanum* as a bioindicator is that it is a herbivore which is liable to contact oil and be similarly affected by oil exposure to the many other herbivorous species found to dominate the 'upper' zones at many of the study sites. This will be discussed in more detail in Chapter 6 (but see Jones and Kaly 1996 and Phillips *et al.* 1997).

An examination of the abundance and size structure of *B. nanum* at study sites for the duration of monitoring established differences between study sites and within a study site over time. The stable 'Southern' sites of Port Noarlunga South and Robinson Point tended to have a greater relative proportion of 'large' animals but 'small' and 'medium' animals dominated all other sites, especially if they were unstable. The abundance of *B. nanum* tended to be less variable in the 'upper' zones, which are recommended as the focus for ongoing monitoring. Peak abundances of 'small' *B. nanum* (representative of successful recruitment) appeared to be roughly in phase across the monitored sites which is likely to reduce the risk of sudden influxes of 'small' animals masking any perturbation related changes in population abundance. To further minimise this risk it is advisable that the three size classes used for preliminary monitoring are censused during ongoing monitoring and that the presence of new recruits is also recorded (discussed in more detail in Chapter 8).

Fluctuations in the abundance of *B. nanum* appeared to be responding to physical parameters such as substrata mobilisation at certain times of the year at 'unstable' sites. At other times abundance changes appeared to be linked to new recruitment or perhaps other biotic variables which were not investigated, such as competition and predation. This highlights the need to monitor the percentage of different substrata grades present in each quadrat in conjunction with *B. nanum* abundance and population structure. In this way substrata disturbances which may confound an investigated perturbation will be identified and the timing of *B. nanum* settlement waves will be known. This information can then be used in an ongoing monitoring program to explain changes at study sites which may be unrelated to an oil perturbation. It may also assist in selecting 'control' sites from the full suite being monitored for inclusion in a Beyond-BACI analysis and may elucidate the mechanism of post-oil spill recovery (e.g. recruitment *versus* local immigration).

For *B. nanum* to be accepted as a suitable bioindicator it remains to be established if it has a cause-and-effect relationship with oil, and how it is likely to be affected by oil exposure at the population level (addressed in Chapter 6). The effect-size (see Bros and Cowell 1987, Osenberg *et al.* 1994 and Mapstone 1995) associated with an oil spill perturbation will also need to be considered (Chapter 8). Another problem that requires investigation is recreational use of study sites, and the effect of the low levels of trampling associated with intertidal sampling in an ongoing monitoring program (addressed in Chapter 7).

A community approach to monitoring would be time consuming and although it may prove useful in determining patterns coincident with an oil spill would still not be able to establish a statistical link with the perturbation (Janson and Vegelius 1981, Faith *et al.* 1987). However, refer to Faith *et al.* (1991) for a discussion of community measures and how they can be statistically associated with a perturbation. Therefore, an assemblage level approach to monitoring, such as that of Dufrêne and Legendre (1997) would be unlikely to prove as suitable for an ongoing monitoring program in GSV as would a Beyond-BACI univariate approach. Assemblage data collected during a monitoring program could be converted to a univariate temporal data series (such as the total number of individuals, the number of taxa, species richness, species evenness, diversity, or dominance) and fed into a Beyond-BACI analysis. Nevertheless, the relationship between such measures and perturbations (such as an oil spill) have not been definitively established (see Gray and Pearson 1982 & Godfrey 1978 *re* diversity indices) and time constraints would limit the usefulness of such an approach in an intertidal context. Furthermore, even under the extreme disturbance the sand drift caused at HCA, not all assemblage based parameters responded in a clearly defined way. Therefore, a Beyond-BACI monitoring program using a population approach and the total abundance of *B. nanum* (excluding animals less than 2mm in diameter) is advocated as the method of choice for ongoing monitoring (see Chapter 8). The timing of ‘new-settlers’ will be recorded and quantified where possible but these will not be included in any Beyond-BACI analysis following an oil perturbation. The recommended allocation of temporal sampling into ‘Times’ and ‘Periods’ is as described for preliminary monitoring as this temporal spacing was capable of detecting a pulse perturbation and reduces the likelihood of serial correlation in the data (refer to Glasby and Underwood 1996).

Chapter 5. Modelling of an Oil Spill at Port Stanvac

5.1 Introduction

The ocean is increasingly exposed to pollution and other anthropogenic disturbances, with coastal regions being most at risk (Blumer 1971, Ehrhardt and Blumer 1972, Overton *et al.* 1994). Oil is one of a range of pollutants that can impact on the marine environment and affect resident invertebrate communities (Suchanek 1993). There is growing public concern about the increasing risk of environmental damage resulting from an accident during the loading or unloading of oil from a tanker (Beer *et al.* 1983). This situation could occur during routine handling of oil at the Port Stanvac Oil Refinery. An oil spill during refinery operation is a potentially highly variable event with the ultimate grounding site being strongly affected by the timing of the spill in reference to ambient tide, wind and wave conditions.

The first step towards assessing oil related environmental damage in the event of an oil spill from the refinery is to predict oil slick motion, spreading of the slick and the likely sites where oil is expected to ground (Beer *et al.* 1983, Wolff *et al.* 1993, Skiba 1995). It is important to be able to predict the latter when utilising a Beyond-BACI monitoring design since this approach relies on pre-impact as well as post-impact assessment of a number of sites, at least one of which is ultimately perturbed.

In order to predict the potential grounding sites of oil spilt during routine refinery operation the most likely points of oil release from the refinery were identified and existing oil spill trajectory models considered. A suitable model was then used to determine potential seasonal grounding sites along eastern Gulf St Vincent (GSV) should an oil spill from the Port Stanvac Oil Refinery occur. The refinery oil spill (which occurred on the 23rd of September 1996) was used to validate and refine the model prior to seasonal modelling commencing.

5.2 Aims

The general aim of the modelling component of this study was to explore the use of computer models to determine the fate of oil spilt from the Port Stanvac Oil Refinery and to adapt a suitable model to the Port Stanvac area.

Specific aims of this chapter were to:

- Use background information concerning the character of oil and its fate when spilt at sea to assist with computer modelling of an oil spill.
- Investigate the use of an appropriate computer model for oil spill assessment within GSV.
- Use the operational oil spill to validate the predictive ability of the 'oil spill model'.
- Predict the most likely sites within the refinery from where an operational oil spill could occur.
- Select the most suitable parameters for use in the modelling of an oil spill and its transport.
- Model the seasonal transport of oil over a full tidal cycle (and under 'dodge' and 'high' amplitude tidal conditions) to predict the most likely sites where oil spilt from the refinery will ground.

5.3 Background

5.3.1 Factors Influencing the Transport of Oil in GSV

Oil is a surface bourn contaminant and tides and wind mainly determine its transport. Over 24 hours or less it is the vector sum of the tide and wind patterns which are important. The wind field is the primary factor producing surface currents which have a velocity which is approximately 3-4% (pers. comm. Petrusovics) or 5% (Clark 1989) of the wind velocity. Currents can show extreme variability in speed and direction due to the influence of variable wind stress and the tidal regime, which includes the dodge tide. The effect of wind can either add or subtract from the tidal flow.

Circulation patterns in GSV are most heavily influenced by west to east moving synoptic pressure systems which are modulated in summer by sea breezes (Petrusevics 1990). As a general rule, the tidal currents along the eastern side of the Gulf flow parallel to the coastline and can reach speeds of up to 30cm/s during spring tide conditions (pers. comm. Petrusevics).

Topography, hydrography and climate are important factors to consider in an oil spill. The timing of an oil spill in relation to the tidal regime and wind conditions will have a major influence on the ultimate destination of spilt oil. For example, a strong on-shore breeze accompanying an incoming tide as it 'turns' is likely to carry pelagic oil directly into (rather than along) the shore. Wind directions along eastern GSV are mainly from the south to south-east in summer and south-west to north in winter (Petrusevics 1990). Therefore, it is likely that wind driven oil transport will predict a net oil movement ranging from north to north-west in summer and from north-east to south in winter. However, summer winds may be very weak and tidal influences may be the major determinant of oil grounding sites at this time of the year.

The local characteristics of the area in which an oil spill occurs also influence the grounding sites of oil and the extent of its impact (Baker 1983). An oil slick in the open ocean is more likely to disperse and thus minimise the resultant ecological damage than oil spilt close to shore in shallow sheltered bays, inlets, estuaries or rivers where hydrography may promote its retention (Baker 1983 & 1991). The position of Port Stanvac within GSV and the enclosed nature of the Gulf are likely to restrict the spread of oil from the refinery to the eastern side of GSV. However, the transport of oil will vary widely due to the previously mentioned factors of season, tidal condition, wind (strength and direction), currents (both tidal and non-tidal), waves and modifying coastal features such as submerged reefs. Human intervention may also act to change the ultimate destination of spilt oil.

Two computer models were considered for use in modelling an oil spill at Port Stanvac. The first of these is a mathematical tidal model being designed specifically for predicting transport of oil spilt at Port Stanvac. This project is being developed by M. Grzechnik under the supervision of Assoc. Prof. J. Noye (Mathematics Dept, University of Adelaide) but was only in its early stages when I commenced this thesis and not available for use (but see Grzechnik 1995). The second model is the FLOWM Model of Dr. J. Bye (Earth Sciences, Flinders University) which will be used to predict the seasonal transport and ultimate destination of pelagic oil.

5.3.2 The Fate of Oil Spilt From the Refinery

The character of oil and its behaviour when spilt at sea and after grounding have been briefly reviewed in Chapter 2 and Appendix D. Oil spilt from the Port Stanvac Oil Refinery is likely to be a moderate amount of either Arabian light crude oil or refined petroleum. The primary points where accidental oil spillage can occur are at the 'Deep Ocean Point' or the 'Wharf Point' (Appendix A; Fig. A.3). Both types of oil are handled at the 'Deep Ocean Point', while refined product alone is exported from the 'Wharf Point'.

Arabian light crude oil and refined product (especially the latter) are predicted to spread quickly to form a thin slick while at sea and to show rapid loss of their volatile components through evaporation (thus reducing their toxicity to intertidal biota). However, a refinery oil spill is likely to occur close to the shore and may rapidly ground before undergoing extensive at-sea weathering thus remaining relatively toxic to biota. If crude oil is spilt under agitated weather conditions it is liable to form a 'water-in-oil' mousse which is expected to weather slowly and to have an enhanced smothering capability once on shore. Beached oil is expected to be rapidly removed from rocky, high-energy sections of GSV but may be retained and entrapped for a longer time in lower energy rocky sections of the coast and may penetrate sandy substrata and act as a chronic oil source.

5.4 Modelling of an Oil Spill

5.4.1 Basic Theories Underpinning Modelling of an Oil Spill

Hoult (1972) theoretically described the spread of oil on calm water. He theorised that since nearly all oil slicks are thin (typically less than a 1/2 inch) and this thickness is much less than the horizontal spread of the slick or the wavelength of the waves below, it can be viewed as if the oil is in vertical hydrostatic equilibrium. Based on this assumption the physics of the spread of oil on water was explained.

Over time the properties of an oil slick vary in response to such factors as evaporation of the lighter constituents, dissolution of the more soluble components and degradation, resulting in a viscous and dense oil with a changed spreading potential due to altered surface tension (Hoult 1972). For crude oils the evaporation of the more volatile components is typically three times as fast as their dissolution into the water. The final area of a slick is reached a certain time after it is spilt, with the spreading process always ending in a surface-tension regime (Hoult 1972). Spread ceases once the net spreading coefficient (σ) changes from positive to negative. For most crude oils σ is positive and a typical value could be 25 dynes cm^{-1} (Hoult 1972). The net spreading coefficient is determined by the mix of surfactants present in the oil which dissolve or evaporate at varying rates and alter the surface tension (Nounou 1980). The temperature, salinity and biological properties of seawater can also affect the value of σ (Hoult 1972). The fact that crude oil is a mix of constituents makes determination of the net spreading coefficient difficult.

It is possible to model the spread of spilt oil on calm sea by considering the different factors (defined as 'spreading laws') which determine the spread as time passes (Hoult 1972). For example, the gravity-inertial law dominates spread at the temporal scale of minutes to an hour, but as evaporation of volatile components and dissolution of soluble components from the oil slick occurs the gravity-viscous law primarily determines oil spread over a temporal scale of an hour to weeks. Beyond this time the viscous-surface spreading law determines the spread of the slick (see Hoult 1972 for further details).

A difficulty in modelling the spread of crude oil, in particular, lies with treating it as a homogeneous bulk product with constant properties when it is in fact a complex mix of hydrocarbons with unique characteristics which are changing over time (Nounou 1980, Baker 1991). If oil changes associated with weathering are not considered the modelling results may not accurately match oil spread under real conditions (Hoult 1972). Although it would be preferable to incorporate weathering changes into modelling of an oil spill at Port Stanvac, a bulk model has been used. This was due to time constraints but should not cause too much inaccuracy since an operational oil spill is likely to occur at close proximity to the shore and to beach within 6-24 hours (or less) depending on tidal conditions. In addition, the primary aims of the modelling were to identify the study sites most likely to be impacted by an oil spill rather than the finer details of oil transport and spread. However, it is expected that such details will eventually be addressed by the work of Grzechnik. The Grzechnik model should also be useful in more accurately predicting circulation patterns in GSV and oil slick destinations.

5.4.2 Recent Work on Oil Transport at Sea

Beer and colleagues (1983) have carried out modelling of near-shore oil trajectories in Spencer Gulf. This series of field experiments involved the simultaneous release and tracking of small quantities of crude oil and drift cards. Data obtained from these experiments were used in association with wind and current information to predict oil slick destinations along the Gulf coastline (Beer *et al.* 1983). It would be informative to repeat this study in GSV at various times in a tidal cycle in different seasons but this would require a large investment of time.

5.4.3 The FLOWM Model

FLOWSPA was the computer program developed in 1970 by the School of Earth Sciences (Flinders University) for thallasso-modelling (Bye and Ng 1994). With minor adjustments to the program it could be adapted to suit a variety of research applications (Bye and Harbison 1991). The model was updated and extended in 1993 to incorporate a dispersive advective component (based on the work of Fadeiro and Veronis 1977) which could be applied to salinity, temperature and tracer concentrations and was then known as the FLOWC Model (see Bye and Ng 1994, Appendix S). A further adaptation of the model allowed incorporation of circulation by wind, waves and swell through longshore processes, tidal progression, and buoyant solute dispersion, as well as including the ability to accommodate time series data (see Appendix T). This updated model was known as the FLOWM Model and was the one used to simulate oil spills in GSV.

Information detailing operation of the FLOWM Model and the theories underlying it can be found in Appendix T. However, clarification of the way in which the model can be used to simulate the transport of buoyant surface solutes (such as oil) needs to be made. Firstly, the model predicts the transport of pelagic oil by assumed that it disperses in a surface layer of thickness (h) in which the concentration of oil is well mixed vertically, but beneath which the concentration of oil is zero. The thickness (h) can be estimated if consideration is given to the buoyancy of the oil and the depth of the wave boundary layer (h_w) which acts to mix the oil downwards in the water column. Another factor influencing the transport of oil is its advection by Lagrangian wave drift. This is not the same as the non-wave induced currents arising by general and tidal circulation. The wave drift (γ) adds a surface water transport component which is directed in the local wind direction. Using these theories and relationships equation 5.1 can be derived (see Appendix U).

$\gamma=1/k(1-\ln h)/h_w$ ---------------- Equation 5.1

where γ=wave drift parameter, k= Von Karman's constant (~0.4), ln h=the natural log of the surface mixing depth of the oil, and h_w=depth of the wave boundary layer

To use a Beyond-BACI approach to monitor the consequences of an oil spill from Port Stanvac it is necessary to predict the most likely sites of intertidal oil accumulation along the eastern coast of GSV. This chapter attempts to use the FLOWM Model for this purpose. The oil spill, which occurred in the refinery from the 'Deep Ocean Point' on The 23rd of September 1996, was used to refine a number of manipulated parameters and validate the model. The latter was achieved by comparing the observed grounding sites of oil with those predicted by the computer simulation which used the wind strength and direction, and the tidal height which prevailed for the duration of the spill. This enabled the optimal parameters pertaining to the passage of a hypothetical oil spill, such as oil decay time and the thickness of the surface layer of the slick, to be used in the seasonal simulations. Validation of a model can be a useful tool and is an integral part of the model building process (Rykiel 1996). However, validation of the seasonal modelling simulations could not be directly tested.

5.5 Materials and Methods

5.5.1 The Operational Oil Spill and Validation of the Model

The Oil Spill

The release of Arabian light crude oil occurred from the 'Deep Ocean Point' at about 12 noon on the 23rd of September 1996. It was also believed that a smaller oil spill occurred on the same day at about 4.00pm (pers. comm Pfennig). Since the accident was under investigation by the South Australian Environmental Protection Authority I was not able to obtain full details of this event. Mobil initially reported that 20L of oil had been spilled and later upgraded the volume to 100L. It has now been reported that about 10,000 litres of oil entered the sea from a hole in a 500m long ship-to-shore rubber hose (Appendix B). The oil was believed to have leaked out close to the ship as it was being unloaded from a Nassau registered tanker (pers. comm. Pfennig).

Tidal heights remained consistently high during the day of the spill (Table 5.1) and it was thought that the majority of the oil grounded by about 10pm on the 23rd of September at low tide (pers. comm. 'oil clean-up' personnel). Heavy seas and rough weather had agitated the slick producing a 'water-in-oil' emulsion (termed a 'chocolate mousse') which was seen on the shore and at the oil-land interface the day after the spill.

Table 5.1 The tidal regime recorded on the day of the operational oil spill (23rd September 1996) is shown. Tidal height is presented in metres (m). Data provided by the National Tidal Facility (NTF), Flinders University, South Australia.

Time	Height of tide (m)
0604	1.71
0900	1.66
1458	1.92
2200	0.97

Tidal conditions prevented access to the study sites selected for preliminary monitoring on the day of the oil spill. However, on the 24th and the 26th of September trips were made to assess the extent of the oil spill and to identify the sites where oil grounded. These trips involved visual assessment of approximately 30km of the eastern coastline of GSV (including all study sites). The initial trip was intended to monitor the spread and location of grounded oil but high tides on this day prevented accurate assessment and animal census at study sites.

All affected areas of the coastline and study sites were observed on the second trip to see if the oil had been redistributed by later tides and to assess the progress of the clean-up. Census of assemblages at all accessible study sites was performed and the presence of oil was scored. Five control sites (Kingston Park, Marino Rocks, PS1, PS2 and PS3), and one 'impact' site (Port Noarlunga South) were able to be censused on this second trip, with the effect of the oil spill on assemblage patterns being considered in Chapter 6.

Observation of the coastline allowed identification of the areas that received the heaviest oiling. A series of photographs were also taken to document relevant features of the oil spill. The visual assessment of the extent and location of intertidal oiling was then used to check the agreement with the hypothetical grounding sites obtained from running simulations in which certain parameters were adjusted.

Use of the FLOWM Model

Information on tidal levels, wind speed and wind direction (obtained from the National Tidal Facility (NTF) at Flinders University) was input into the FLOWM Model to predict the sites where oil would ground given the prevailing conditions and the known point of oil release (the 'Deep Ocean Point'). Information obtained from the NTF included 64 hours of data covering conditions 28 hours before the oil spill and well after the time when the majority of oil was believed to have grounded. The model used the wind field to calculate wind induced surface currents.

A bathymetry matrix, which includes GSV, was generated using Navigational Map AUS. 781. To produce this matrix a section of the map was enlarged and a grid applied, with each grid interval being equivalent to 186.9m. Next, each grid intercept and the depth (in fathoms) were entered into Excel, Version 5.0 as a *csv file. Missing depth values were interpolated and the resulting matrix consisted of 71 columns to the east and 109 rows to the north and corresponded to a surface area of

270km^2 which included the relevant section of the eastern Gulf shoreline. The *csv file was then input into the FLOWM package as described in Bye and Ng (1994) (Appendix T). The coordinates of relevant instrument points (points on the grid where the amount of oil was to be measured) were also entered into the model. The main instrument points were the 'Deep Ocean Point' (the point of oil release), the mouth of the Onkaparinga River, and slightly offshore positions representing all study sites other than PS1A and HCB.

For modelling purposes the oil was treated as a 'bulk' substance and assumed to be constant over time with no change in its properties. Parameters which were manipulated in the model under the various simulations included the degree of wave drift, the thickness of the water surface layer in which the oil was dispersed (h) and the oil decay time. Actual values for the wind strength and direction and tidal height (measured at Port Stanvac and provided by the NTF) for the duration of the simulations were input as hourly time series data. The model was run for 64 hours, with the actual time of the major oil release (12 noon on the 23rd of September) corresponding to 28 hours in the computer simulations. The model was also used to consider what would happen if oil was released under ambient conditions corresponding to the second small oil spill which was believed to occur at approximately 4.00pm, or 32 hours in the computer simulations.

The results of the simulations were presented graphically (along with the change in tidal height over the same period) and compared to field observations. The volume of oil introduced in the simulations was 100L (approximately 80kg) and this was released over a half hour period corresponding to 28-28.5 hours in the case of the major oil spill, and 32-32.5 in the case of the smaller spill, at a rate of 0.05kg s^{-1}. The same volume of oil was used in both the first and second spill simulations since the actual volume of oil released was not definitely known at the time of modelling and it was the grounding sites rather than the volume of oil beaching which were of interest.

One problem encountered with the FLOWM Model was that pelagic oil which reached the model boundaries was lost from the simulation while in a 'real' spill all oil present in the system (ocean) has the potential to be recirculated. Another problem was that the model does not account for oil stranded on the coastline. In a 'real' oil spill, oil which is stranded on the shore higher than subsequent tides can reach is effectively removed from the volume of circulating oil, but under appropriate conditions this oil can be redistributed and re-enter the system.

As a rough approximation of oil retention on a rocky coast (the coastal loss factor) it could be supposed that 1.7% of oil incident at the water-land interface as the tide recedes is retained on shore. This was a very conservative estimate (and was likely to underestimate the real situation) but was based on the knowledge that rocky substrata does not readily retain oil. If it is assumed that beached oil is not removed by subsequent tides, the amount of simulated oil actually retained on the shore can be estimated over a set amount of time. This is done by measuring the amount of oil arriving at the 'instrument' study sites and applying the coastal loss factor to this volume. Based on these assumptions the actual amount of oil accumulating intertidally at study sites was calculated for one of the oil spill simulations used to validate the FLOWM Model. This simulation used release of 100L (approx. 80kg) of crude oil from the 'Deep Ocean Point' at 28 hours of simulation time in combination with a surface mixing depth of 0.003m, a wave drift factor of 15.4 and an oil decay time of 0.34 days.

Since the oil spill from the refinery involved the release of crude oil the simulations pertaining to this event used a range of values which were considered realistic of parameters relevant to this oil type. These included the surface mixing depth (h) of the oil while it was at sea, the strength of wave drift (γ) and the presence or absence of long-shore drift. A long-shore drift component (see Appendix 5.1b for a description) was included in all simulations presented graphically in this chapter. The manipulated parameters giving the best concordance between hypothetical and actual grounding sites were then adopted for use in modelling the seasonal transport of oil. It is the relative amount of oil arriving at instrument points which is important and since the actual volume of oil observed at study sites was not quantifiable a direct comparison could not be made between observed and simulated oiling levels.

Simulations to test the predictive ability of the model were initially run at half resolution, which meant the model could not differentiate between the Port Stanvac study sites. This level of resolution represented a huge saving in time while the model was being refined and the 'best' parameters were being selected. Once the optimal parameters had been identified the simulations were re-run at full resolution. The graphs generated from simulations of use in validating the FLOWM Model have been included in the "*Results*" section of this chapter.

5.5.2 Predicted Grounding Sites on a Seasonal Basis

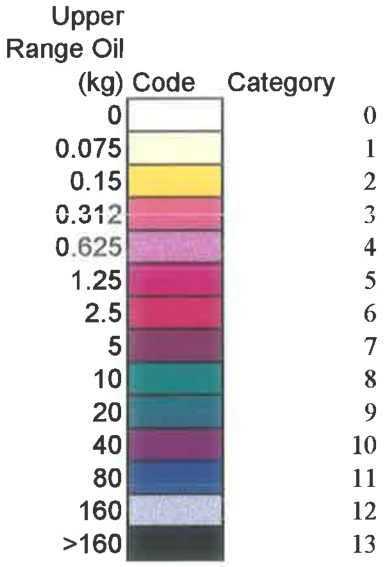
The 'optimal' parameter values identified in matching the observed oil grounding sites with those predicted from the computer simulations were retained for use in modelling of the likely seasonal grounding sites of oil. The bathymetry matrix used previously was again used. The instrument points of interest in seasonal modelling were the previously identified study sites and either the 'Deep Ocean Point' or the 'Wharf Point'. The seasonal simulations were carried out separately for crude oil and petroleum spilt from the 'Deep Ocean Point' but only release of refined product was modelled from the 'Wharf Point'. Separate simulations were carried out using low amplitude ('dodge') and 'high' amplitude tides to investigate grounding sites under these tidal extremes. All simulations were run at full resolution for this component of the study.

The timing of oil release was adjusted for each seasonal simulation to cover the full tidal cycle with simulated oil release occurring every three hours (at 24, 27, 30 & 33 hours of modelling time). 1000L of oil released over a half-hour period was used in the seasonal modelling simulations. This was a small volume but served the primary aim of predicting likely seasonal grounding sites. The period of time over which the simulated oil was discharged was thought to be realistic of an operational oil spill, which is likely to be rapidly detected and therefore (hopefully) controlled.

The results of the seasonal modelling were separately plotted as graphs (in the same form as those presented for the modelling of the actual oil spill) but due to the large number generated (160) the primary trends have been summarised and presented as matrices. To achieve this the amount of oil measured at those instrument points which corresponded to study sites was coded (Table 5.2). Then the coding was applied to the amount of oil recorded at specific times up to 24 hours after the simulated oil release under various seasonal conditions. The times selected were 3, 6, 9, 12 and 24 hours after oil release (Table 5.3). It must be noted that the oil coding system has been applied to oil recorded at the relevant instrument points, which is not the same as predicting the amount of oil grounding at these sites.

Table 5.2 The coding system used to categorise the amount of oil (in kg) recorded at relevant instrument points (corresponding to study sites) during seasonal modelling of the likely grounding sites of oil on eastern GSV. Seasonal modelling involved release of 1000L (approximately 800kg) of either crude oil or refined product over a half-hour period. x corresponds to the actual value of oil within the identified oiling range.

The Amount of Oil (kg)
0
$0.000< x \leq 0.075$
$0.075< x \leq 0.015$
$0.015< x \leq 0.312$
$0.312< x \leq 0.625$
$0.625< x \leq 1.250$
$1.250< x \leq 2.500$
$2.500< x \leq 5.00$
$5.00< x \leq 10.00$
$10.00< x \leq 20.00$
$20.00< x \leq 40.00$
$40.00< x \leq 80.00$
$80.00< x \leq 160.0$
160.00<



Upper Range Oil (kg)	Code	Category
0	⬜	0
0.075	🟨	1
0.15	🟨	2
0.312	🟥	3
0.625	🟪	4
1.25	🟥	5
2.5	🟥	6
5	🟥	7
10	🟩	8
20	🟦	9
40	🟪	10
80	🟦	11
160	🟦	12
>160	⬛	13

Table 5.3 The identified times of interest following computer simulations of the release of oil at different points in the tidal cycle (shown in column 1) on a seasonal basis. The aim of seasonal modelling was to predict the comparative extent of oiling at study sites in GSV if an oil spill occurred from Port Stanvac. The trialed timing of oil release were 24, 27, 30 and 33 hours of computer simulation time. Cells in the table hold the actual computer simulation times (in hours) at which study site oiling was measured which correspond to 3, 6, 9, 12 & 24 hours post oil release.

	Time since the release of oil (hours)				
Oil Release (hrs)	3	6	9	12	24
24	27	30	33	36	48
27	30	33	36	39	51
30	33	36	39	42	54
33	36	39	42	45	57

Seasonal simulations utilised the average wind stress components presented in Bye (1976) to account for wind induced influences. The most important manipulated parameters used in the seasonal simulations pertaining to a crude oil spill are shown in Table 5.4. The majority of these were consistent whether the oil released was crude oil or refined product. Where this was not the case, parameter values relating to a petroleum spill have been separately presented (Table 5.5). The surface mixing depth of pelagic oil was estimated taking into account various parameters (such as wave height), while the average seasonal 'dodge' tidal amplitude and maximum tidal amplitude were calculated using tidal height data collected at Port Stanvac over 1995 and provided by the NTF. Other parameters which are mentioned in Appendices S, T & U and which were specific to GSV have been provided by Dr. Bye (refer to Bye 1976). The average seasonal height of waves in GSV was not measured by the NTF, so this parameter was estimated. The decay time used in crude oil simulations was 0.34 days, while a shorter decay time of 0.17 days was used in the simulations involving refined product, which was assumed to weather at twice the rate of the crude oil. The wave drift parameter (γ) was estimated using formula 5.1.

Table 5.4 The main parameters estimated or calculated for inclusion in the seasonal oil spill simulations involving crude oil. Wind stress components (Nm^{-2}) are shown towards the north and east respectively and were obtained from Bye (1976). Wave drift was calculated as shown in Equation 5.1 and is unitless. The seasonal wave height (or wave boundary layer depth) was estimated, as was the surface mixing depth (although the results of the actual oil spill simulation were taken into account in estimation of the latter). The tidal amplitudes were calculated as seasonal averages using tidal height data provided by the NTF. The oil decay time used in the simulations was 0.34 days. All parameters are shown in metres unless otherwise specified. Parameters marked with * are consistent for both the crude oil and refined petroleum simulations.

	Season			
Parameter	Summer	Autumn	Winter	Spring
Wind Stress (North) Nm^{-2} *	0.0167	0.0129	-0.02550	0.0189
Wind Stress (East) Nm^{-2} *	0.0053	0.0350	0.0950	0.0694
Surface mixing depth of oil (h)	0.050	0.050	0.100	0.100
Minimum tidal amplitude *	0.471	0.201	0.414	0.310
Maximum tidal amplitude *	1.071	1.110	1.140	1.080
Wave height (h_w) *	1.000	0.800	1.500	1.500
Wave drift (γ)	9.990	12.400	5.500	5.500

Table 5.5 The main parameters estimated or calculated for inclusion in the seasonal oil spill modelling simulations in relation to a petroleum spill. Only those values which differed between crude oil (refer to Table 5.4) and refined oil have been shown. Petroleum was assumed to disperse in a very thin surface layer of 0.003m in all seasons, and to have an oil decay time of 0.17 days (e.g. to decay at twice the rate of the crude oil). The seasonal wave height (or wave boundary layer depth) was estimated and is shown in Table 5.4, and this was used along with the surface mixing depth (h) to estimate wave drift (γ) as shown in Equation 5.1. Wave drift is unitless and the surface mixing depth of the oil is in metres.

	Season			
Parameter	Summer	Autumn	Winter	Spring
Surface mixing depth of oil (h)	0.003	0.003	0.003	0.003
Wave drift (γ)	17.023	21.279	11.349	11.349

5.6 Results

5.6.1 The Operational Oil Spill and Validation of the Model

5.6.1.1 Observations and Assessment of Oil Spill Effects

On both assessment trips to GSV it was apparent that spilt oil had beached over quite a wide area extending from the jetty close to Witton Bluff to slightly south of the Port Noarlunga South site. Oil had also entered the mouth of the Onkaparinga River, which was boomed to prevent it travelling further into this waterway. Port Noarlunga South was exposed to oiling (and was designated an 'impact' site). Witton Bluff was also exposed to oiling but the high tides seen during and following the oil spill minimised any visible evidence of damage at this site. The restricted access to Witton Bluff prevented its use in post oil spill monitoring. No other study sites were obviously exposed to oil and these remaining sites served as unoiled 'controls'. The extent and nature of the oil spill has been visually shown in Plates 5.1-5.7.

It was apparent that the high tides which were seen during and immediately following the oil spill (Table 5.1) had carried oil across the 'impact' site (without leaving any obvious residues) and deposited it high on the shore beyond the mid-eulittoral area designated for biological sampling. The rough weather (which led to choppy seas with waves up to 2m) broke up the slick and resulted in the oil forming a 'mousse'. It would appear that the rapid breakup of the slick and the prevailing high tides protected the mid-eulittoral zones at Port Noarlunga South and Witton Bluff from apparent acute oil damage. Due to the lack of obvious oil residue in the area designated for sampling at Port Noarlunga South a Beyond-BACI analysis was not performed. However, the deposition of oil higher on the shore meant that before being stranded this oil would have overlaid the sampled area on a layer of water. This situation could result in direct or indirect effects on intertidal biota. Therefore, a multivariate analysis of animal assemblage patterns was used to investigate subtle changes coincident with the oil spill. This involved using data gathered on the 26th of September 1996 as well as 'preliminary' data and subjecting the combined data set to a SSH MDS Ordination (see Chapter 4, section 4.3.2). The results of this analysis will be given in Chapter 6.

Plate 5.1 The oil spill occurred from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. Oil grounded intertidally at high shore levels and was raked up and manually removed from the beaches.

Plate 5.2 Manual removal of oil from the shore of the Onkaparinga River Estuary.

Plate 5.3 A boom *in situ* in the Onkaparinga River Estuary to restrict oil transport into this waterway following the oil spill.

Plate 5.4 Heavy seas and rough weather on the day of the oil spill caused a water-in-oil emulsion termed a 'mousse' to form. This was comprised of 50-80% water dispersed in the oil phase and is seen here as a chocolate coloured material left by the receding tide on sand near Witton Bluff.

Plate 5.5 A closer examination of the mousse which formed under the agitated at-sea conditions prevailing at the time of the oil spill.

Plate 5.6 Obvious fresh oil deposits left by the receding tide at the low water mark on the shore at Port Noarlunga South.

Plate 5.7 The clean-up in progress at the Port Noarlunga South site on the 26th of September 1996. The study site is the most distant reef seen in the plate, and was designated as an 'impact' site.

5.6.1.2 Validation of the FLOWM Model

The Initial Oil Spill Simulations

The first computer simulations using the FLOWM Model involved the initial oil spill, which occurred at 12 noon (equivalent to 28 hours simulation time) on the 23rd of September 1996. Various oil decay times were trialed but varying this parameter was found to result in similar patterns of oil reaching the study sites although the amount of oil was influenced by the decay time used. For example, a more rapid decay time resulted in less oil reaching a particular point on the model sea or model shore. Therefore, although a number of simulations were tried using various oil decay times, the graphs included in this chapter which relate to modelling of the actual oil spill utilised an oil decay time of 0.34 days. It was thought that this would allow determination of the comparative degree of oiling affecting study sites even if the selected decay time was not realistic of the 'real' oil decay time.

The half-resolution modelling simulations mainly investigated the effect on the amount of oil reaching the study sites when the surface mixing depth of the oil and the wave drift factor were manipulated. Since the final thickness of an oil slick was reported in the literature to be about 0.003m (Hoult 1972), this was initially used as the surface mixing depth in the model. Other surface mixing depths which were trialed were 0.01, 0.05, and 0.10m. These values were used in combination with wave drift factors ranging from 2.5-20.0. The best half-resolution simulations applicable to the major (28 hour) oil spill, have been presented graphically (Figs 5.1-5.5). Simulations have been graphed over 28-64 model hours and the tidal cycle corresponding to this time interval has been plotted along with the amount of oil recorded at the point of oil release (the 'Deep Ocean Point'). The level of oiling experienced by the main study sites has also been graphed. As previously mentioned, the amount of oil recorded at study sites is the actual amount recorded close to the shore at a particular time but does not necessarily correspond to the amount of beached oil. The latter can be hypothetically determined using the coastal loss factor under receding tidal conditions.

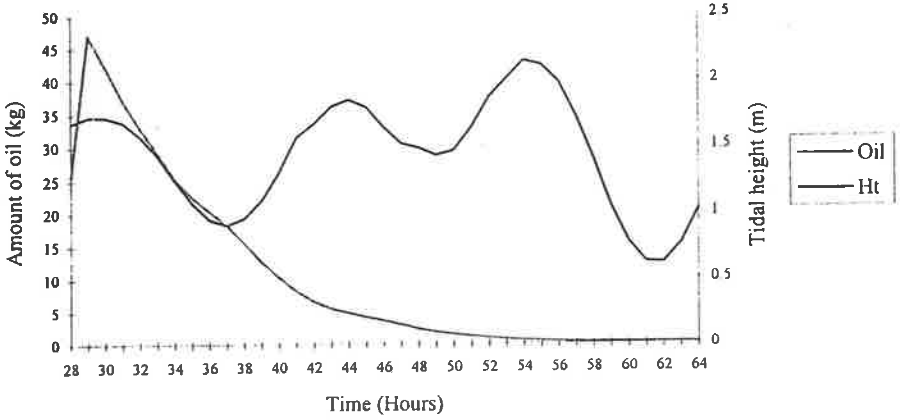
It had been reported that the majority of the oil released in the 'real' oil spill had grounded by 10pm on the day of the spill (equivalent to 46 hours of simulation time). Therefore, the relative amount of oil present at study sites after 50 hours of simulated modelling time was compared for similarities with the pattern of oiling seen at study sites during the 'real' oil spill. This amount of simulation time encompassed two low tides and was presumed to account for the majority of the oil reaching beaches. The results from the graphs have been summarised as Table 5.6.

Table 5.6 A comparison of the degree of oiling of instrument points (representing the main study sites) between 28-50 hours of simulated 'FLOWM' modelling time. The simulation involved the release of 100L (approximately 80kg) of Arabian light crude oil at 28 hours from the 'Deep Ocean Point'. This table summarises the results of Figs. 5.1-5.5. The decay time of the oil has been set to 0.34 days but the surface mixing depth (h) of the oil and the influence of wave drift (γ) have been manipulated. Study sites have been separated into their location groupings of 'Northern', 'Central' and 'Southern' and the maximum amounts of oil (at any one time) reaching the sites by 50 hours of simulated modelling time have been tabled. The maximum amount of oil reaching the sites represents the peak values shown in Figs. 5.1-5.5 <u>not</u> the accumulated amount of oil recorded at the particular instrument point over the 50 hours of interest. Abbreviations for study sites are; 'Northern'; KP=Kingston Park, MR=Marino Rocks, HCA=Hallett Cove A, 'Central'; PS=Port Stanvac sites (PS1, PS2 & PS3), and 'Southern'; WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point.

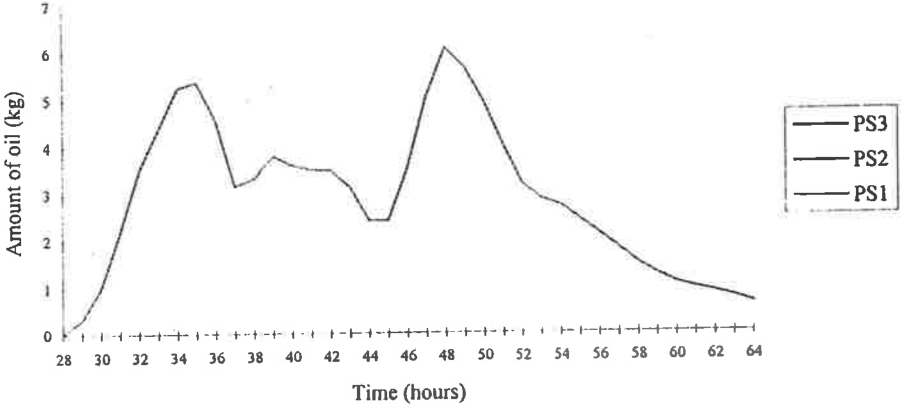
Figure	Adjusted parameters		Maximum oil reaching site (kg)		
	h (m)	γ	'Northern'	'Central'	'Southern'
5.1	0.003	20	KP=0.00 MR=0.03 HCA=0.85	PS=5.65	WB=8.31 PNS=0.00 RP=0.00
5.2	0.050	10	KP=0.00 MR=0.04 HCA=0.85	PS=0.51	WB=0.21 PNS=0.02 RP=0.02
5.3	0.050	6	KP=0.00 MR=0.02 HCA=1.84	PS=3.16	WB=0.19 PNS=0.02 RP=0.02
5.4	0.10	5	KP=0.00 MR=0.00 HCA=0.01	PS=0.17	WB=0.02 PNS=0.00 RP=0.00
5.5	0.50	4	KP=0.00 MR=0.00 HCA=0.00	PS=0.04	WB=0.00 PNS=0.00 RP=0.00

Fig. 5.1 The amount of crude oil recorded at instrument points in a half resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the x-axes, the amount of oil recorded at a particular instrument point is shown on the y-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 20 and the surface mixing depth was 0.003m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

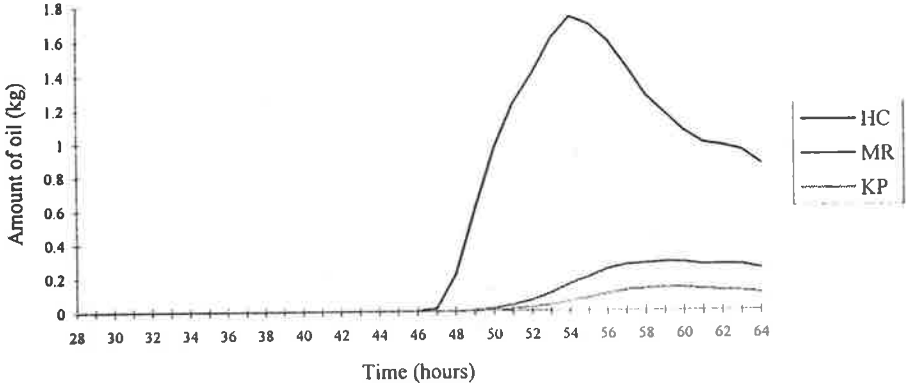
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

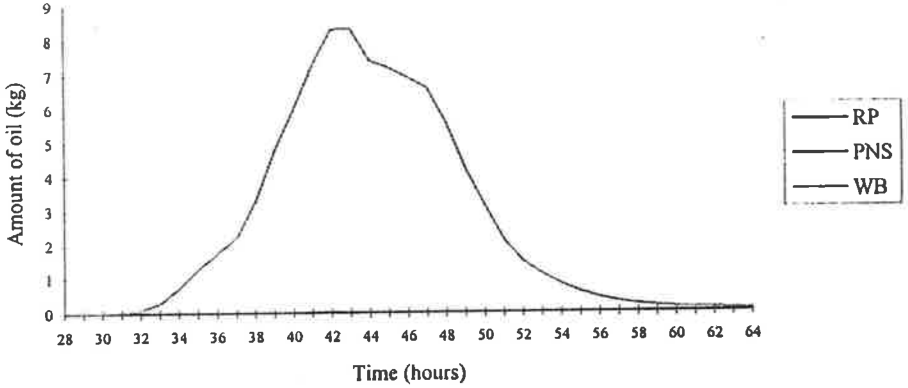
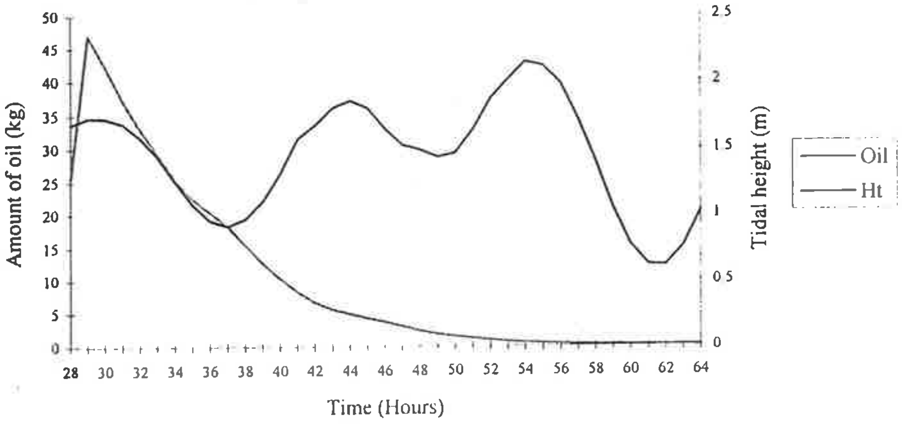
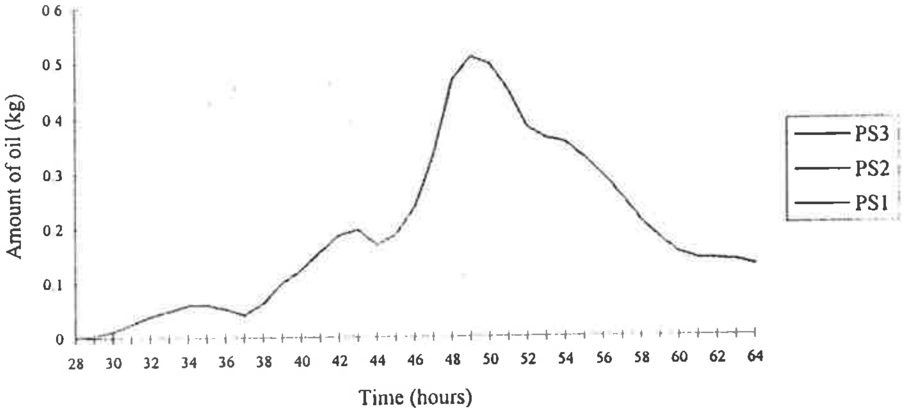


Fig. 5.2 The amount of crude oil recorded at instrument points in a half resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 10 and the surface mixing depth was 0.05m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

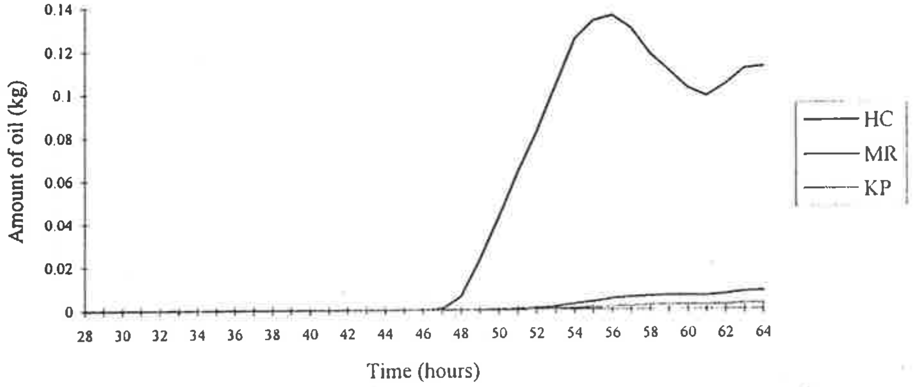
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

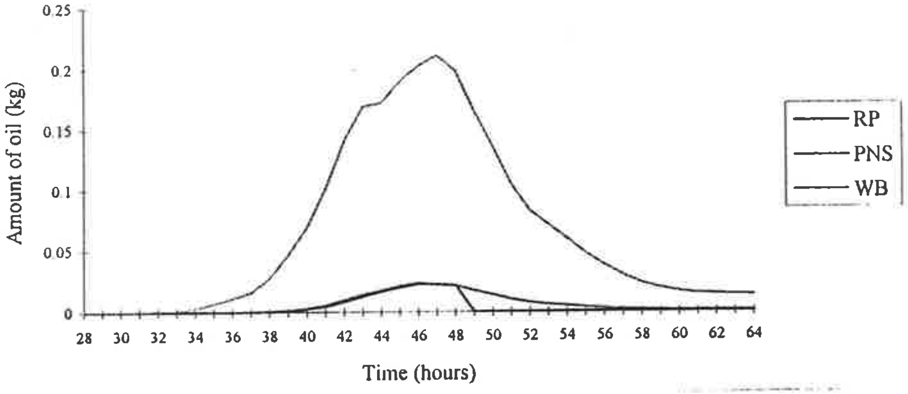
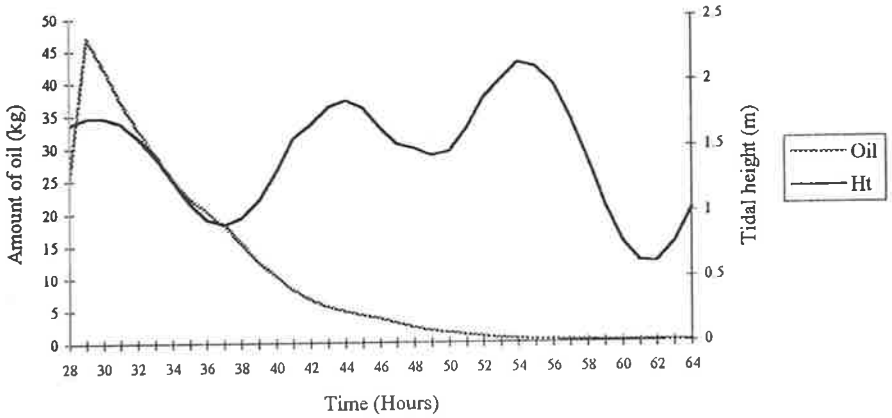
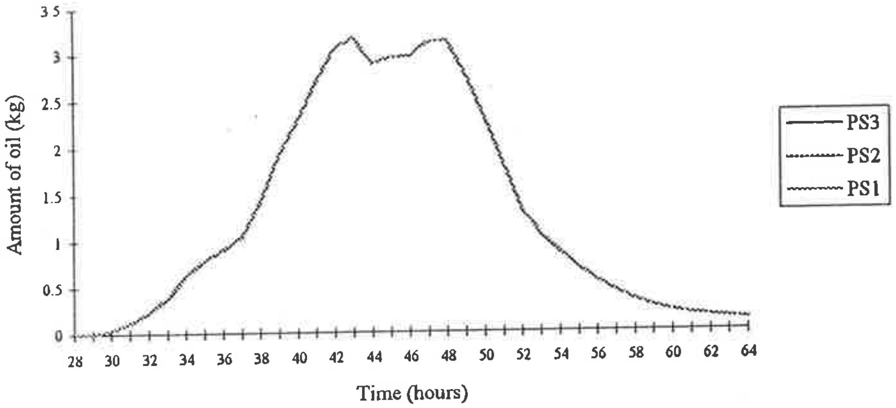


Fig. 5.3 The amount of crude oil recorded at instrument points in a half resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half-hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the x-axes, the amount of oil recorded at a particular instrument point is shown on the y-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 6 and the surface mixing depth was 0.05m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

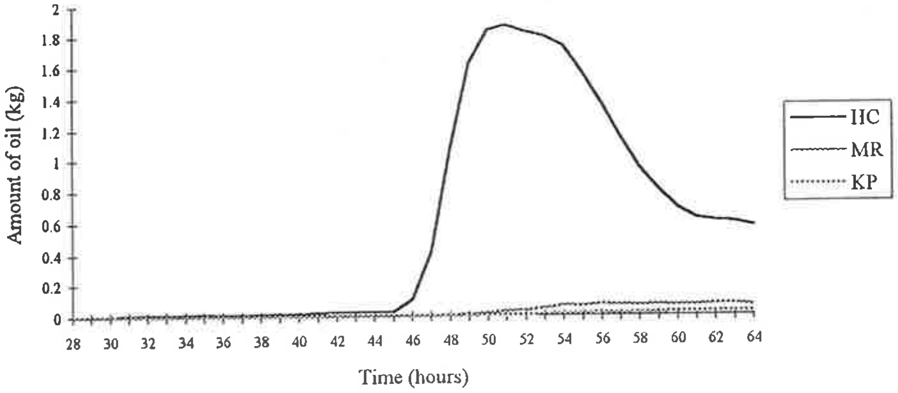
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

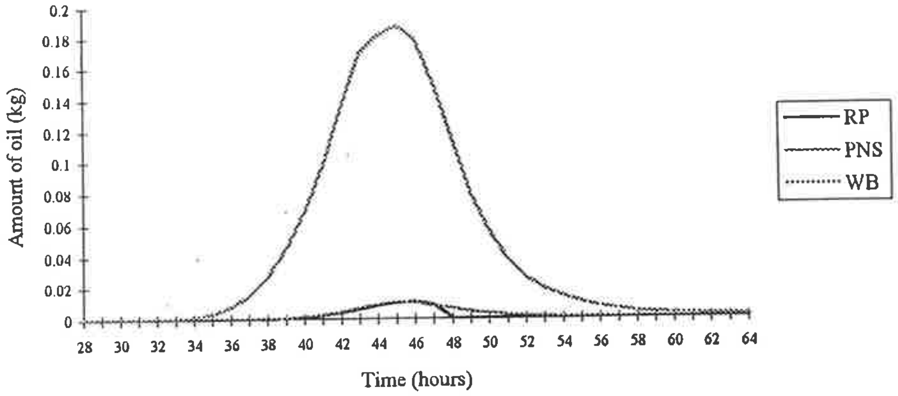
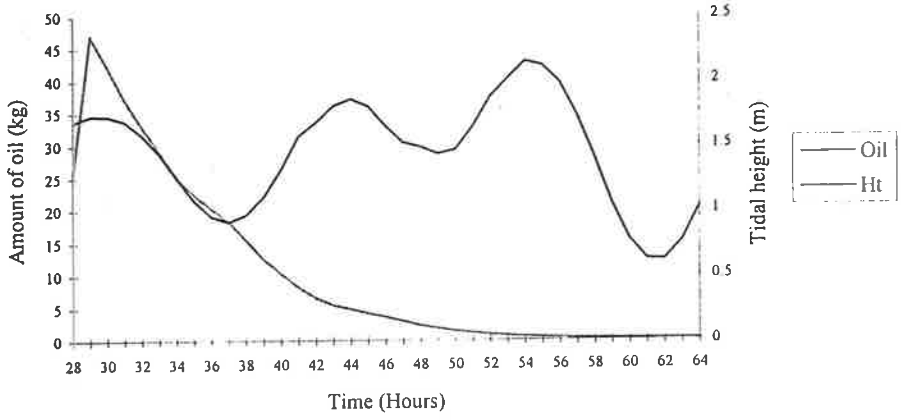
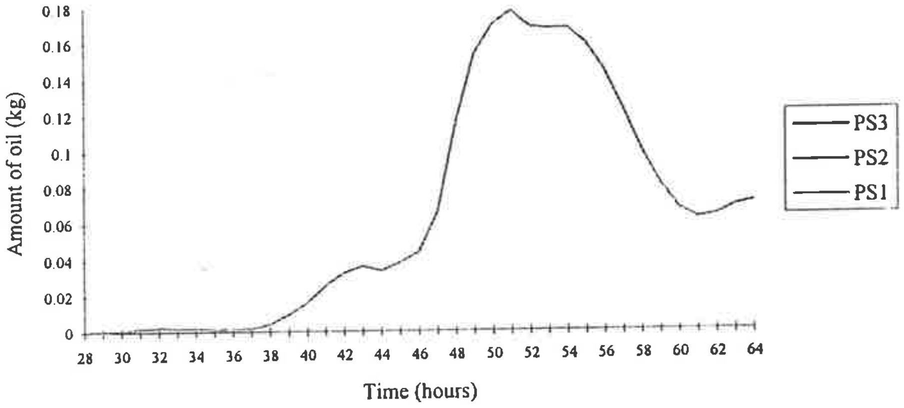


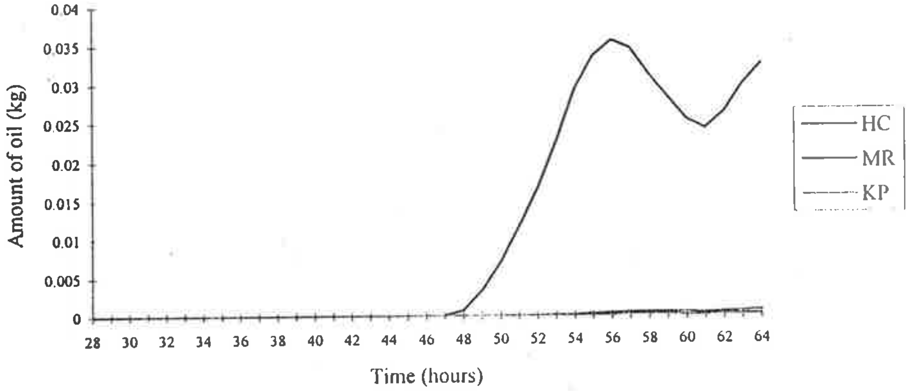
Fig. 5.4 The amount of crude oil recorded at instrument points in a half resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 5 and the surface mixing depth was 0.10m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).



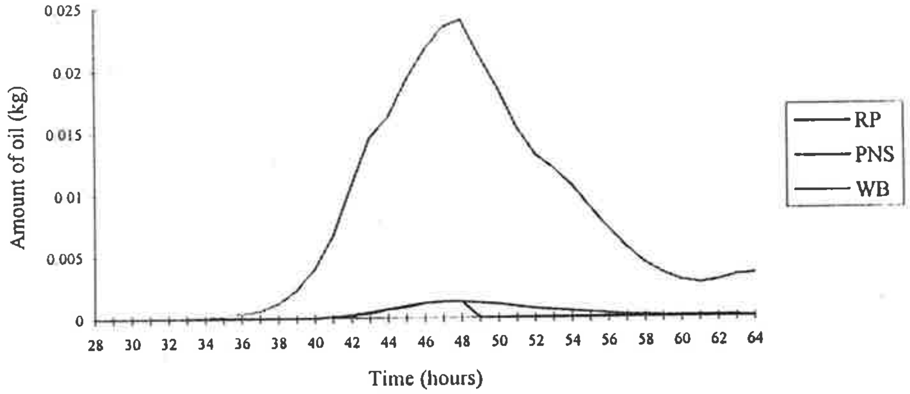
a) Deep Ocean Point



b) 'Central' Sites



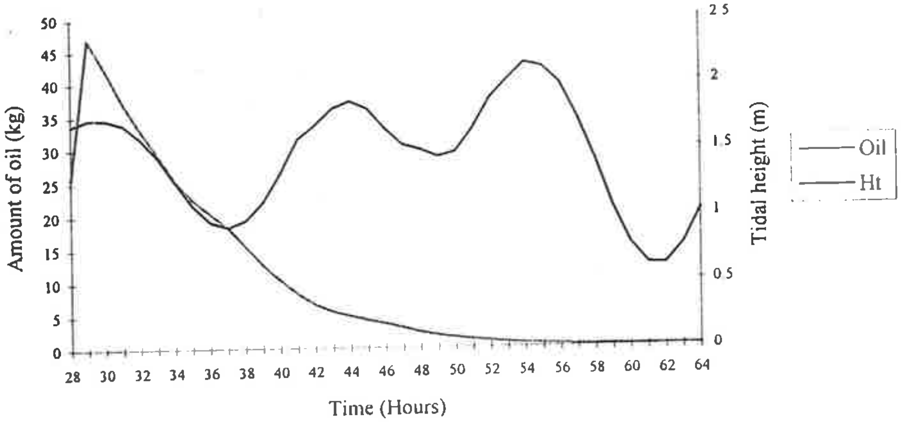
c) 'Northern' Sites



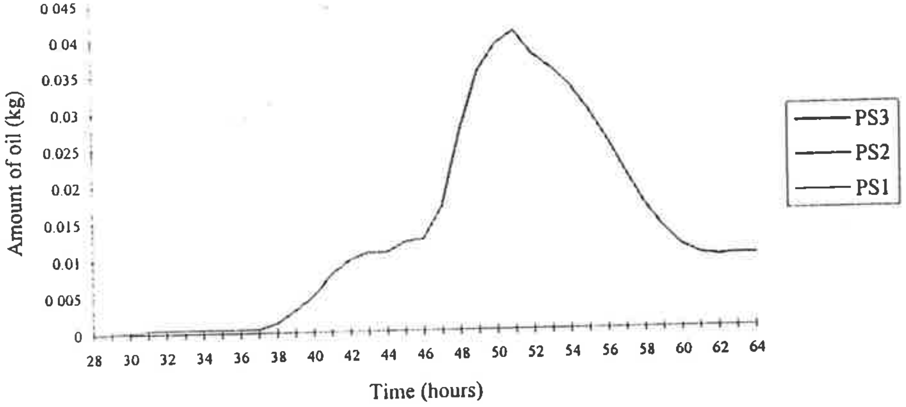
d) 'Southern' Sites

Fig. 5.5 The amount of crude oil recorded at instrument points in a half resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 4 and the surface mixing depth was 0.50m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

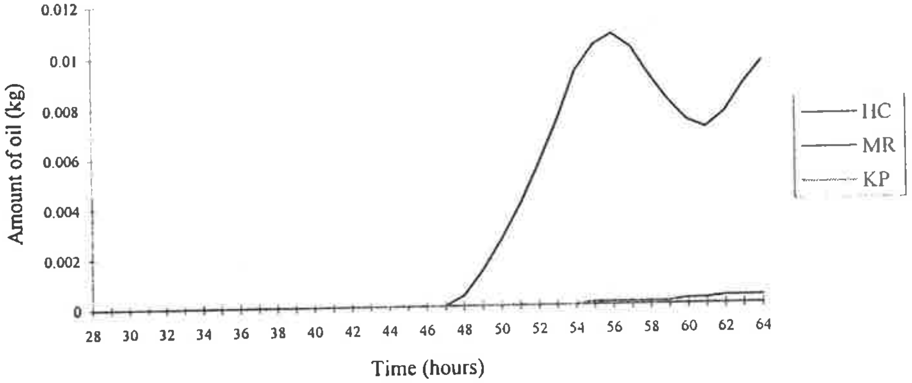
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

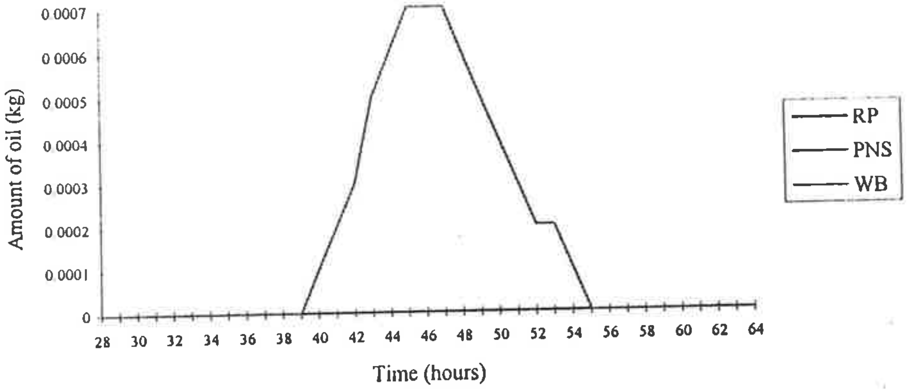
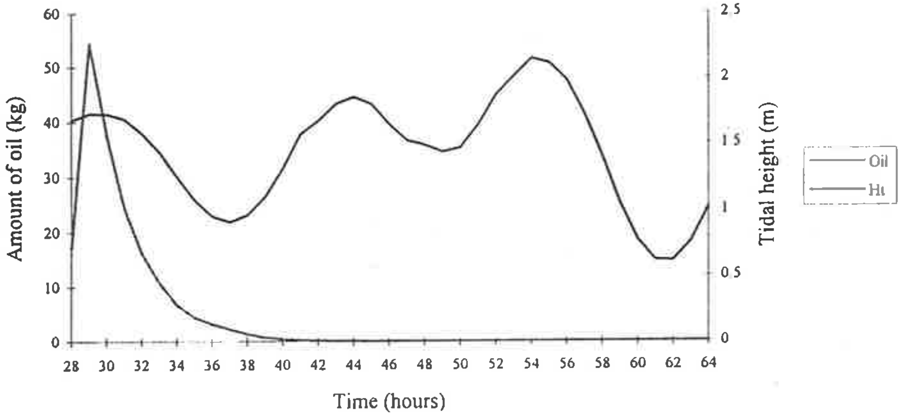
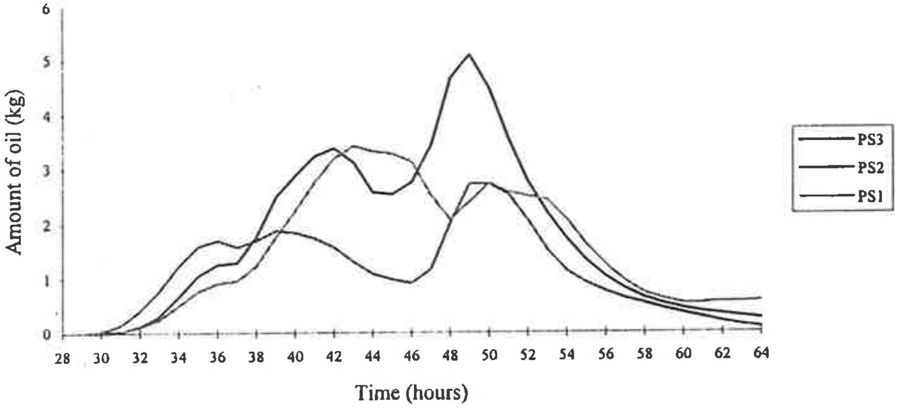


Fig. 5.6 The amount of crude oil recorded at instrument points in a full resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 15.4 and the surface mixing depth was 0.003m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

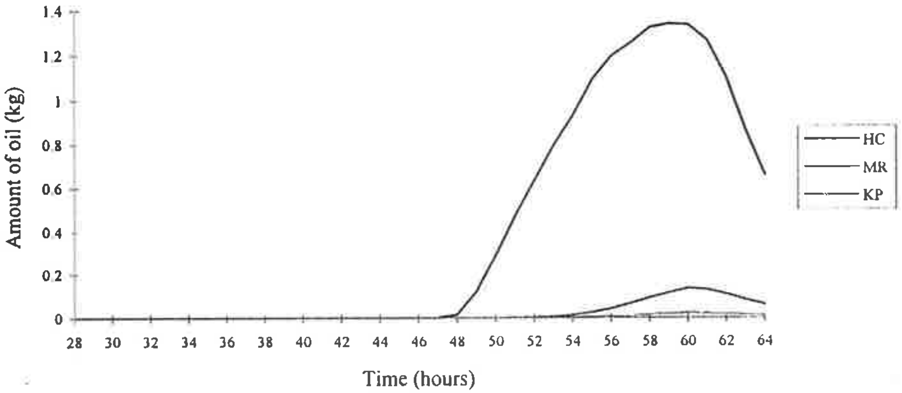
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

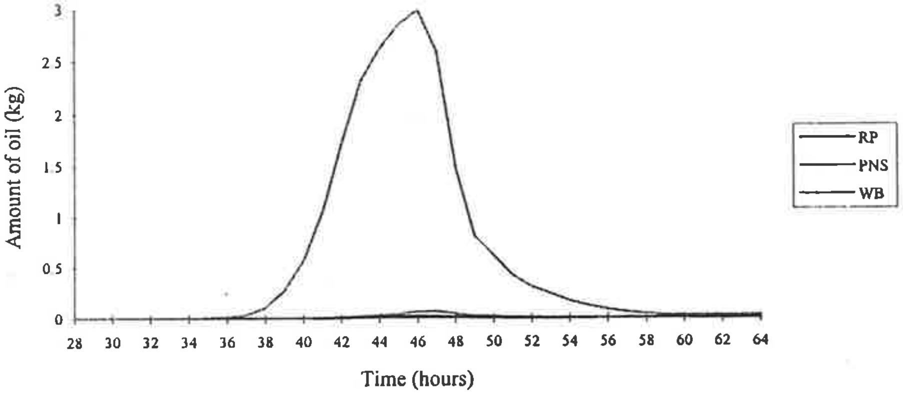
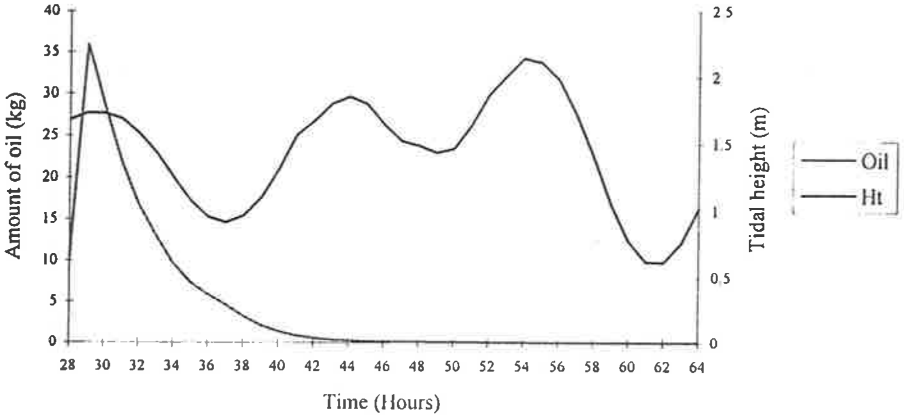
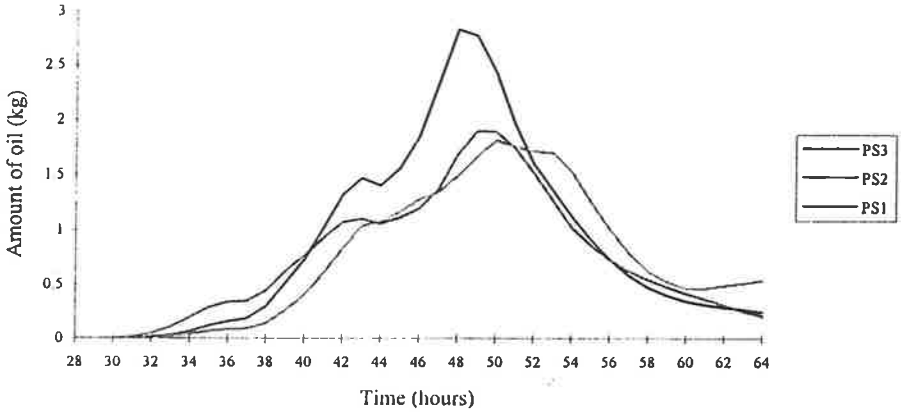


Fig. 5.7 The amount of crude oil recorded at instrument points in a full resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 10, the decay time was 0.34 days and the surface mixing depth was 0.05m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

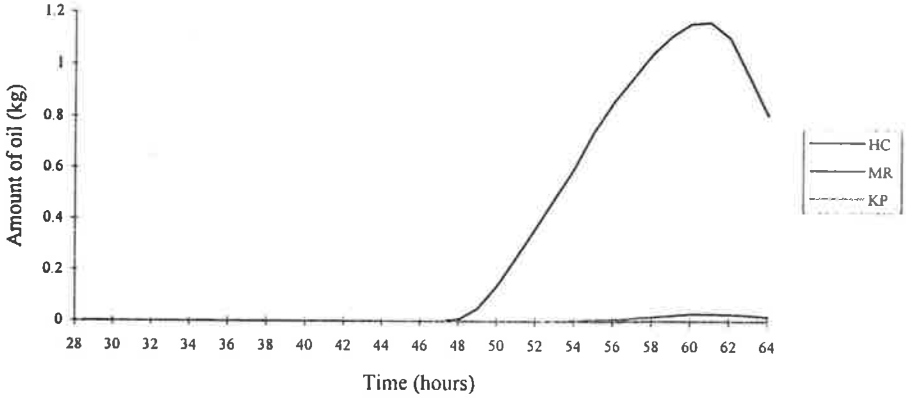
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

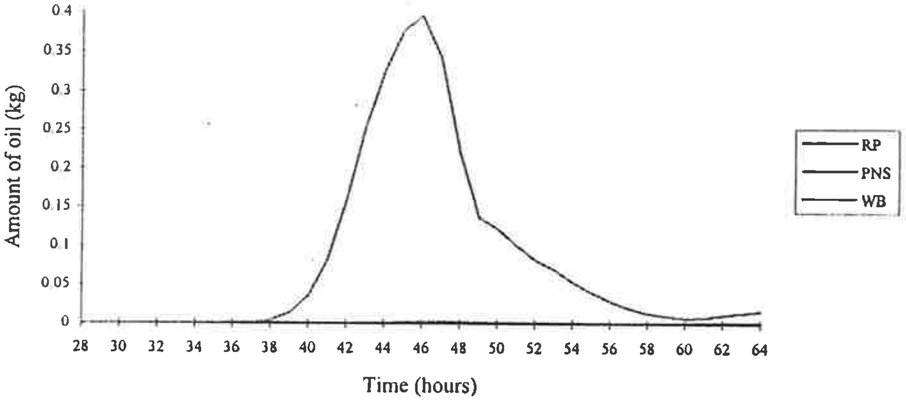
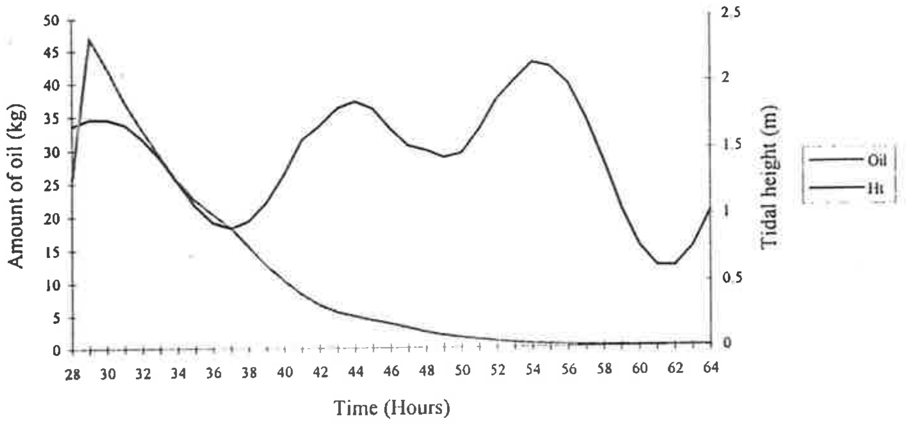
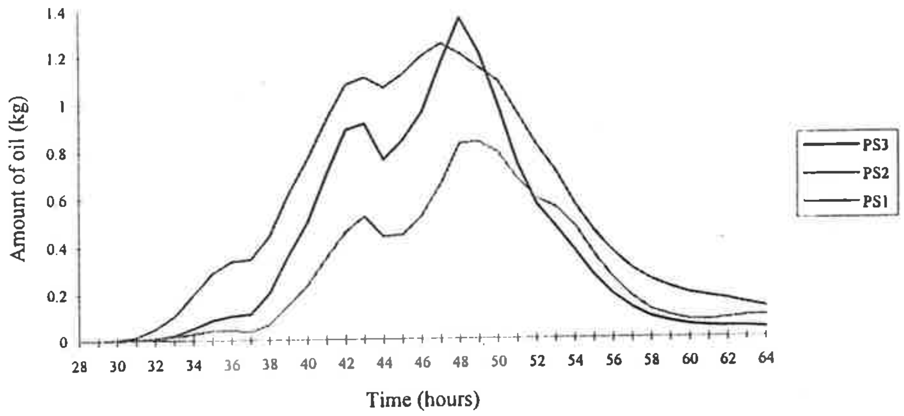


Fig. 5.8 The amount of crude oil recorded at instrument points in a full resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 28 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 10, the decay time was 0.17 days and the surface mixing depth was 0.05m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

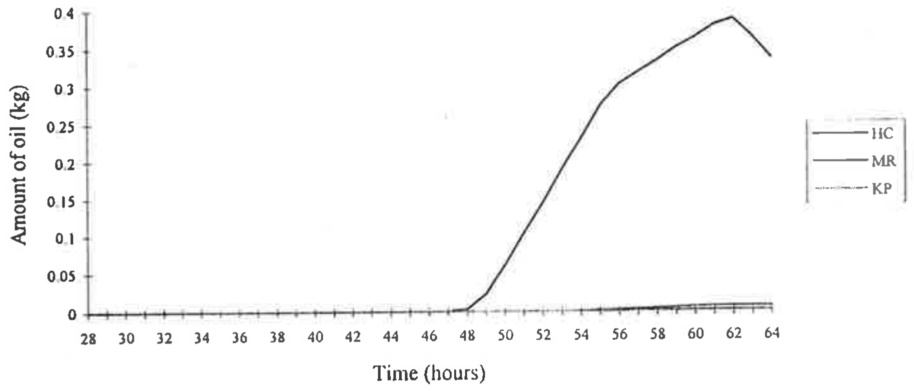
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

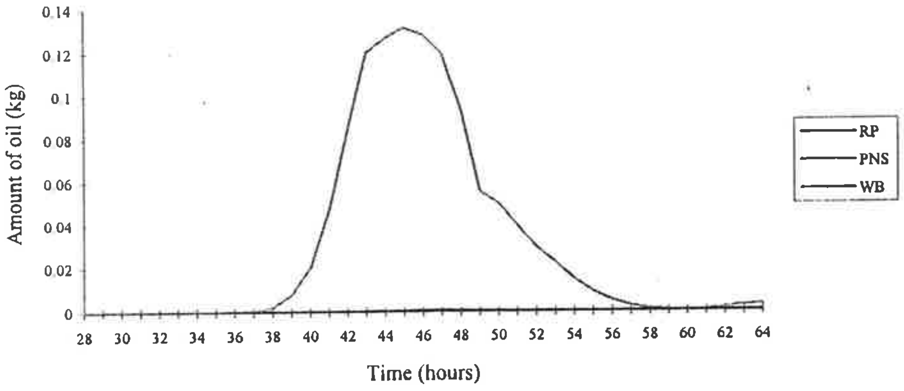
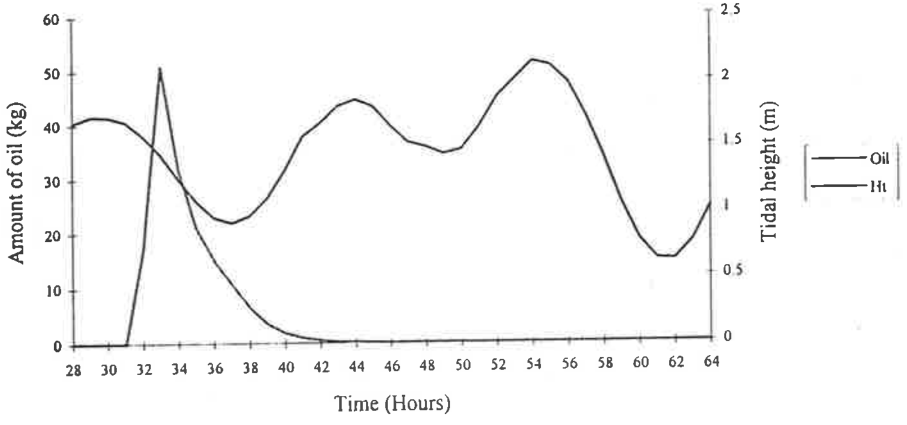
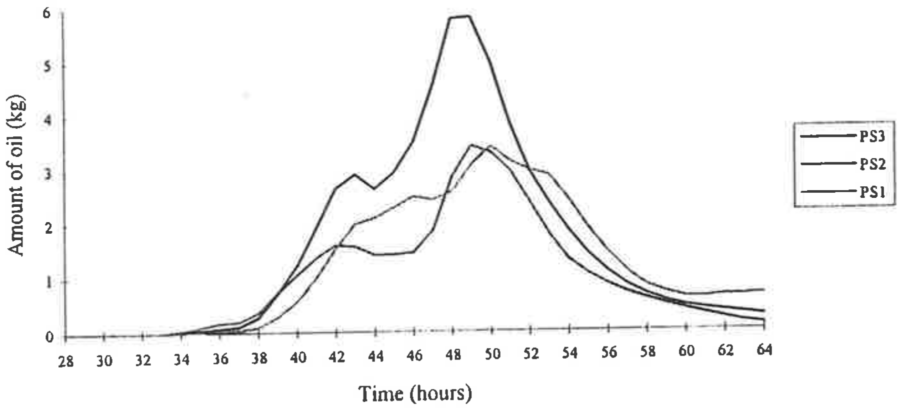


Fig. 5.9 The amount of crude oil recorded at instrument points in a full resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 32 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 15.4 and the surface mixing depth was 0.003m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).

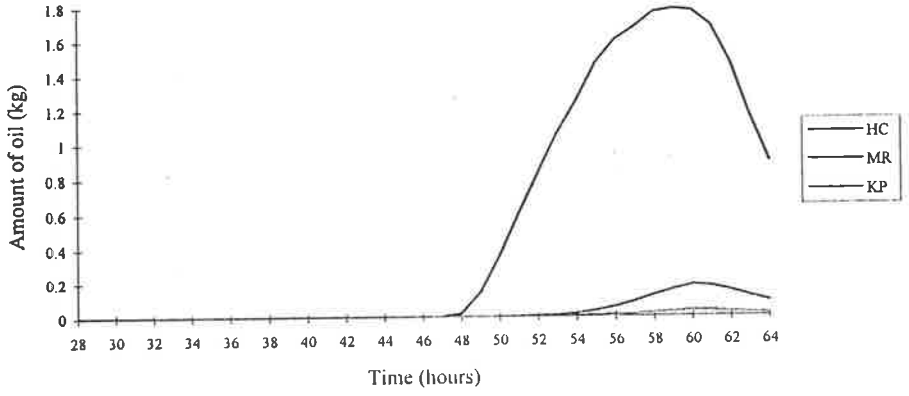
a) Deep Ocean Point



b) 'Central' Sites



c) 'Northern' Sites



d) 'Southern' Sites

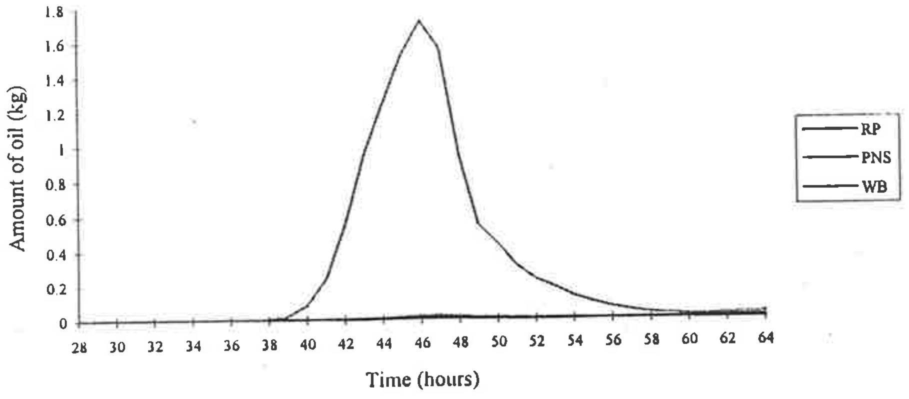
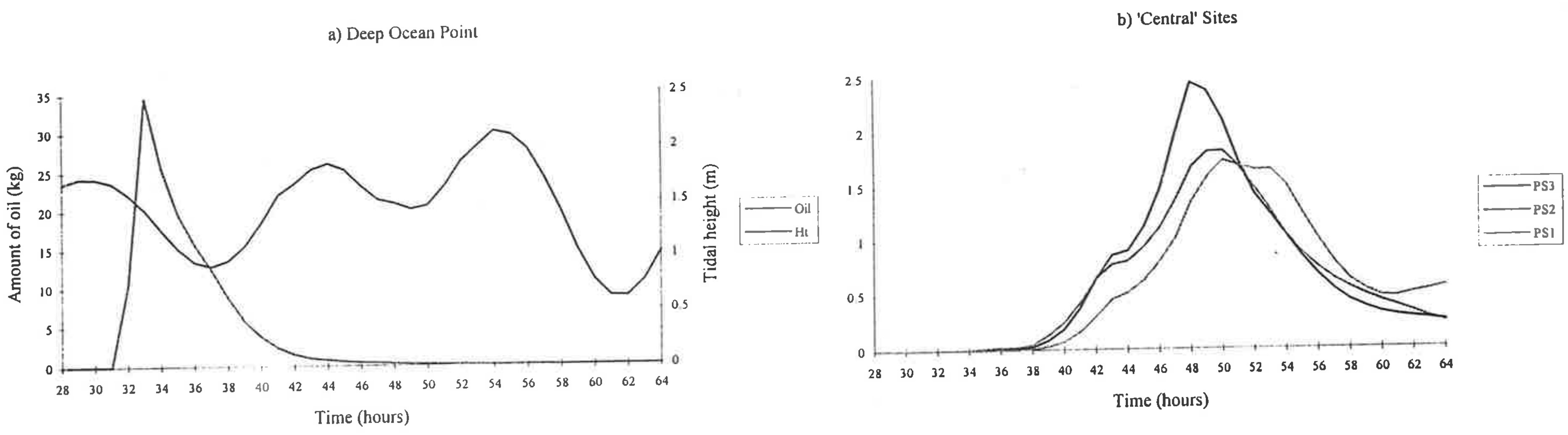
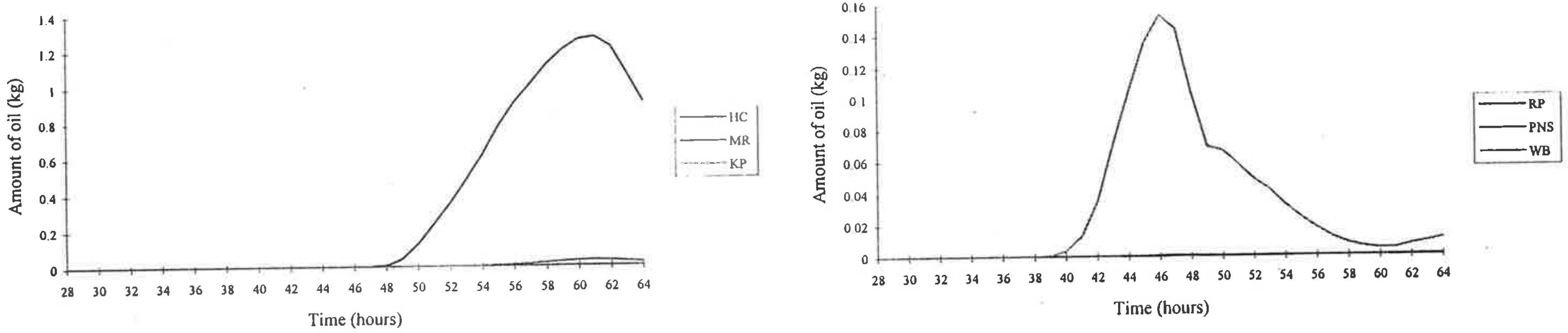


Fig. 5.10 The amount of crude oil recorded at instrument points in a full resolution FLOWM computer simulation of the oil spill occurring from the 'Deep Ocean Point' at the Port Stanvac Oil Refinery on the 23rd of September 1996. The amount of oil used in the simulation was 80kg. The computer simulation was run for 64 hours with the initial oil release occurring over a half hour period commencing at 32 hours of modelling time. The modelling time in hours is shown on the *x*-axes, the amount of oil recorded at a particular instrument point is shown on the *y*-axes, while the tidal height (Ht) (in m) occurring on the day of the oil spill is shown on the y_1 axis in a). The wave drift factor used in the simulation was 9.1 and the surface mixing depth was 0.05m. The amount of oil present is shown at a) the 'Deep Ocean Point', b) 'Central' Sites; PS1, PS2 & PS3, c) 'Northern' Sites; Hallett Cove A (HCA), Marino Rocks (MR) & Kingston Park (KP) and c) 'Southern' Sites; Robinson Point (RP), Port Noarlunga South (PNS) & Witton Bluff (WB).



a) Deep Ocean Point

b) 'Central' Sites



c) 'Northern' Sites

d) 'Southern' Sites

It was apparent that altering the surface mixing depth of the oil and the amount of wave drift could affect the sites where oil grounded and the amount of oil reaching instrument points (Figs 5.1-5.5 & Table 5.6). The half resolution modelling simulation which most closely resembled the pattern of oiling seen with the actual oil spill occurred when a surface mixing depth of 0.003m and a wave drift component of 20 were used (Fig. 5.1). However, in this simulation although Witton Bluff recorded a higher amount of oiling than all other study sites (Table 5.6) no oil was detected at Port Noarlunga South which was heavily oiled in the 'real' oil spill. Another problem with the results of all half-resolution simulations was the generally high oiling levels seen at 'Central' (Port Stanvac) sites, inconsistent with the 'real' oil spill (Table 5.6).

The full resolution (28 hour) oil spill simulations (Figs. 5.6-5.8) were able to differentiate between the 'Central' study sites in terms of their exposure to oiling. These simulations gave a finer resolution (and potentially more accurate) result compared with the half-resolution modelling simulations. The oiling pattern which most closely approximated what was seen with the actual oil spill was achieved using a surface mixing depth of 0.003m and a heavy wave drift factor of 15.4 (Fig. 5.6). By 46 hours of modelling time all 'Southern' sites recorded peak amounts of oil, with Witton Bluff receiving maximum oiling. No oil had reached the 'Northern' study sites by 46 hours but all 'Central' sites recorded high oil levels by this time (Fig. 5.6). Increasing the surface mixing depth and decreasing the influence of wave drift resulted in less oil reaching the 'Southern' sites and comparatively more oil reaching the 'Northern' study sites (where the volume peaked by about 60 hours). This result was not consistent with the actual oil spill (Figs 5.6-5.8). The effect obtained by altering the decay factor can be seen by comparing Figs 5.7 and 5.8. It is readily apparent that a shorter decay time results in less oil reaching a site. In all full resolution simulations oil reached the 'Central' study sites in relatively large amounts which was not consistent with the lack of obvious oil at these sites following the actual oil spill.

The Second (Small) Oil Spill Simulations

The simulations used to test the likely grounding sites of oil spilt from the 'Deep Ocean Point' at 4.00pm (32 hours of simulation time) were conducted in the same way as described for the initial oil spill. However, only two of the graphs resulting from the full simulation runs have been included in this chapter (Figs 5.9 & 5.10). By the time the full resolution simulations were run the relationship between the wave drift factor, the surface mixing depth and the depth of the wave boundary layer (H_w) had been considered (formula 5.1). Based on this relationship and using an estimated H_w value of 1.1m, a wave drift factor of 15.4m was used in conjunction with a surface mixing depth of 0.003 (Fig. 5.9), and a wave drift factor of 9.1 was used with a surface mixing depth of 0.05m (Fig. 5.10). Decreasing the weighting of the wave drift factor and increasing the surface mixing depth of the oil, resulted in less oil reaching the study sites but comparatively more ending up at 'Northern' study sites, which again did not match the pattern of oiling observed in the field.

The later release simulations were characterised by the majority of the oil reaching 'Central' study sites, especially PS3, while 'Southern' sites received more oil than 'Northern' sites (Figs. 5.9 & 5.10, Table 5.7). However, if only the simulation time up to 46 hours was considered (corresponding to the time when the majority of oil was said to have grounded) the result more closely matched the situation in the field. By 46 simulation hours no oil reached the 'Northern' sites, maximum amounts had not yet been recorded at 'Central' sites, and peak amounts had reached the 'Southern' sites (Figs. 5.9 & 5.10). The simulation which most closely matched the 'real' oiling patterns, involved the shallower surface mixing depth and the greater weighting of the wave drift parameter. It would appear from the results of these simulations that the initial oil spill had a greater influence on oil contamination at study sites than did the smaller (second) oil spill. This was consistent with information provided by the EPA.

Table 5.7 A comparison of the degree of oiling recorded at instrument points (representing the main study sites) between 28-50 hours of simulated 'FLOWM' modelling time after the release of 100L (approximately 80kg) of Arabian light crude oil at 32 hours from the 'Deep Ocean Point'. This table summarises the results of Figs 5.9 & 5.10. Oil decay time was set at 0.34 days but the surface mixing depth (h) of the oil and the influence of wave drift (γ) have been manipulated. Study sites have been separated into their location groupings of 'Northern', 'Central' and 'Southern', and the maximum amount of oil (at any one time) reaching the sites by 50 hours of simulated modelling time has been tabled. The maximum amount of oil reaching the sites represents the peak values shown in Figs 5.9 & 5.10 not the accumulated amount of oil recorded at the particular instrument point over the 50 hours of interest. Abbreviations for study sites are; 'Northern': KP=Kingston Park, MR=Marino Rocks, HCA=Hallett Cove A, 'Central': PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, 'Southern': WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point.

Figure	Adjusted parameters		Maximum oil reaching site (kg)		
	h (m)	γ	'Northern'	'Central'	'Southern'
5.9	0.003	15.4	KP=0.000 MR=0.000 HCA=0.359	PS1=3.400 PS2=3.409 PS3=5.796	WB=1.715 PNS=0.021 RP=0.005
5.10	0.050	9.1	KP=0.000 MR=0.000 HCA=0.013	PS1=0.172 PS2=0.180 PS3=0.244	WB=0.015 PNS=0.000 RP=0.000

Oil left on Rocky Intertidal Substrata

As a crude approximation of the amount of oil left at study sites as the high tide receded, the coastal loss factor of 1.7% was applied to Fig. 5.6. The simulation times where conditions of a receding high tide prevailed occurred at 32, 44 and 54 hours so these times were targeted as the times when oil was likely to be stranded. The increasing heights of sequential high tides (see Fig. 5.6a) meant that oil left by the previous high tide could be contacted (and therefore potentially remobilised) by the next high tide. However, for the purpose of this exercise it was assumed that all oil accounted for as accumulating on the rocky shore by the coastal retention factor was entrapped in rocky substrata and retained on the shore. The patterns of oil retention resulting from the computer simulation shown in Fig. 5.6 revealed the greatest oil retention at 'Central' study sites, minimal oil retention at 'Northern' study sites and moderate oil retention at Witton Bluff and Port Noarlunga South (Table 5.8). The total amounts estimated to be accumulating on the shore were minimal compared to the total amount of oil recorded at the study site instrument points (and therefore the water-shore interface) over the 28-64 hours of computer simulation (Fig. 5.6).

Table 5.8 An approximation of the amount of oil retained intertidally at study sites in a simulated oil spill using a surface mixing depth of 0.003m, a wave drift factor of 15.4, and an oil decay time of 0.34 days (Fig. 5.6). Under these conditions, 100L (approx. 80kg) of crude oil was released from the 'Deep Ocean Point' at 28 hours of simulation time and was assumed to be retained on rocky shores only when a high tide was receding. The coastal retention factor used in this calculation of oil accumulation was 1.7% of the incident oil at the water-shore interface at the appropriate point in the tidal cycle. It was assumed that the oil was not remobilised by the next incoming high tide.

	The amount of oil retained on the shore (kg)			
	The simulated time of oil retention			
Study Site	32 hours	44 hours	54 hours	Total
Kingston Park	0.00000	0.00000	0.00002	0.00002
Marino Rocks	0.00000	0.00000	0.00022	0.00022
Hallett Cove A	0.00000	0.00000	0.01578	0.01578
PS1	0.00182	0.05637	0.03515	0.09334
PS2	0.00690	0.01840	0.01920	0.04460
PS3	0.00200	0.04360	0.02920	0.07480
Witton Bluff	0.00000	0.04449	0.00281	0.04730
Port Noarlunga South	0.00000	0.00051	0.00005	0.00056
Robinson Point	0.00000	0.00022	0.00000	0.00022

5.6.2 The Predicted Seasonal Grounding Sites of Spilt Oil

The results of modelling simulations to predict seasonal grounding sites of oil spilt at various times within a tidal cycle under the extremes of 'dodge' and maximum amplitude tidal conditions were separately considered for the two most likely points of oil release within the refinery. These points were identified as the 'Deep Ocean Point' and the 'Wharf Point'. Oil released from the 'Deep Ocean Point' could be either crude oil or refined product (petroleum), while only the latter is handled at the 'Wharf Point'. The parameters used for the two different types of oil have been previously presented (Tables 5.4 & 5.5). It was necessary to simplify the patterns of oiling seen at study sites under different seasonal influences due to the large number of graphs generated. Therefore, the data generated from the modelling simulations has been presented as seasonal oiling matrices with the level of oiling being assessed up to 24 hours following oil release (refer to Tables 5.2 & 5.3).

5.6.2.1 Oil Released from the 'Deep Ocean Point'

Crude Oil

The matrices pertaining to the amount of Arabian light crude oil reaching study sites under the influence of different seasonal factors are shown as Figs. 5.11-5.14. Results generated from the summer simulations were consistent whether the oil was released under 'high' amplitude or 'low' amplitude tidal conditions with the maximum oiling occurring at Hallett Cove and 'Central' study sites (Fig. 5.11). However, 12 to 24 hours following oil release, regardless of the timing of this release within the tidal cycle, very low levels of oiling were noted at some of the 'Southern' sites. The autumn simulations again showed consistent trends whether the oil was released under 'high' or 'low' tidal regimes, with the 'Northern' study sites receiving the maximum amount of oiling, and Hallett Cove being the first 'Northern' site exposed to this pollutant (Fig. 5.12). Oil released under the influence of 'low' tidal amplitudes never reached the 'Central' or 'Southern' sites, while minimal amounts of oil reached PS1 and PS2 under the influence of a more extreme ('high' amplitude) tidal range.

The simulations pertaining to the destination of crude oil under the influence of winter conditions were again consistent whether the oil was released under a 'high' or 'low' amplitude tidal regime and regardless of the timing of that release (Fig. 5.13). At no stage was oil recorded at 'Central' or 'Southern' study sites during these simulations and only very low levels of oil reached the 'Northern' study sites of which Hallett Cove was the most affected. More oil reached Hallett Cove when the oil was released under a 'high' amplitude tide at 30 hours of simulation time, while the 'low' amplitude tidal simulations were always characterised by extremely low levels of oiling (Fig. 5.13).

The patterns of oiling seen at study sites under spring conditions closely approximated trends seen in winter, with the 'Northern' study sites receiving the most exposure to oil (Fig. 5.14). However, the level of oiling recorded at these sites was consistently higher than was seen in winter, and Marino Rocks and Kingston Park received some exposure to oil 12-24 hours after its release. When the tidal amplitude used in the spring modelling was high, PS1 and PS2 occasionally received minimal amounts of oil, but no oil reached these sites when simulations involved a 'low' tidal amplitude (Fig. 5.14).

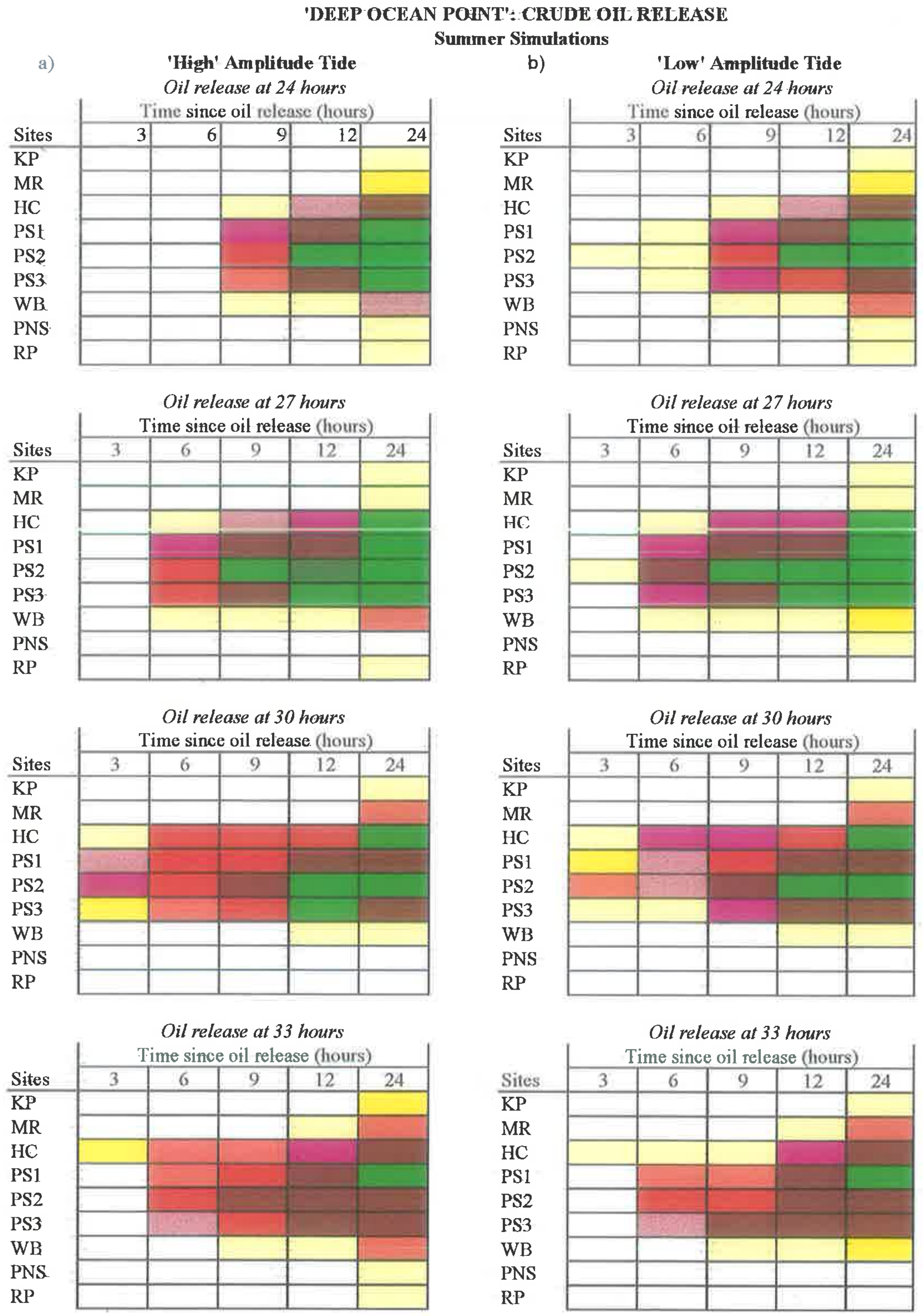
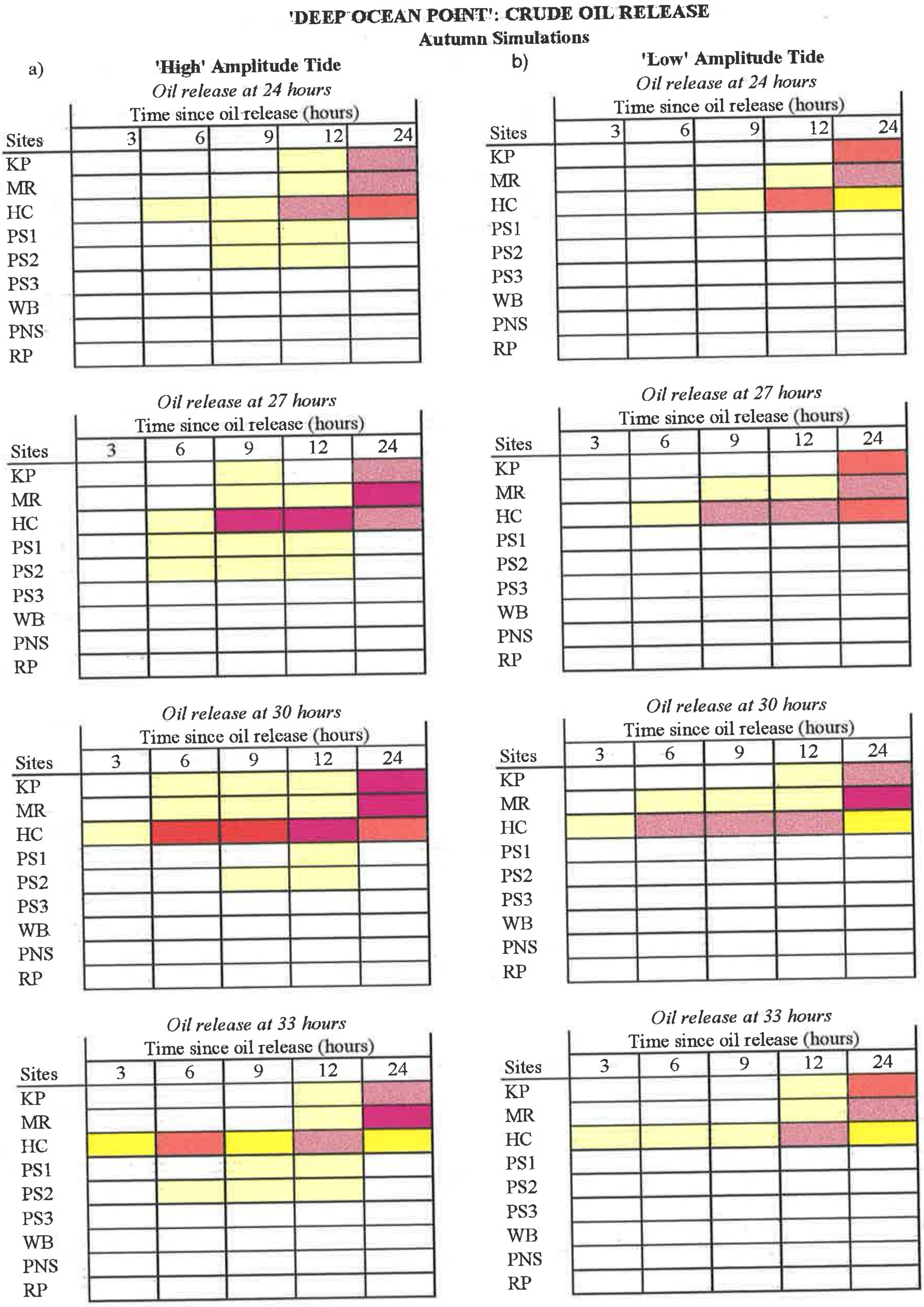


Fig. 5.11 The amount of crude oil predicted to reach study sites under simulated summer conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).



'DEEP OCEAN POINT': CRUDE OIL RELEASE

Autumn Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟫
MR				🟨	🟫
HC		🟨	🟨	🟫	🟧
PS1			🟨	🟨	
PS2			🟨	🟨	
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟨		🟫
MR			🟨	🟨	🟪
HC		🟨	🟪	🟪	🟫
PS1		🟨	🟨	🟨	
PS2		🟨	🟨	🟨	
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP		🟨	🟨	🟨	🟪
MR		🟨	🟨	🟨	🟪
HC	🟨	🟥	🟥	🟪	🟧
PS1				🟨	
PS2			🟨	🟨	
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟫
MR				🟨	🟪
HC	🟡	🟧	🟡	🟫	🟡
PS1			🟨	🟨	
PS2		🟨	🟨	🟨	
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					🟧
MR				🟨	🟫
HC			🟨	🟧	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					🟧
MR			🟨	🟨	🟫
HC		🟨	🟫	🟫	🟧
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟫
MR		🟨	🟨	🟨	🟪
HC	🟨	🟫	🟫	🟫	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟧
MR				🟨	🟫
HC	🟨	🟨	🟨	🟫	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.12 The amount of crude oil predicted to reach study sites under simulated autumn conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).

'DEEP OCEAN POINT': CRUDE OIL RELEASE

Winter Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR					🟨
HC				🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR					🟨
HC			🟨	🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR					🟨
HC	🟨	🟨	🟨	🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR				🟨	🟨
HC	🟨	🟨	🟨	🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC				🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR					🟨
HC		🟨	🟨	🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

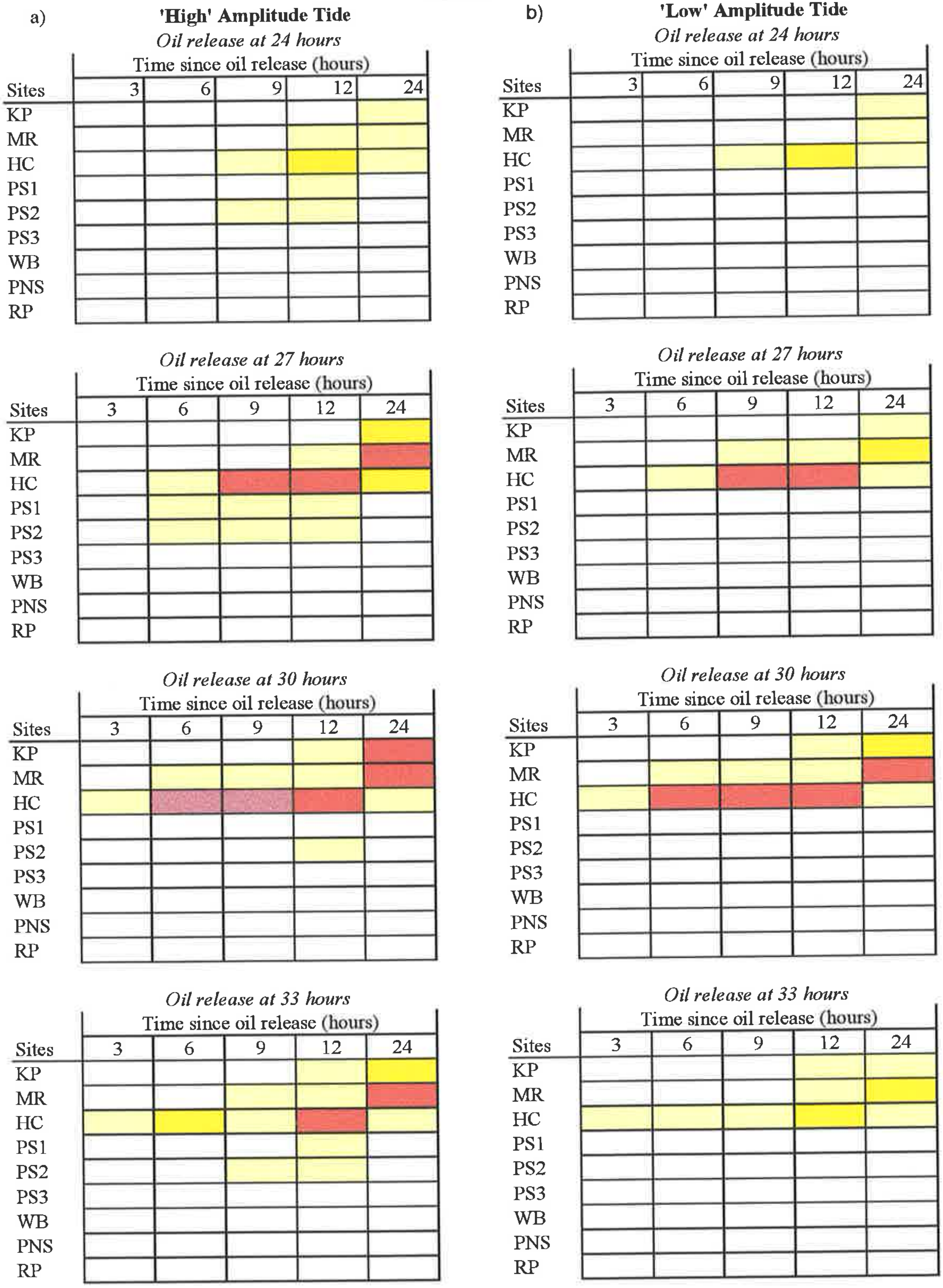
Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR					🟨
HC	🟨	🟨	🟨	🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					🟨
MR					🟨
HC			🟨	🟨	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.13 The amount of crude oil predicted to reach study sites under simulated winter conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).



'DEEP OCEAN POINT': CRUDE OIL RELEASE

Spring Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					░
MR				░	░
HC			░	🟨	░
PS1				░	
PS2			░	░	
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					🟨
MR				░	🟥
HC		░	🟥	🟥	🟨
PS1		░	░	░	
PS2		░	░	░	
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				░	🟥
MR		░	░	░	🟥
HC	░	🟪	🟪	🟥	░
PS1					
PS2				░	
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				░	🟨
MR			░	░	🟥
HC	░	🟨	░	🟥	░
PS1				░	
PS2			░	░	
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					░
MR					░
HC			░	🟨	░
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					░
MR			░	░	🟨
HC		░	🟥	🟥	░
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				░	🟨
MR		░	░	░	🟥
HC	░	🟥	🟥	🟥	░
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

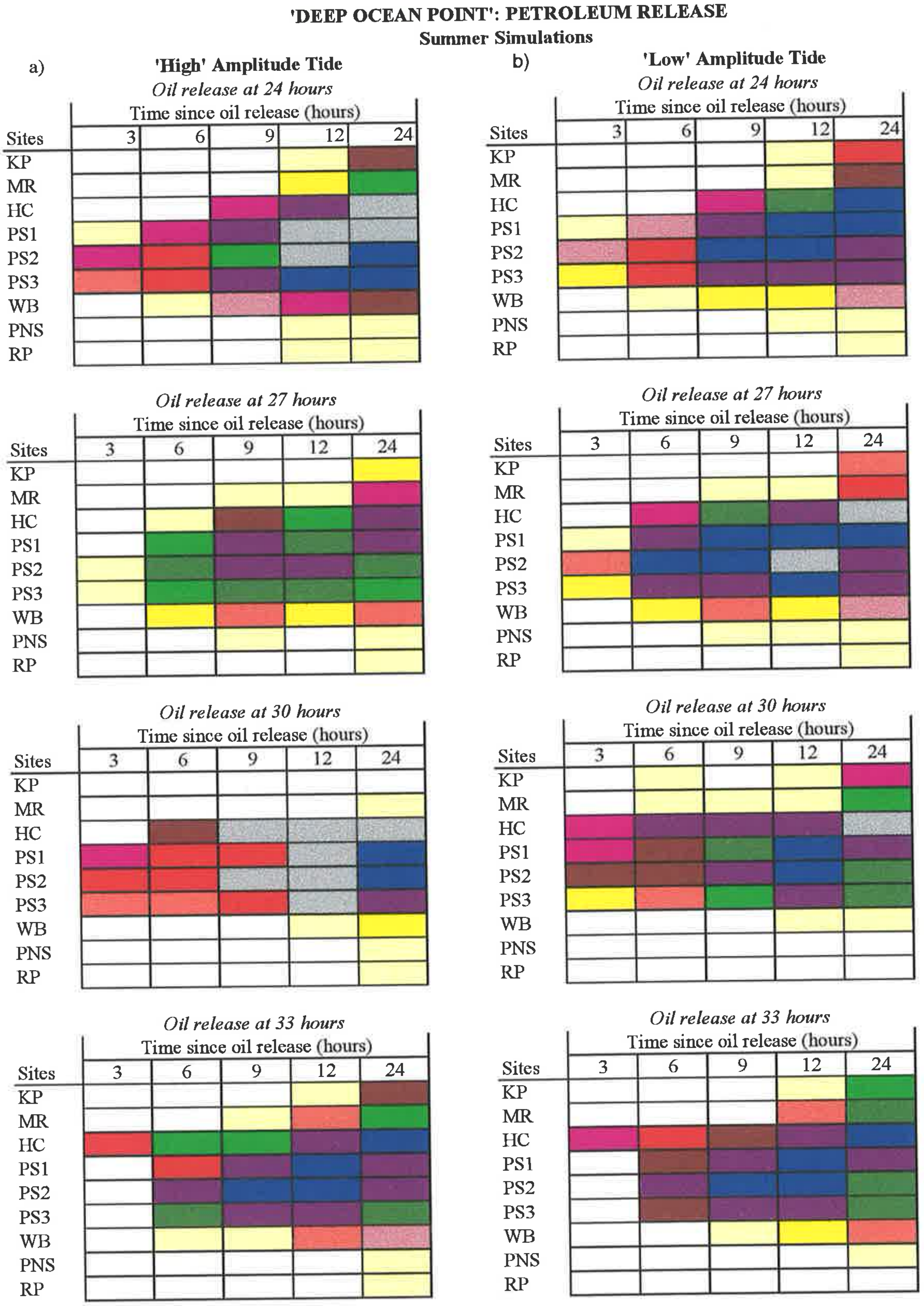
Sites	3	6	9	12	24
KP				░	░
MR				░	🟨
HC	░	░	░	🟨	░
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.14 The amount of crude oil predicted to reach study sites under simulated spring conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).

Petroleum

When petroleum release from the 'Deep Ocean Point' was simulated some differences in the pattern of oiling were seen compared to the results of the crude oil simulations. Simulations under summer conditions revealed a broad exposure of study sites to oil and higher levels of oiling compared to the equivalent simulations involving crude oil (Fig. 5.15). In general, Hallett Cove and PS2 received greater summer exposure to petroleum than the other study sites. However, high petroleum exposure occurred at PS1 and PS3, moderate exposure occurred at Witton Bluff, and petroleum was also recorded at Marino Rocks; in all cases the levels of exposure were comparatively higher under the influence of 'low' amplitude tides (Fig. 5.15).

Autumn simulations tended to result in moderate to high levels of oiling at all 'Northern' study sites. Petroleum occasionally reaching PS1 and PS2 in very small amounts if it was released at 30 or 33 hours of simulation time and influenced by a 'high' amplitude tide (Fig. 5.16). When petroleum was released in winter it was rare for it to reach any of the study sites regardless of the prevailing tidal conditions (Fig. 5.17). Petroleum released under spring conditions reached the 'Northern' sites but was never recorded at the other study sites (Fig. 5.18).



'DEEP OCEAN POINT': PETROLEUM RELEASE

Summer Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟫
MR				🟡	🟩
HC			🩷	🟪	▒
PS1	🟨	🩷	🟪	▒	▒
PS2	🩷	🟥	🟩	▒	🟦
PS3	🟧	🟥	🟪	🟦	🟦
WB		🟨	▨	🩷	🟫
PNS				🟨	🟨
RP				🟨	🟨

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					🟡
MR			🟨	🟨	🩷
HC		🟨	🟫	🟩	🟪
PS1		🟩	🟪	🟢	🟪
PS2	🟨	🟢	🟪	🟪	🟢
PS3	🟨	🟩	🟢	🟢	🟩
WB		🟡	🟧	🟡	🟧
PNS			🟨		🟨
RP					🟨

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					
MR					🟨
HC		🟫	▒	▒	▒
PS1	🩷	🟥	🟥	▒	🟦
PS2	🟥	🟥	▒	▒	🟦
PS3	🟧	🟧	🟥	▒	🟪
WB				🟨	🟡
PNS					🟨
RP					🟨

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟫
MR			🟨	🟧	🟩
HC	🟥	🟩	🟩	🟪	🟦
PS1		🟥	🟪	🟦	🟪
PS2		🟪	🟦	🟦	🟪
PS3		🟢	🟪	🟪	🟢
WB		🟨	🟨	🟧	▨
PNS					🟨
RP					🟨

b) **'Low' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟥
MR				🟨	🟫
HC			🩷	🟢	🟦
PS1	🟨	▨	🟪	🟦	🟦
PS2	▨	🟥	🟦	🟦	🟪
PS3	🟡	🟥	🟪	🟪	🟪
WB		🟨	🟡	🟡	▨
PNS				🟨	🟨
RP					🟨

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP					🟧
MR			🟨	🟨	🟥
HC		🩷	🟢	🟪	▒
PS1	🟨	🟪	🟦	🟦	🟦
PS2	🟧	🟦	🟦	▒	🟪
PS3	🟡	🟪	🟪	🟦	🟪
WB		🟡	🟧	🟡	▨
PNS			🟨	🟨	🟨
RP					🟨

Oil release at 30 hours

Time since oil release (hours)

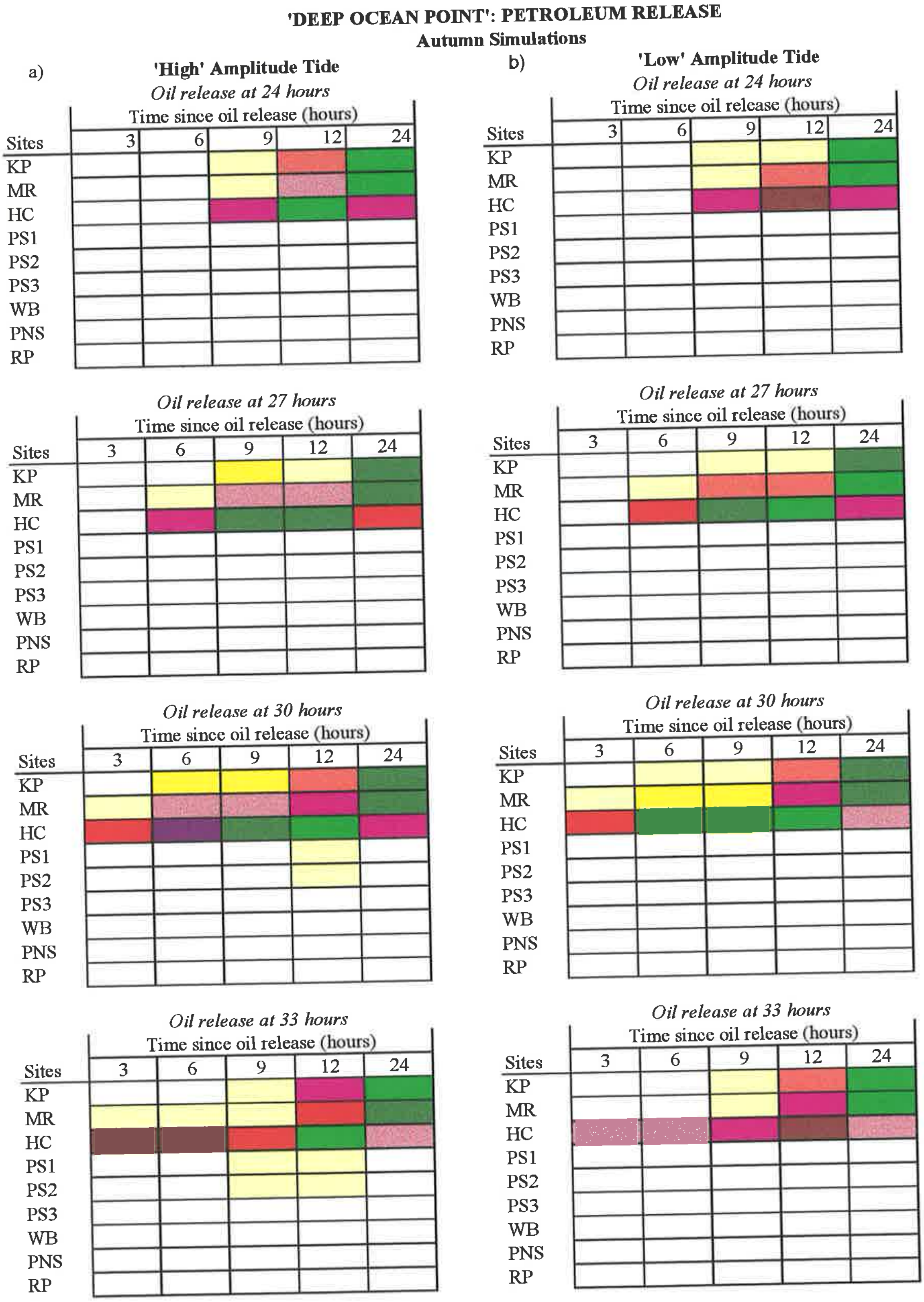
Sites	3	6	9	12	24
KP		🟨		🟨	🩷
MR		🟨	🟨	🟨	🟩
HC	🩷	🟪	🟪	🟪	▒
PS1	🩷	🟫	🟢	🟦	🟪
PS2	🟫	🟫	🟪	🟦	🟢
PS3	🟡	🟧	🟩	🟪	🟢
WB				🟨	🟨
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP				🟨	🟩
MR				🟧	🟢
HC	🩷	🟥	🟫	🟪	🟦
PS1		🟫	🟪	🟦	🟪
PS2		🟪	🟦	🟦	🟢
PS3		🟫	🟪	🟪	🟢
WB			🟨	🟡	🟧
PNS					🟨
RP					

Fig. 5.15 The amount of petroleum predicted to reach study sites under simulated summer conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).



'DEEP OCEAN POINT': PETROLEUM RELEASE

Autumn Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟨	🟧	🟢
MR			🟨	▨	🟢
HC			🟪	🟢	🟪
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟡	🟨	🟩
MR		🟨	▨	▨	🟩
HC		🟪	🟩	🟩	🟥
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP		🟡	🟡	🟧	🟩
MR	🟨	▨	▨	🟪	🟩
HC	🟥	🟣	🟩	🟢	🟪
PS1				🟨	
PS2				🟨	
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟨	🟪	🟢
MR	🟨	🟨	🟨	🟥	🟩
HC	🟫	🟫	🟥	🟢	▨
PS1			🟨	🟨	
PS2			🟨	🟨	
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟨	🟨	🟢
MR			🟨	🟧	🟢
HC			🟪	🟫	🟪
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟨	🟨	🟩
MR		🟨	🟧	🟧	🟢
HC		🟥	🟩	🟢	🟪
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP		🟨	🟨	🟧	🟩
MR	🟨	🟡	🟡	🟪	🟩
HC	🟥	🟩	🟩	🟢	▨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Time since oil release (hours)

Sites	3	6	9	12	24
KP			🟨	🟧	🟢
MR			🟨	🟪	🟢
HC	▨	▨	🟪	🟫	▨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.16 The amount of petroleum predicted to reach study sites under simulated autumn conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).

'DEEP OCEAN POINT': PETROLEUM RELEASE

Winter Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR				🟨	
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

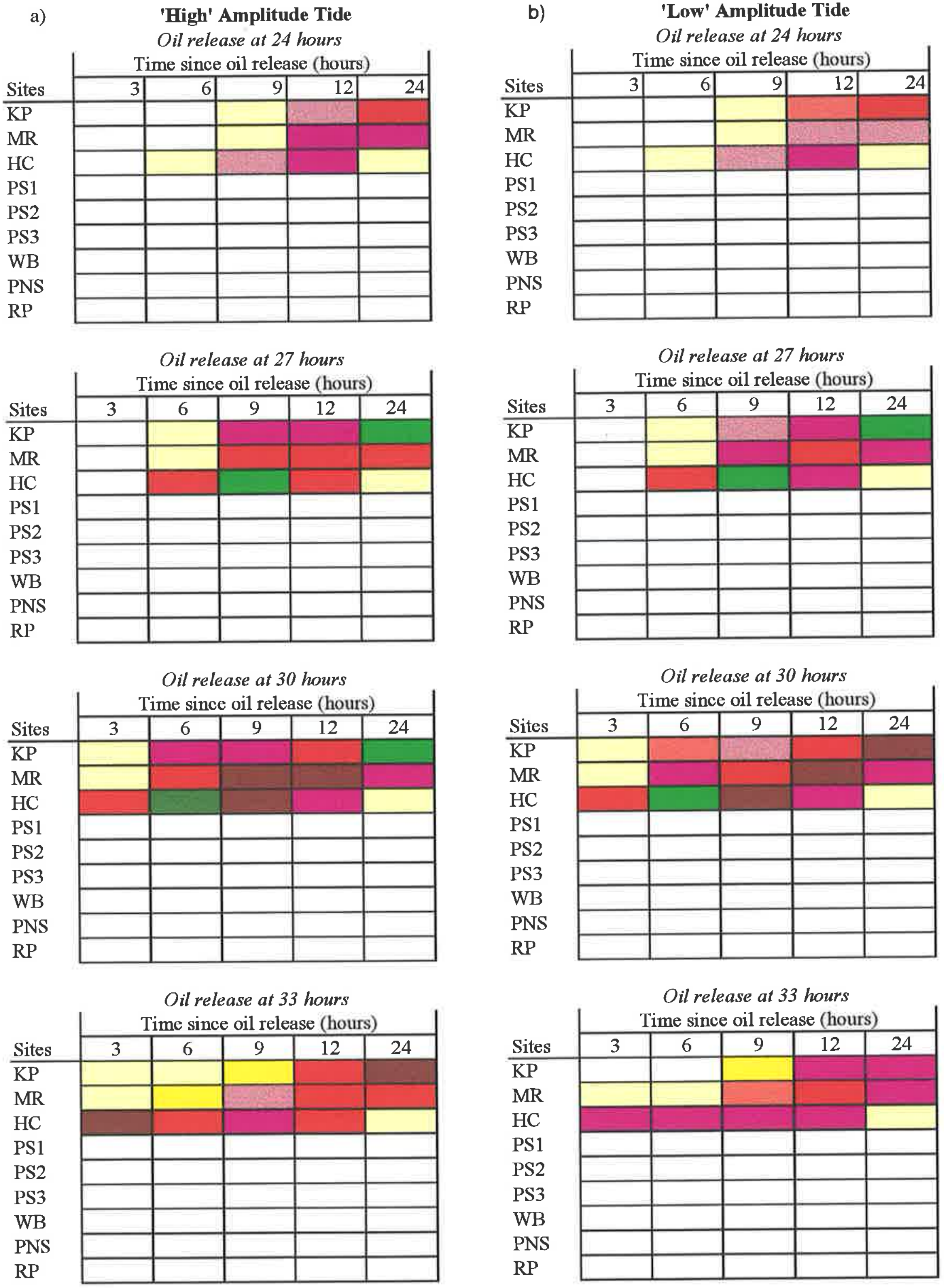
Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP					
MR					
HC					
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.17 The amount of petroleum predicted to reach study sites under simulated winter conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).



'DEEP OCEAN POINT': PETROLEUM RELEASE

Spring Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP			🟨	▨	🟥
MR			🟨	🟪	🟪
HC		🟨	▨	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP		🟨	🟪	🟪	🟩
MR		🟨	🟥	🟥	🟥
HC		🟥	🟩	🟥	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟨	🟪	🟪	🟥	🟩
MR	🟨	🟥	🟫	🟫	🟪
HC	🟥	🟩	🟫	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟨	🟨	🟡	🟥	🟫
MR	🟨	🟡	▨	🟥	🟥
HC	🟫	🟥	🟪	🟥	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP			🟨	🟧	🟥
MR			🟨	▨	▨
HC		🟨	▨	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP		🟨	▨	🟪	🟩
MR		🟨	🟪	🟥	🟪
HC		🟥	🟩	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟨	🟧	▨	🟥	🟫
MR	🟨	🟪	🟥	🟫	🟪
HC	🟥	🟩	🟫	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP			🟡	🟪	🟪
MR	🟨	🟨	🟧	🟥	🟪
HC	🟪	🟪	🟪	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.18 The amount of petroleum predicted to reach study sites under simulated spring conditions when released from the 'Deep Ocean Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).

5.6.2.2 Oil Released from the 'Wharf Point'

Petroleum released from the 'Wharf Point' tended to spread broadly across the range of study sites under simulated summer conditions. Low to moderate levels of petrol reached Witton Bluff, and occasionally the other 'Southern' study sites, while high levels were recorded at 'Central' study sites and Hallett Cove, and moderate levels were recorded at the remaining 'Northern' sites 12-24 hours after the release of the pollutant (Fig. 5.19). The simulated release of petroleum in all seasons other than summer resulted in exposure of only the 'Northern' sites to oiling (Figs 5.20-5.22). Moderate to heavy oiling of 'Northern' sites was predicted in autumn (Fig. 5.20) and spring (Fig. 5.22). Petroleum release from the 'Wharf Point' in winter primarily contaminated the Hallett Cove site, but this season was characterised by generally lower levels of oiling than were seen in other seasons (Fig. 5.21).

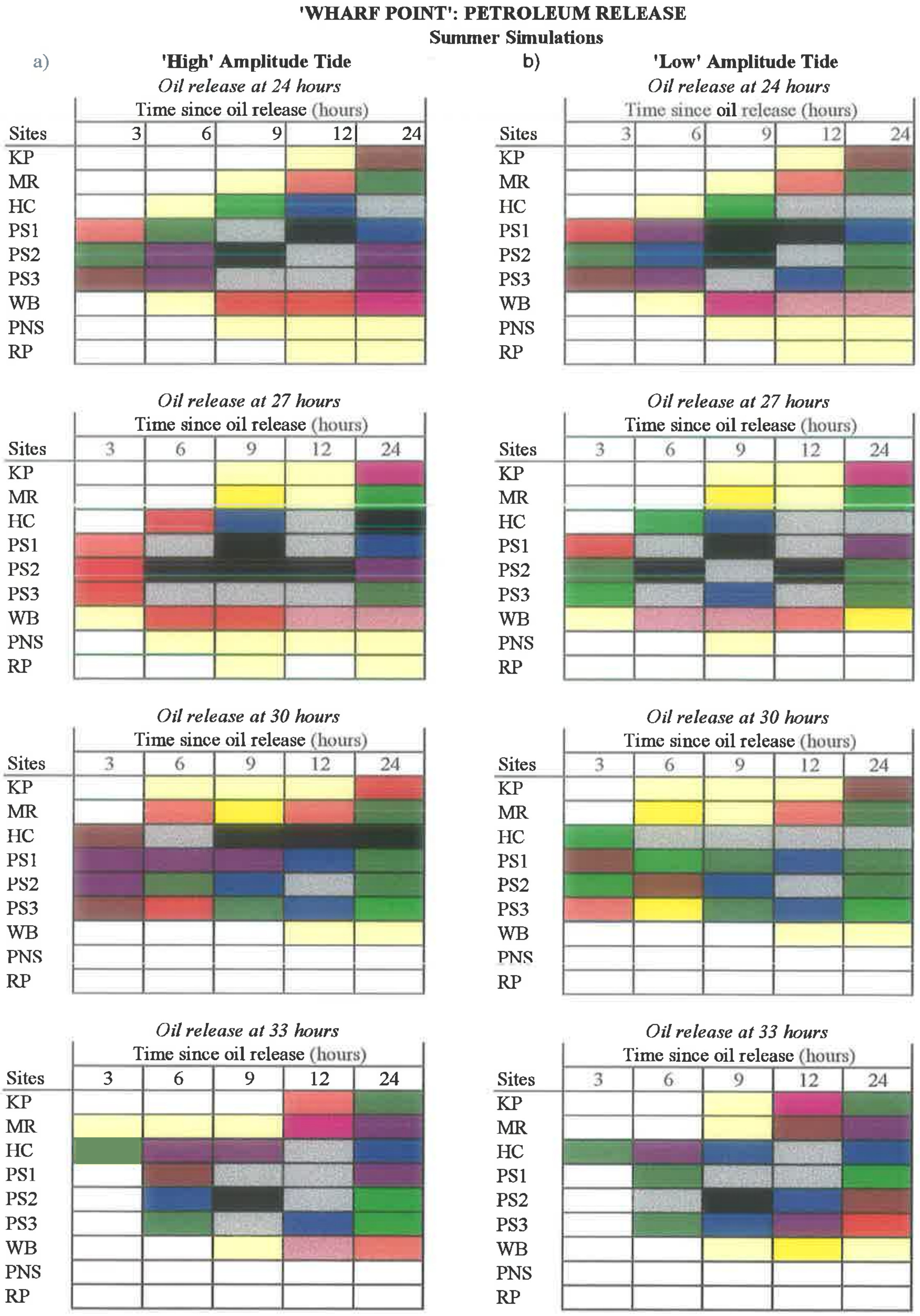
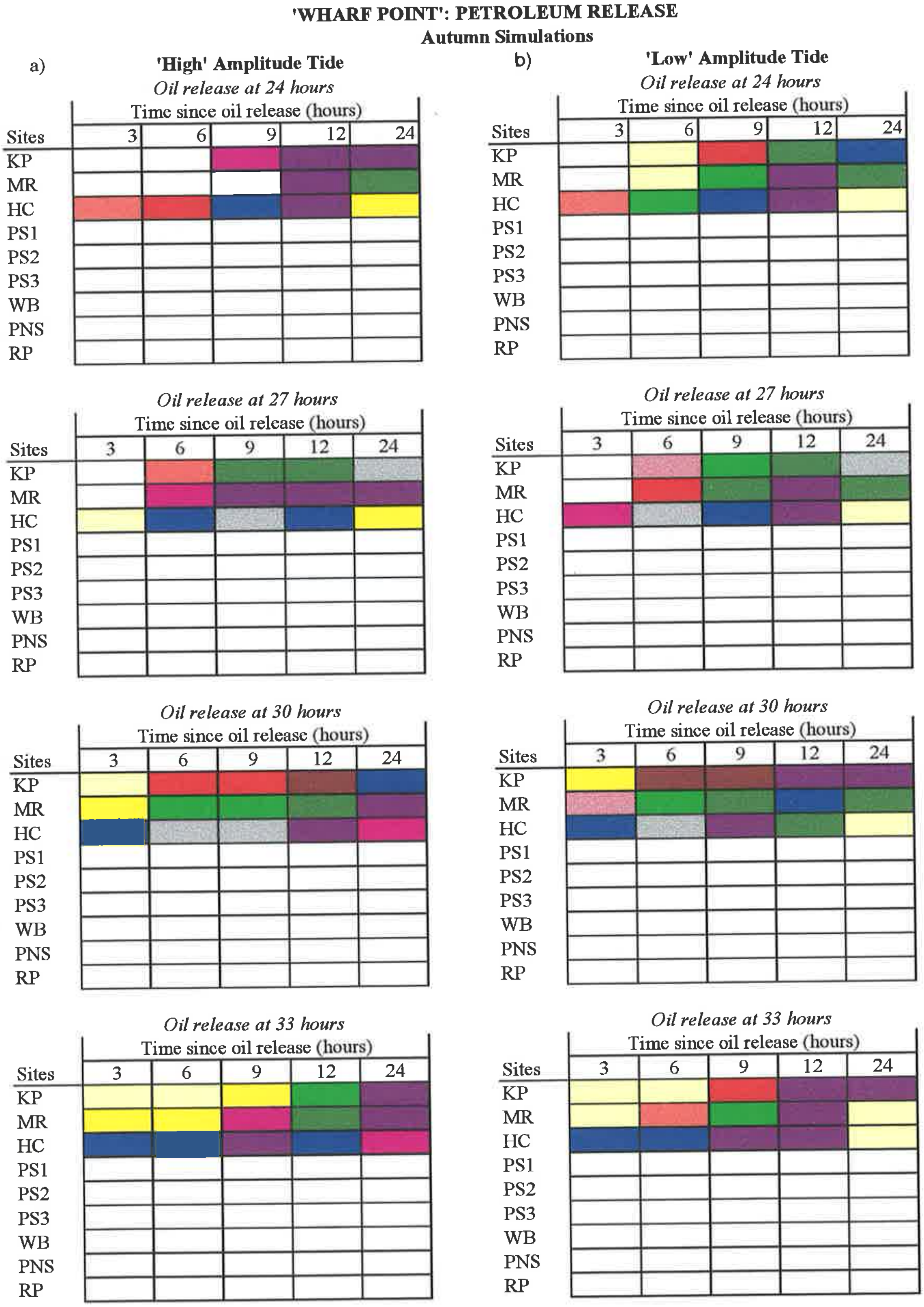


Fig. 5.19 The amount of petroleum predicted to reach study sites under simulated summer conditions when released from the 'Wharf Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).



'WHARF POINT': PETROLEUM RELEASE

Autumn Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP			🟣	🟪	🟪
MR				🟪	🟩
HC	🟧	🟥	🟦	🟪	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP		🟧	🟩	🟩	▨
MR		🟣	🟪	🟪	🟪
HC	🟡	🟦	▨	🟦	🟨
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟡	🟥	🟥	🟫	🟦
MR	🟨	🟢	🟢	🟩	🟪
HC	🟦	▨	▨	🟪	🟣
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟡	🟡	🟨	🟢	🟪
MR	🟨	🟨	🟣	🟩	🟪
HC	🟦	🟦	🟪	🟦	🟣
PS1					
PS2					
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP		🟡	🟥	🟩	🟦
MR		🟡	🟢	🟪	🟩
HC	🟧	🟢	🟦	🟪	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP		🟠	🟢	🟩	▨
MR		🟥	🟩	🟪	🟩
HC	🟣	▨	🟦	🟪	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

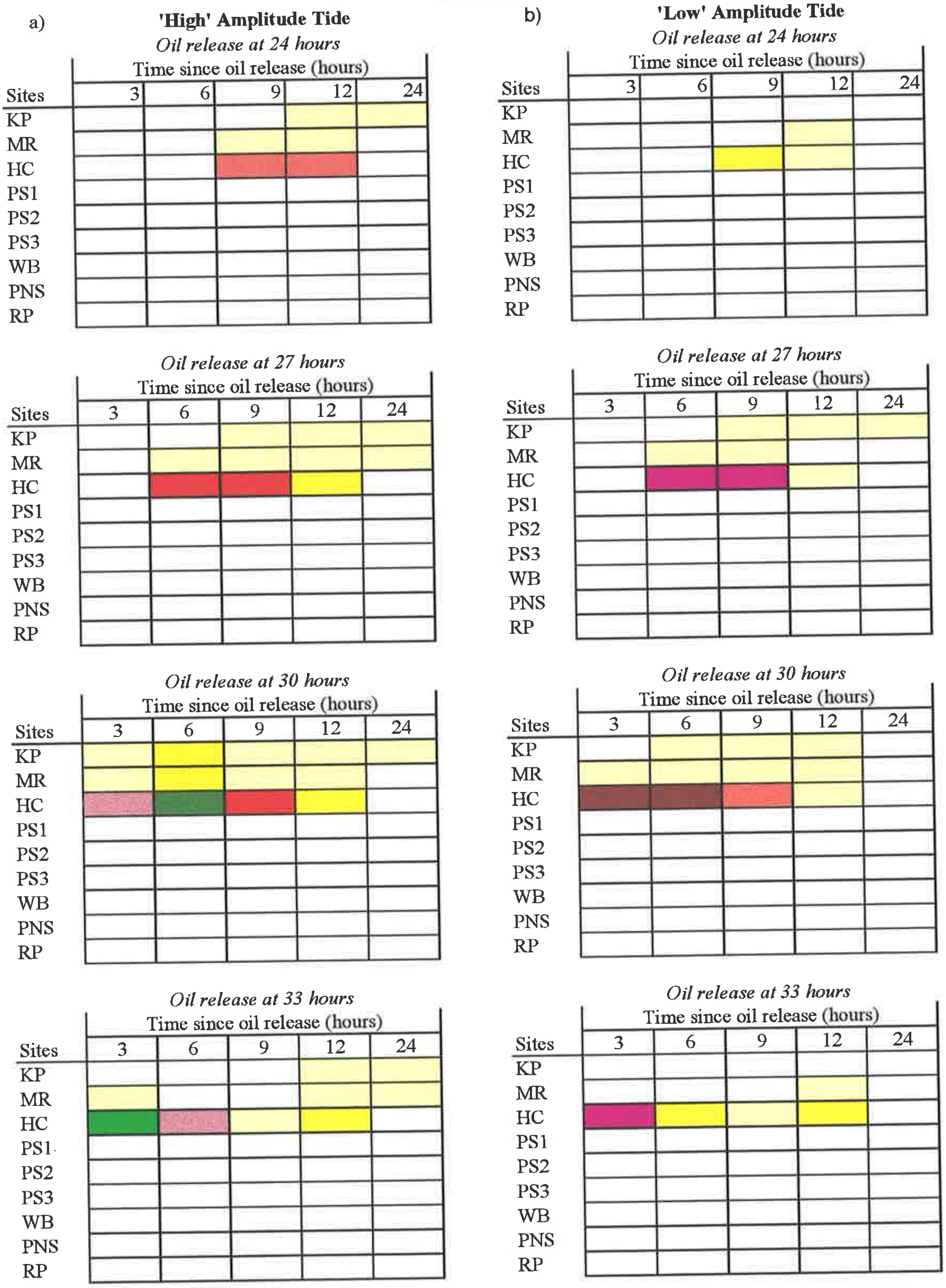
Oil release at 30 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟨	🟫	🟫	🟪	🟪
MR	🟠	🟢	🟩	🟦	🟩
HC	🟦	▨	🟪	🟩	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

	Time since oil release (hours)				
Sites	3	6	9	12	24
KP	🟡	🟡	🟥	🟪	🟪
MR	🟡	🟧	🟢	🟪	🟡
HC	🟦	🟦	🟪	🟪	🟡
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.20 The amount of petroleum predicted to reach study sites under simulated autumn conditions when released from the 'Wharf Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).



'WHARF POINT': PETROLEUM RELEASE
Winter Simulations

a) **'High' Amplitude Tide**

Oil release at 24 hours

Sites	3	6	9	12	24
KP				🟡	🟡
MR			🟡	🟡	
HC			🟧	🟧	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Sites	3	6	9	12	24
KP			🟡	🟡	🟡
MR		🟡	🟡	🟡	🟡
HC		🟥	🟥	🟨	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Sites	3	6	9	12	24
KP	🟡	🟨	🟡	🟡	🟡
MR	🟡	🟨	🟡	🟡	
HC	🩷	🟩	🟥	🟨	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Sites	3	6	9	12	24
KP				🟡	🟡
MR	🟡			🟡	🟡
HC	🟩	🩷	🟡	🟨	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

b) **'Low' Amplitude Tide**

Oil release at 24 hours

Sites	3	6	9	12	24
KP					
MR				🟡	
HC			🟨	🟡	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 27 hours

Sites	3	6	9	12	24
KP			🟡	🟡	🟡
MR		🟡	🟡		
HC		🟪	🟪	🟡	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 30 hours

Sites	3	6	9	12	24
KP		🟡	🟡	🟡	
MR	🟡	🟡	🟡	🟡	
HC	🟫	🟫	🟧	🟡	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Oil release at 33 hours

Sites	3	6	9	12	24
KP					
MR				🟡	
HC	🟪	🟨	🟡	🟨	
PS1					
PS2					
PS3					
WB					
PNS					
RP					

Fig. 5.21 The amount of petroleum predicted to reach study sites under simulated winter conditions when released from the 'Wharf Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).

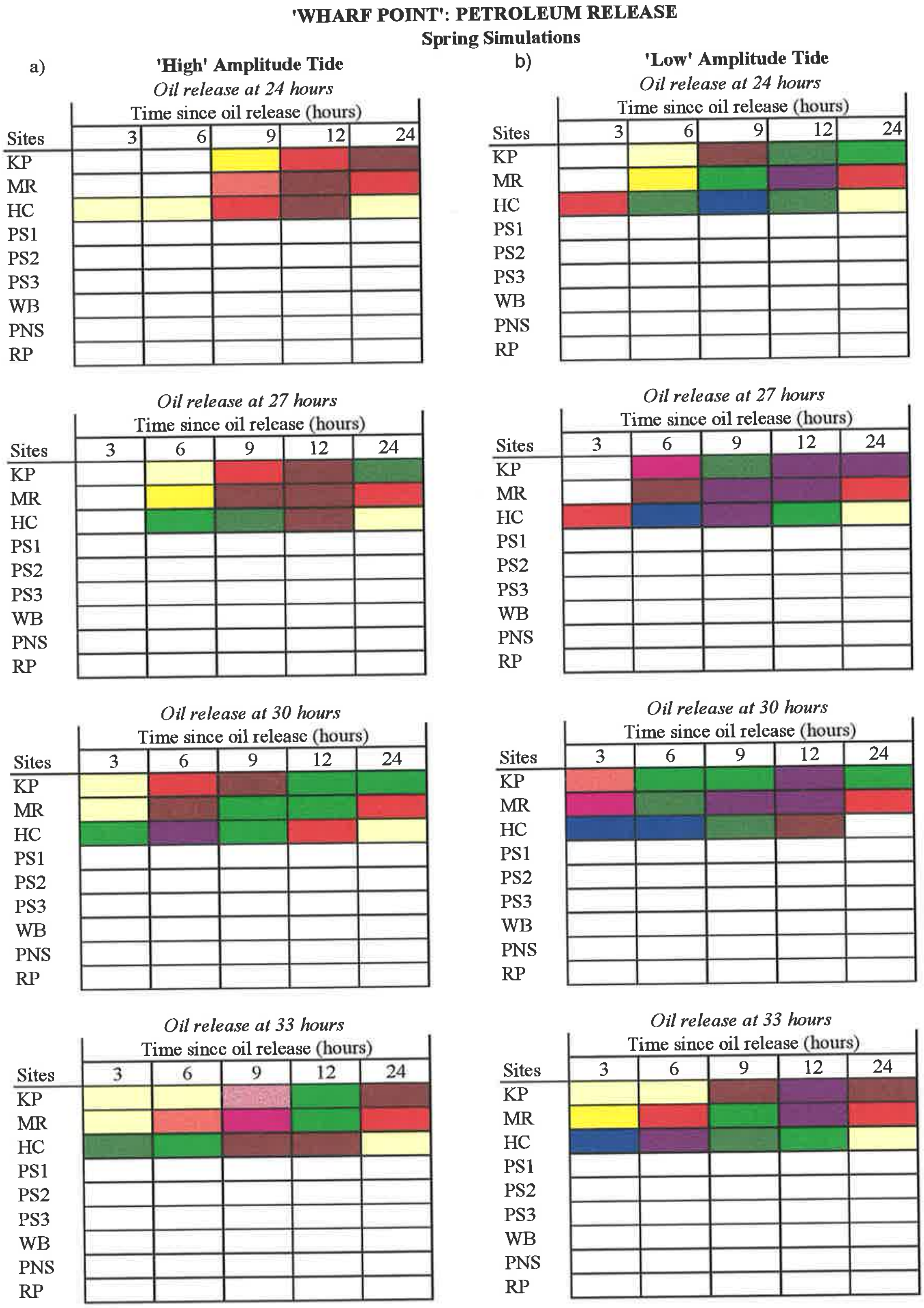


Fig. 5.22 The amount of petroleum predicted to reach study sites under simulated spring conditions when released from the 'Wharf Point'. Site abbreviations are; KP=Kingston Park, MR=Marino Rocks, HC=Hallett Cove A, PS1=Port Stanvac 1, PS2=Port Stanvac 2, PS3=Port Stanvac 3, WB=Witton Bluff, PNS=Port Noarlunga South, RP=Robinson Point. The coding system used to categorise the extent of oiling is shown in Table 5.2. 'High' tidal amplitude simulations are shown in column a) and 'low' tidal amplitude simulations are shown in column b).

5.7 Discussion

5.7.1 Validation of the FLOWM Model

The simulations used to recreate the 'real' oil spill revealed some differences between the patterns of oiling occurring in the field and those predicted. The full resolution simulation, which most closely matched the observed patterns of oiling, utilised a surface mixing depth of 0.003m and a wave drift factor of 15.4 (Fig. 5.6). This simulation matched the observed oiling pattern seen at study sites in the relative degree of oil contamination at Witton Bluff but, unlike the situation in the field, Port Noarlunga South received only low levels of oil contamination. The simulation also deviated from the real situation in the heavy oiling levels received by 'Central' study sites. Another difference was that the simulation predicted the late arrival (after 48 hours of simulation time) of oil to 'Northern' study sites, particularly Hallett Cove, while in the field no oiling of these sites was observed.

There could be a number of reasons for the differences between the observed oil grounding sites and those predicted from the 'best' simulation. Firstly, the oil spill simulation used hourly time series data (including wind strength and direction and tidal conditions), while minor variations, particularly in wind strength and direction, over temporal scales of hours or less would have constantly been occurring in the field. However, an examination of 6-minutely data provided by the NTF did not indicate a large discrepancy between these values and the hourly data used in the model. Therefore, the use of hourly time series data in the simulation (instead of more frequent readings) would not appear to account for the differences between the predicted and the actual oil grounding sites.

A more likely factor contributing to differences between the observed and predicted grounding sites of oil was the way in which the spill occurred and how it was handled. The specific location of the leak was not able to be exactly identified meaning that the point of oil spillage used in the simulation may not have been accurate. This could have influenced the predicted grounding sites of oil. Since the oil spill was being investigated by the EPA full details of how the spill was handled by refinery staff and clean-up contractors were not available to me. For example, it was rumoured that dispersant had been used close to where the spill occurred. If this was the case it may explain the lack of visible oiling at Port Stanvac sites which were predicted to be heavily oiled by the oil spill simulation. If dispersant had been used it was likely that this would have occurred close to the point of oil release and that this action would have reduced the amount of obvious oil transported and deposited at study sites, particularly those located within the refinery boundaries. It must be noted that although dispersant removes visible oil from the system the oil is still present (in an altered form) and both this and the dispersant itself can be extremely toxic to intertidal organisms. It is also possible that booms were deployed between 'Central' study sites and the point of oil release which may account for the lack of obvious oiling of these sites. However, although a boom was observed to be in use in the Onkaparinga River there were no substantiated reports of booms being used at other points in GSV.

Use of the time series data provided by the NTF could introduce a source of inaccuracy into the simulations since it was collected at one point in Port Stanvac. The FLOWM program assumes that parameters such as wind strength and direction and tidal height are consistent across the entire bathymetry grid although it does incorporate a long-shore drift component in the modelling. Such an assumption does not consider the modifying influences of local topography which would be especially relevant close to shore and could have major effects on parameters such as the tidal regime, wind strength and direction, and the form and magnitude of wave action. By ignoring the influence and importance of such local effects the simulation could not be expected to mimic the 'real' field dynamics and accurately predict ultimate grounding sites of spilt oil.

Another reason for the differences between observed and predicted oil grounding sites was the coarseness of the bathymetry matrix used as a basis for all modelling simulations. The matrix grid interval corresponded to 186.9m meaning that an error in location of the point of oil release by one grid unit translates as a 186.9m deviation from the 'true' point of oil release in that dimension. This would be expected to have a major impact on the predicted oil grounding sites. A broad grid interval can also result in distortion in the positioning of the study sites along the model shore. The use of such a large grid interval was necessary as the data (including depth profiles and coastal contours) provided on Navigational Map AUS. 781 from which the bathymetry matrix was compiled lacked enough detail to enable generation of a finer resolution matrix. If compilation of a finer resolution bathymetry matrix had been possible with an acceptable degree of accuracy then it was likely the model simulations would have enabled a closer fit between the realised and predicted locations and extent of oiling.

Another problem with modelling of the oil spill was the treatment of the oil as a homogeneous bulk product. This fails to account for changes in the oil and its behaviour as it weathers which may have influenced the amount of oil reaching particular sites. The use of a decay factor attempted to provide some realism to the way in which oil behaved in the model but without extensive testing, unfortunately beyond the scope of this thesis, it was not possible to more accurately simulate oil spread and its temporal behaviour. The difference which altering the oil decay time had on the amount of oil reaching a particular point on the model sea (or shore) has been previously mentioned. In addition, oil circulating in the model sea is lost from the circulating oil volume once it travels beyond the edge of the model boundaries. This could be overcome by increasing the size of the GSV area included in a particular simulation.

The model also lacked realism in its failure to account for oil present at the water-land interface. An accurate representation of how oil behaves in the field at proximity to the coastline requires a mechanism where an oil spill model incorporates a coastal retention factor linked to the substrata type and the tidal regime. Although this was attempted it was not possible to incorporate a realistic coastal retention factor into the FLOWM Model in the time available. Stranded oil can be remobilised by a subsequent high tide unless it has been entrapped in rocks or retained deep in soft sediment. Therefore, a realistic oil spill model useful in predicting close-shore oil movement needs to have the ability to remove stranded oil from the circulating oil volume but be able to consider this oil if it is later redistributed, either in whole or part. This is clearly a complex situation and beyond the objectives of this thesis.

The amount of oil left on the shore using the estimated coastal retention factor and the simulation parameters pertinent to Fig. 5.6 gives a crude approximation of oil retention on a rocky shore (see Table 5.7). The calculations could only be made on the basis of a number of assumptions, therefore illustrating the complexities needing to be addressed to incorporate a coastal retention factor into the FLOWM Model. However, the primary aim of using the FLOWM Model was not to predict the volume of oil retained at study sites but rather the exposure of the sites to oil. Oil may be carried across a site on a body of water, or be left on a site prior to being remobilised, either of which can perturb an area. Therefore, it was considered satisfactory to predict the amount of oil at the water-land interface rather than the amount of oil retained on shore. The latter was predicted to be minimal due to the domination of rocky substrata at study sites.

Despite the differences between the observed oil spill grounding sites and those predicted from the simulated oil spill, the model was still thought to be a useful tool in predicting what could happen in an oil spill and was retained for predicting seasonal grounding sites of spilt oil.

5.7.2 Seasonal Modelling

Problems with the Seasonal Simulations

A number of the difficulties mentioned in relation to validation of the FLOWM Model also applied to the seasonal simulations. Clearly the treatment of oil as a bulk product, the failure to consider its fate at the water-land interface, and the coarseness of the bathymetry matrix have important implications to the seasonal predictions. More specific problems pertaining to the seasonal simulations were the use of seasonal averages for tidal amplitude and wind strength and direction. The huge variability in these parameters has been indicated in Chapter 4 (Figs 4.3a & b, 4.4a & b and 4.5a & b). This variability is especially evident when considering the direction and strength of the prevailing winds. Another problem with using seasonal averages in relation to wind strength and direction was that the sea breezes accompanying an incoming tide were not considered in the simulation. In fact, the use of average wind strength and direction data ensures that the model treats the wind field as a constant for the duration of the simulation.

The use of averages in relation to tidal amplitudes under 'dodge' and 'high' amplitude tidal extremes was likely to give an idea of the patterns of oiling due to tidal influences but could not possibly encompass the full range of outcomes which could occur on a seasonal basis. The model also assumed that the tidal amplitude was constant for the duration of the simulation. An additional problem was the need to predict the wave height (as accurate data on this parameter was not available). If this information was available the problems of temporal variability (discussed in relation to tidal amplitudes and wind strength and direction) would apply.

Release of Oil from the 'Deep Ocean Point'

When crude oil was released from the 'Deep Ocean Point' under simulated summer conditions it was predicted to ground predominantly at 'Central' sites and Hallett Cove. However, 12-24 hours after oil release very small amounts of this pollutant were recorded at some of the 'Southern' sites. Autumn simulations predicted maximum oiling at 'Northern' study sites and only small amounts of oil reaching some of the 'Central' sites under the influence of a 'high' amplitude tide. Winter simulations predicted very low levels of oil reaching 'Northern' sites, particularly Hallett Cove, while simulations under spring conditions predicted similar grounding sites but larger volumes of oil arriving.

When the simulations involved the release of petroleum in summer the majority of study sites were predicted to be perturbed but Hallett Cove and PS2 were most vulnerable to oil exposure. The amount of petroleum reaching sites was greater under the influence of 'low' amplitude tides. Autumn simulations predicted high levels of oiling at all 'Northern' study sites and occasional small volumes reaching PS1 and PS2. Winter simulations rarely resulted in petroleum reaching any of the study sites, while only 'Northern' sites were affected by oil in spring.

Release of Oil from the 'Wharf Point'

Petroleum released from the 'Wharf Point' under simulated summer conditions tended to spread broadly to study sites. However, in all other seasons simulations predicted that the 'Northern' study sites would be most susceptible to petroleum exposure. Winter simulations were characterised by lower levels of petroleum contamination than any other season.

Seasonal Predictions

Regardless of the type of oil released, the timing of that release within the tidal cycle, and whether oil was spilt from the 'Deep Ocean Point' or the 'Wharf Point', it would appear from the seasonal simulations that 'Northern' sites, particularly Hallett Cove, and 'Central' study sites are most likely to be perturbed. However, minimal oiling of study sites was predicted in winter when the winds are primarily north-east to south (Petrusovics 1990). If north-east winds dominate in winter then oil is likely to be carried out to sea unless tidal influences override the influence of the wind. This could account for the low levels of oiling seen at all sites in winter simulations.

The failure of the FLOWM model to consider the influence of sea breezes accompanying an incoming tide in the seasonal simulations may have underestimated the amount of oiling occurring at some of the study sites. However, the importance of this point would depend on how far the oil had been transported prior to the sea breeze and incoming tide combining to drive oil towards the shore.

5.7.3 Implications to the Ongoing Monitoring Program

The problems in validating the FLOWM Model in reference to the observed refinery oil spill indicated that further modifications could be made to improve the applicability of this model to the project. This would be an interesting research direction to follow but was not possible in the available time. When the modelling work of Grzechnik is completed it is recommended that his model be considered as a tool for predicting likely seasonal oil grounding sites along eastern GSV.

The seasonal trends identified in the FLOWM simulations predict that 'Northern' and 'Central' study sites are most likely to be perturbed by oil exposure in the event of an oil spill. However, the variability seen in oil distribution and in the factors affecting oil transport (namely the vector sum of tide and wind patterns) made accurate prediction of grounding sites extremely difficult. Therefore, it is recommended that the ongoing monitoring program includes as many study sites as possible depending on the 'time-cost' involved. It is also recommended that the sites chosen for ongoing monitoring should be widely spread along the eastern coast of GSV. This would maximise the likelihood of at least one site being oiled, while reducing the chance that all will be oiled, an important consideration when using a Beyond-BACI monitoring design.

Chapter 6. Selection of a Bioindicator

6.1 Introduction

It is now widely accepted that chemical methods are not suitable as a stand-alone means of pollutant monitoring. Pollutant levels can indicate the extent and nature of contamination in an aquatic system but cannot establish the biological risks and consequences of the contaminant *in situ* (Herricks and Cairns 1982, Krivolutzky 1986, Soule 1988, Borgmann and Munawar 1989, Sloterdijk *et al.* 1989, Cairns and Mount 1990, Cairns *et al.* 1993). Living organisms are able to temporally integrate pollution effects and indicate the bioavailability and biomobility of pollutants (Moriarty 1983, Storey and Edward 1989, Burton and Scott 1992, Stronkhorst 1992. They can synthesise responses to other stressors and processes at work in a system (Cairns and Van der Schalie 1982, Krivolutzky 1986, Pellerin-Massicotte *et al.* 1989, Cairns *et al.* 1993, Rippon and Chapman 1993). Pollution should be viewed as a biological phenomenon that acts on living organisms and in this context the only meaningful way of monitoring requires a biological approach (Carballo *et al.* 1996). The use of biological indicators (bioindicators) to assess water quality in Australia has increased since the late 1970s and is now widely employed to quantify the ecological 'quality' or 'health' of a system (Phillips 1980, Browder 1988, Maher and Norris 1990, Swaileh *et al.* 1994).

The use of bioindicators in ecological assessment assumes that the indicator reflects the quality of its environment (Johnson *et al.* 1993). If ambient physical and chemical conditions are modified the altered environment will favour some species, have little affect on others and cause damaging changes to the rest according to their individual tolerances (Cairns and Van der Schalie 1982, Johnson *et al.* 1993, Carballo *et al.* 1996). When conditions are outside the optimal physical and chemical ranges of a species, changes in their presence/absence, abundance, morphology, physiology or behaviour may arise (Johnson *et al.* 1993). If a species is abundant within a system it is assumed this is because its requirements are being satisfactorily met. However, the reverse cannot be inferred as explanations including the presence of geographical barriers, occupation of a species functional niche, or the influence of normal lifecycle events (such as predation) may account for the absence of a species (Johnson *et al.* 1993).

Biological systems are hierarchically arranged into subcellular, cellular, individual, population, community and ecosystem levels and all can be potentially affected by pollutant exposure (Sastry and Miller 1981, Herricks and Cairns 1982, Cairns 1983, Axiak *et al.* 1988, Soule 1988, Vega *et al.* 1989, Keough and Mapstone 1995). Pollutant stress usually affects biota at lower levels of biological organisation but effects can accumulate and influence the population, community or ecosystem (Sastry and Miller 1981, Cairns *et al.* 1993, Carballo *et al.* 1996). It is only when pollutant induced change impacts at or above the level of the population that significant ecological effects occur (Sindermann 1988, Suchanek 1993). This was an important consideration in the design of a monitoring program for Mobil, Port Stanvac, and a population-level monitoring focus was adopted. This was necessary due to the high time investment required in community-level monitoring and the difficulties in associating change at this level with a perturbation (Keough and Mapstone 1995). Therefore, oil exposure will be considered to have an impact in Gulf St Vincent (GSV) if changes in the abundance or population variance of a selected indicator species are statistically significant (see Sladeck 1965, Underwood 1994a & Grasmuck *et al.* 1995).

Having previously decided that a Beyond-BACI design was the most appropriate way of monitoring for an oil perturbation in GSV the next step was to select a suitable bioindicator. This required determination of the ideal characteristics a hypothetical bioindicator should have, and a comparison with the known or postulated characteristics of intertidal invertebrate fauna found at study sites (see Chapters 3 & 4). A cause-and-effect relationship between oil (both crude and refined) and any species appearing to meet the majority of bioindicator criteria was then investigated experimentally. The choice of an appropriate bioindicator is the focus of this phase of the project.

6.2 Aims

The broad aim of this chapter was to identify the most appropriate bioindicator to use in a Beyond-BACI monitoring program designed to assess the consequences of an operational oil spill from the Port Stanvac Oil Refinery. This required an understanding of the behaviour, life history, mode of exposure and likely effects of oil on the common species encountered at GSV study sites.

The specific aims of this chapter were to:

- Use the literature review investigating the use of bioindicators (Chapter 2) to determine the primary characteristics a species requires to be a useful monitoring tool.
- Use the literature review investigating the likely effects of oil on intertidal animals (Chapter 2), the results of preliminary monitoring (Chapter 4), field observations and some small-scale behavioural experiments to identify potential bioindicators.
- Determine the behaviour and life history traits of dominant animals at GSV sites to elucidate their usefulness as bioindicators.
- Establish the cause-and-effect relationship between species that appear to be suitable as bioindicators, and oil.

6.3 Bioindicator Criteria and Dominant Intertidal Animals in GSV

A literature review pertaining to the use of bioindicators and the effects of oil on intertidal biota has been included in Chapter 2 of this thesis. This review was used to identify the primary criteria a species should exhibit to be a useful intertidal monitoring tool. Common animals found in the 'upper' zones at study sites in GSV (see Chapter 4) were then considered in reference to their life history strategies and behaviour (Table 6.1) and their ability to meet the bioindicator criteria (Table 6.2).

6.3.1 Marine Bioindicator Criteria

Warwick (1993) has reviewed various Northern Hemisphere organisms for their potential as marine indicators. Epifauna colonising hard surfaces make good bioindicators because they are non-motile and can be sampled non-destructively and repeatedly. Mobile fauna on hard surfaces are also easy to identify and census non-destructively but have a direct dependence on the plants they graze (in the case of herbivores) and may be indirectly affected by algal changes (Warwick 1993, Jan *et al.* 1994, Keough and Mapstone 1995).

The ideal hypothetical intertidal bioindicator for a Beyond-BACI monitoring program should exhibit the following characteristics:

- Free from taxonomic problems and easily recognised and identified by nonspecialists. This will remove uncertainties which could complicate long-term monitoring and inter-site comparisons (Hellawell 1986).
- An established cause-and-effect relationship with the disturbance of interest (including likely pollutant effects on different stages in the organism's life history) (Cairns 1974, Hellawell 1986, Underwood and Peterson 1988, Keough and Quinn 1991, Cairns *et al.* 1993, Keough and Mapstone 1995) at the appropriate biological level of interest (Widdows 1985). It is an advantage if the species is well suited to laboratory studies as this facilitates determination of causality between the pollutant and the organism (Hellawell 1986).
- Low genetic and ecological variability (Hellawell 1986).

- Ubiquitous at a range of similar sites and sufficiently numerous to allow statistical conclusions to be drawn (Cairns *et al.* 1993, Underwood 1993a).
- Limited mobility in reference to the spread of the pollutant, meaning that the organism is unlikely to be able to actively avoid contacting the contamination (, Davies *et al.* 1993, Warwick 1993, Keough and Mapstone 1995).
- Some biological or ecological significance e.g. in terms of community structure and balance (Cairns *et al.* 1993).
- Sensitive but not too sensitive to the stressor of interest and not demonstrating an all-or-nothing response to the pollutant (Cairns *et al.* 1993).
- Preferably not overly sensitive to confounding factors which may be operating in the area (Keough and Mapstone 1995). However, changes in the bioindicator should be integrative and indicative of more general changes in the area (Keough and Mapstone 1995) so that it effectively 'summarises' information from many unmeasured indicators (Cairns *et al.* 1993).
- Easy to assess and accurately quantify e.g. not displaying cryptic behaviour (Phillips 1980, Garrity and Levings 1990) and preferably able to be non-destructively and cost-effectively sampled (Moriarty 1983, Humphrey *et al.* 1989, Cairns *et al.* 1993, Swaileh *et al.* 1994).
- Sufficiently long-lived to allow the sampling of more than one year-class (Phillips 1980). A relatively long life history is advantageous as it allows monitoring to be integrated over a range of spatial and temporal scales (Hellawell 1986).
- The indicator should not show strong serial correlation between sampling times but this can be managed by manipulating the sampling intervals or by using an analysis which incorporates serial correlation (Keough and Mapstone 1995).
- It is an advantage if the ecological characteristics of the indicator are well known and it has a relatively narrow and specific range of ecological tolerances (Hellawell 1986, Johnson *et al.* 1993).

Table 6.1 A comparison of the life history strategies and characteristics of numerically dominant animals found in the 'upper' zone at GSV sites. N.B. Lecithotrophic veliger larvae feed on a yolk sac, while planktotrophic larvae feed on plankton[1]. N/A indicates information not available or not found. References; [1]Shepherd and Thomas 1989, [2]Quinn *et al.* 1992, [3]Underwood 1974, [4]Underwood 1978b, [5]Underwood 1975b, [6]Mackay and Underwood 1977, [7]Anderson 1962, [8]Branch and Branch 1981, [9]Beovich and Quinn 1992, [10]Mapstone 1978.

Species	Occurrence	Feeding	Longevity	Reproduction
Austrocochlea constricta	Mid-eulittoral zone.[2,3]	Herbivorous; grazes epilithon.[1,2]	Postulated to be similar to *N. atramentosa*.	In NSW breeds throughout the year with no resting period and a reproductive peak in Oct-Nov.[3] Fertilisation is external and larvae are short term lecithotrophic (independent of plankton availability).[3]
Austrocochlea concamerata	Mid-eulittoral zone.[2]	Herbivorous; grazes epilithon.[1,2]	Postulated to be similar to *N. atramentosa*.	Breeding believed to be similar to *A. constricta*.[2]
Bembicium nanum	Mid-eulittoral zone, often occurring with *A. constricta* and *A. concamerata*.[2,3]	Herbivorous; grazes epilithon.[1,2] This animal has a narrow radula with short teeth, designed to remove surface microalgae from the substratum. It feeds at a slower rate than *N. atramentosa* and *C. tramoserica*.[4]	Estimated to be 4-8 years; reproductive maturity estimated at 10-12 months post settlement.[5]	Spawns from August-March with a resting period in autumn.[3] Produces yellow egg capsules attached to rocks which contain 100-200 white eggs (0.1 mm diam.) from which planktotrophic veligers emerge after 18-28 days.[1] Veligers postulated to spend up to a year in the plankton.[5]
Cellana tramoserica	Mid-eulittoral zone.[2,4]	Herbivorous; grazes epilithon and macroalgal sporelings.[1,2,3] This animal has a radula with a few large teeth in each row which probably allows it to bite deeper into the substratum than *N. atramentosa* and *B. nanum*.[4] Tends to be homing.[6]	Postulated to live for at least 2-3 years, but accurate estimates have yet to be made.[1]	Spawns from June-October with accumulation of mature oocytes from the end of spawning until the next breeding season. Eggs; planktonic, larvae; short term lecithotrophic.[3,7]
Littorina unifasciata	Concentrated in upper littoral and supralittoral zones, but can extend into the mid-eulittoral zone[1,2]. Often found aggregating in cracks and crevices on rocks.[1]	Herbivorous; grazes mainly lichens but also eats diatoms and algal sporelings.[2,8] Intense intraspecific competition is believed to be responsible for limiting the availability of its food.[8]	N/A	Reported to breed throughout the year[1], but the main spawning period is over 5 months in summer and autumn, with a resting period but no period during which mature oocytes are stored.[3] It lays pelagic egg capsules, consisting of 2000-4000 planktonic eggs (0.1-0.14mm diam.) which hatch in a few days as veligers.[1] Larvae; long term planktotrophic.[3]
Nerita atramentosa	Found in or below the mid-eulittoral zone, tending to aggregate in cracks and crevices or under boulders.[2]	Herbivorous; grazes epilithon.[1,2] This animal has a thin radula with well-developed lateral teeth which presumably scrape surface microalgae from a relatively large area of hard substratum at a rapid rate.[4]	Estimated to be 3-5.5 years; reproductive maturity est. 20 months after settlement.[5]	Short spawning period in summer, although it can be variable[3,7], with no rest period in the cycle, and a 6 month period of accumulation and storage of mature oocytes.[3] Calcareous white, flattened, elliptical dome-shaped capsules (2mm long and 1.4mm wide) are laid in summer and autumn.[2,3] The capsules are filled with a jelly matrix and contain 20-40 yolky yellow eggs. Larvae develop to a late veliger stage in the capsule and are released approximately 14 days after laying when the capsule breaks down.[1]
Chthamalus antennatus	Often very abundant in the upper eulittoral zone, with patchy occurrences in the rest of the eulittoral zone.[2]	Filter feeding.[2]	N/A	This species is hermaphroditic, producing planktonic larvae which settle out primarily in summer.[2] The adults are sessile.[2]
Siphonaria diemenensis	Mid-lower eulittoral region.[2]	Herbivorous; feeds primarily on macroalgae including foliose algae.[2,9] Tends to be homing, returning to a home scar after foraging.[2]	N/A	This species is hermaphroditic, laying spiral shaped egg cases in spring and summer which are attached to the substratum by a girdle. The egg cases contain spherical eggs (0.1mm diam.) in a jelly matrix. Larvae develop to veliger stage before being liberated into the water when the girdle disintegrates.[1,2,10] In captivity larvae have been observed to hatch after 7-10 days but veligers may take weeks to escape from the egg capsules.[10]

Table 6.2 Dominant species present in the 'upper' zones at GSV sites (apart from Witton Bluff) were considered in terms of their usefulness as bioindicators in an intertidal monitoring program. This was decided by matching the species against a list of criteria which were deemed important for a bioindicator to exhibit. Bioindicator criteria were determined from a literature review of bioindicators and the characteristics they should ideally display within the context of an intertidal monitoring program in GSV. The cryptic behaviour referred to in this table is a tendency for animals to aggregate under rocks, in crevices or in rock pools which would make census difficult and potentially inaccurate. References used to compile this table were; [1]Mackay and Underwood 1977, [2]Shepherd and Thomas 1989, [3]Underwood 1978b, [4]Chasse 1978, [5]Baker 1991, [6]Suchanek 1993, [7]Battershill and Bergquist 1982. N/A indicates data not available or not known.

	Potential Bioindicator Species at GSV sites							
Bioindicator Criteria	*A. constricta*	*A. concamerata*	*B. nanum*	*C. tramoserica*	*L. unifasciata*	*N. atramentosa*	*C. antennatus*	*S. diemenensis*
Easily recognised	yes	yes	yes	yes	yes	yes	yes	yes
Ubiquitous at GSV sites	yes	no	yes	no	yes	yes	yes	no
Numerically abundant (at 7 or 8 sites)	no	no	yes	no	no	no	no	no
Limited mobility in reference to the pollutant (oil) spread	yes (refer to 'dislodgment experiments' in Chapter 7)	not assessed but likely to be yes	yes (refer to 'dislodgment experiments' in Chapter 7)	yes (often homing)[1]	not assessed but likely to be yes	yes (refer to 'dislodgment experiments' in Chapter 7)	yes (sessile)	not assessed but likely to be yes (often homing)[2]
Biological significance	competes with other herbivores and occupies space on rocky shores[2,3]	competes with other herbivores and occupies space on rocky shores[2,3]	numerical dominance but competitively inferior to some herbivores[3]	competes with other herbivores and occupies space on rocky shores[2,3]	similar to other littorines on a range of rocky shores & tolerant to desiccation[2]	competitively superior to *C. tramoserica* & *B. nanum*[3]	sessile filter-feeder, can be a dominant space occupier on some shores[2,3]	competes with other herbivores and occupies space on rocky shores[2,3]
Representative of other species	yes (GSV sites dominated by herbivores)	yes (GSV sites dominated by herbivores)	yes (GSV sites dominated by herbivores)	yes (GSV sites dominated by herbivores)	yes but occurs in 'upper' eulittoral zone and grazes on a different suite of plants (including lichens) than mid-eulittoral species	yes (GSV sites dominated by herbivores)	no, filter feeder	yes (GSV sites dominated by herbivores)
Responsive to pollutant but not overly sensitive	not tested, but mortalities in *Austrocochlea* spp. have been reported with oil exposure[4]	not tested	yes (see 'oil experiments'), no acute mortality on exposure to WSF or crude oil 'slick'	not tested, generally sensitive to fresh crude oil but can live in contact with weathered crude[5,6]	not tested, a related Littorinid suffered >50% mortality on acute exposure to a large volume of crude oil[4]	not tested, mortalities of 23 & 5% and gonadal damage following a 3 week exposure to a Shell Co. condensate[7]	not tested, can be smothered by a large crude spill but reasonably resistant[5,6]	not tested
Cryptic behaviour	yes; observed at higher concentrations in rock pools[3], under rocks and in crevices	yes; observed at higher concentrations in rock pools, under rocks and in crevices	no	no	yes; observed at higher concentrations in rock crevices. Tends to have a contagious distribution in quadrats	yes; observed at higher concentrations in rock pools, under rocks and in crevices	no but contagiously distributed within quadrats	no (generally) but was found under rocks at sites with low water retention
Should not show serial correlation between sampling times	N/A	N/A	yes (see Chapter 4)	N/A	N/A	N/A	N/A	N/A

6.3.2 Dominant Intertidal Animals and Their Characteristics

Gastropods are frequently the most conspicuous and diverse group of animals seen on rocky shores (Underwood and Chapman 1995). This was found to be true of the targeted section of the mid-eulittoral zone (designated the 'upper' zone) at the majority of selected study sites (see Chapter 4). The 'upper' zones at study sites were comprised primarily of herbivorous gastropods including *Bembicium nanum*, *Nerita atramentosa*, *Austrocochlea spp.*, *Cellana tramoserica, Siphonaria diemenensis* and *Notoacmea* spp., while variable numbers of barnacles (primarily *Chthamalus antennatus*) and mussels (mainly *Xenostrobus pulex*) also occurred but generally dominated at lower shore levels. The most common animals found at GSV study sites during the preliminary phase of this project and their lifestyle and relevant life-history traits are shown in Table 6.1.

The substrata dominating study sites typically appeared bare of conspicuous plant life except within rock pools and low-lying areas. However, it is expected that epilithon would be present at these 'bare' sites, providing a major food source for herbivores (Underwood 1979, Hawkins and Hartnoll 1983a & b, Hill and Hawkins 1990). Although epilithon is likely to be directly affected by oiling and to have secondary effects on the herbivores which graze it due to sampling and quantification difficulties (MacLulich 1986, Hill and Hawkins 1990) this material will not be considered in the search for suitable bioindicators.

6.3.3 The *A Priori* Bioindicator

Herbivorous gastropods found in the 'upper' zones at study sites in GSV typically shared broadly similar life history strategies (Table 6.1). However, when intertidal species were categorised against important bioindicator criteria (a subset of the criteria listed in section 6.3.1) it was apparent that only *B. nanum* met the majority of the bioindicator requirements (Table 6.2). This species was selected as the *a priori* bioindicator of choice for a population based Beyond-BACI monitoring program. The abundance of *B. nanum* was also used as the variable of interest when considering the statistical effects of the perturbations investigated in Chapter 4. A number of herbivorous gastropods could have been useful bioindicators but their low densities precluded them from further consideration.

The possible stages within the lifecycle of *B. nanum* where oil is likely to modify 'normal' processes are shown in Fig. 6.1 and the postulated mechanisms of action are shown in Table 6.3. Minimal research had directly addressed the effects of oil exposure on *B. nanum* so it was necessary to postulate potential effects from the literature review of oil and invertebrates (see Chapter 2).

Table 6.3 The postulated mechanisms of hydrocarbon impact as either the water soluble fraction (WSF) or visible form (e.g. crude oil or petroleum) on the processes and lifestages of *Bembicium nanum* shown in Fig. 6.1. Hydrocarbons can result in *B. nanum* mortality or a range of sublethal changes at any of the arrowed points in Fig. 6.1 and can also affect epilithon (which they graze) and a range of intertidal animal species. It must be noted that the postulated effects of oil exposure were generally inferred on the basis of studies involving other invertebrates (particularly herbivorous gastropods). Concentration abbreviations; ppm=parts per million, ppb=parts per billion. References; [1]Suchanek 1993, [2]Nounou 1980, [3]Laubier 1980, [4]Baker 1991, [5]Blackman *et al.* 1973, [6]Krupp and Jones 1993, [7]Chasse 1978, [8]Baker 1983, [9]Nelson-Smith 1973b, [10]Hyland and Schneider 1976, [11]Battershill and Bergquist 1982, [12]Guzmán *et al.* 1991, [13]Swaileh *et al.* 1994, [14]Styles 1992.

Process, stage or material	Postulated effect of oil on the arrowed processes, stages or materials presented in Fig. 6.1
a: planktonic, pelagic stage	WSF lethal to larvae and juveniles at 0.1-1ppm[1] and sublethal to larvae and juveniles at 1-10ppb.[2] Animals are likely to ingest the WSF (either directly or by eating plankton which are coated with or have assimilated hydrocarbons) and can be coated with larger hydrocarbon particles.[1] Exposure may cause narcotic effects such as decreased swimming ability, diminished feeding competence (e.g. capture or handling of planktonic food), decreased buoyancy and altered predator avoidance behaviour.[1] As hydrocarbons become fixed in structures with a high fat or lipoprotein content a variety of functions specific to the particular structures could be affected (refer to c, d & f for effects on post-settlement individuals).[2,3]
b: settlement	A film of oil, petrol taint or formation of bitumen on the shore may make substrata unsuitable for larval settlement. Crude oil may bind sand to hard substrata or increase its surface temperature (see the 'crude oil experiment' in this chapter) which may make it difficult for larvae to adhere to rocky substrata or to survive if they do adhere. However, oil is likely to rapidly weather and many animals can tolerate weathered residual oil.[1,4] Oil also tends to be readily mechanically debrided from rocky shores, particularly if they are very exposed, which reduces the contact time and therefore the impact of beached oil.[4] It is also possible that the presence of small quantities of oil on hard substrata may make it attractive to incoming settlers.
c: recruitment of settlers	As described for settlement effects oil may alter the substratum by physically changing it. Crude oil present as a slick may smother or cause dislodgment of newly settled individuals, or may interfere with the food supply and act via this pathway.[2,3,4] It is also possible that oil may differentially affect interacting species already present on the shore, freeing space for settlement and subsequent recruitment.
d: grazing	Oil may make it difficult to graze by covering epilithon or the radula of a *B. nanum* individual. Either situation is likely to result in less epilithon being ingested per unit grazing effort. Narcotic effects induced by oiling, such as closure of the operculum, will also prevent or impair feeding.[5] Any residual damage in tissues or alteration in processes such as respiration will also cause energy to be partitioned away from feeding effort and into repair processes.[1] Sublethal changes induced by hydrocarbons entering the body (such as abnormal liver, pancreatic or digestive functions and excessive production of mucus) can also slow down grazing rates or grazing efficiency and processing of ingested food which could then have a feedback effect on grazing rates.[2,3]
e: epilithon	Oil may physically smother epilithon and remove a food source for herbivores or decrease the nutritional value of the material.[1] However, in small amounts oil may enhance epilithon growth in general or promote selective growth of some algal constituents at the expense of those which are more susceptible to oiling.[7,8] It is possible that epilithon coated with crude oil may suffer from necrosis, desiccation and burning), or may experience reduced or absent photosynthetic rates.[9] When hydrocarbons enter plant cells they can also interfere with intercellular membranes and regulation of essential metabolic processes.[9] Any of these changes will decrease plant productivity which may ultimately have negative secondary effects on herbivores (e.g. decreased growth rates, fecundity and longevity). Hydrocarbons may coat epilithon or become incorporated into its algal cells to be ingested and be eaten by *B. nanum* as they graze. Ingested oil tainted epilithon can then potentially impact on *B. nanum* growth, functioning and development if present in sufficient quantities.
f: growth and longevity	The WSF of oil is lethal to adults at concentrations of 1-100ppm, and has been reported to cause sublethal changes in adult invertebrates at concentrations of 10-100ppb.[10] Hydrocarbons can become fixed in high fat structures such as the liver, pancreas and gonads and in lipoproteins including plasma and nervous tissue.[2,3] Sublethal changes which can occur include depressed growth, altered respiration rates (increased at low concentrations of hydrocarbons, and depressed at higher concentrations), altered feeding patterns and rates, difficulties with osmoregulation, altered stimuli responses, increased susceptibility to disease, necrosis and increased tumour incidence.[1,10,11] Increased mucus secretion has been noted in mucus membranes exposed to oil which can impede respiration and feeding.[12] Any of these changes may decrease the survival chances of the individual and are likely to result in growth depression and a reduction in longevity. If the changes are sufficiently widespread they may ultimately result in population-level effects. If oil differentially affects intertidal species it may alter the outcomes of competitive interactions, potentially altering community structure.[1] Ostial closure and/or overweighting by crude oil can increase the risk to animals of displacement to areas which may be unfavourable, but such behaviour in response to a small, localised oil spill may enable animals to be transported to unoiled areas. Crude oil may physically smother adult animals if present in large enough volumes and can kill all invertebrates on an affected shore.[4]
g: reproduction	Hydrocarbons have been reported to result in cellular disruption within the gonads of *N. atramentosa* and similar changes would be expected with *B. nanum.*[10] It is postulated that this would decrease the fecundity and reproductive success of affected animals. Some molluscs show a seasonal susceptibility to oil[13], and it is predicted that if animals had enlarged gonads at the time of exposure to oil, more of the hydrocarbons may end up in gonadal tissue and cause greater disruption to reproductive function than if the exposure occurred at some other time. It is also possible that genetic abnormalities may arise in response to high exposures to hydrocarbons and affect the viability of future generations.[14]
h: eggs	The WSF of oil or exposure to a slick may damage eggs within the capsules by disrupting normal development (e.g. by raising the temperature of the eggs). Oil induced cytogenic changes have been reported in the eggs and embryos of bivalves [14] and similar changes may occur in *B. nanum.* Crude oil may also smother and/or glue eggs to the rocks or alternatively overweight them and result in their detachment. Any of these effects will reduce the survival potential of the eggs and diminish the numbers of juveniles entering the planktonic population from a particular area.

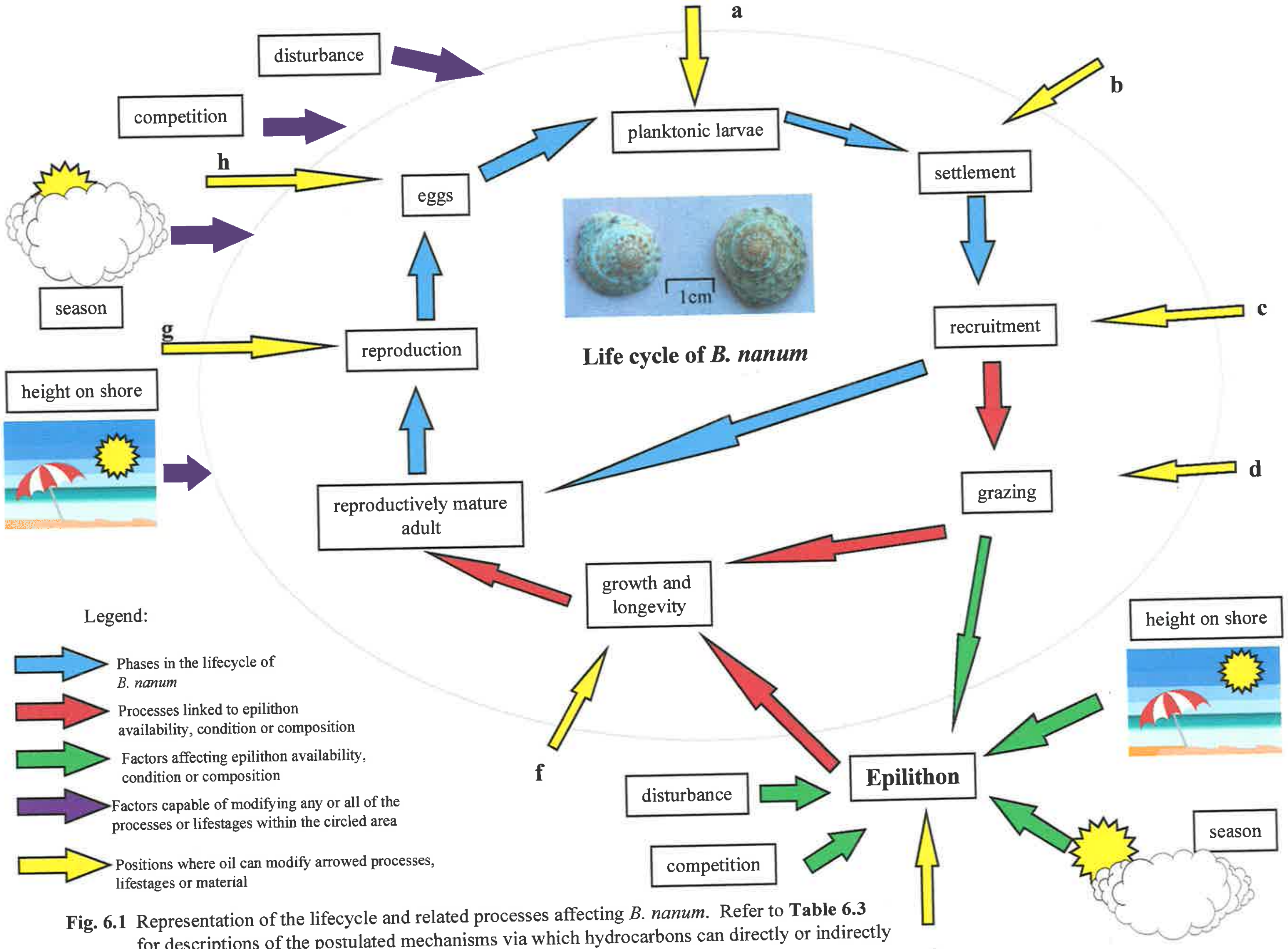


Fig. 6.1 Representation of the lifecycle and related processes affecting *B. nanum*. Refer to **Table 6.3** for descriptions of the postulated mechanisms via which hydrocarbons can directly or indirectly impact on this species.

6.3.4 *B. nanum* as a Bioindicator

Taxonomy

Taxonomically *B. nanum* belongs to;

Phylum- Mollusca,
Class- Gastropoda,
Sub-Class- Prosobranchia,
Order- Mesogastropoda,
Superfamily- Littorinacea,
Genus- *Bembicium* Philippi,
Species- *nanum* (Lamarck).

Lifestyle and Reproduction

B. nanum was the only animal sufficiently abundant at the majority of study sites to be useful in a statistical analysis of environmental impacts (see Chapters 3 & 4 and Table 6.2). This species was one of a number of herbivorous gastropods found at GSV sites but its numerical dominance coupled with its ability to live higher on the shore than other gastropods (except *Littorina* spp.) and thus be readily censused made it the most suitable *a priori* bioindicator.

B. nanum is a small herbivore which generally attains a maximum width of about 2 cm (Quinn *et al.* 1992). Longevity of individuals has been estimated at between 4-8 years, and reproductive maturity in some populations in New South Wales has been estimated to occur at an average shell width of 11 mm, 10-12 months after settlement on the shore (Underwood 1975b). The longevity of this species means that individuals are likely to survive in a local population through several consecutive years of sparse larval recruitment.

B. nanum females spawn yellow egg masses primarily in spring (Shepherd and Thomas 1989) but the spawning season extends from August to March (Underwood 1974, Table 6.1). Approximately 100-200 creamy white eggs about 0.1 mm in diameter and surrounded by a transparent oval envelope with dimensions of 0.2 x 0.19 mm are contained within transparent jelly-like egg capsules. These are flattened oval to bean-shaped structures about 2.0-2.5 mm long and 1.0-1.5 mm wide and are attached to the rocks (Shepherd and Thomas 1989). The young develop in the capsules for 18-28 days after which they emerge as planktotrophic veligers. It has been suggested that the veligers spend "probably several weeks" in the plankton (Shepherd and Thomas 1989, pg 844) but the extended planktonic phase may last as long as a year (Underwood 1975b).

The Postulated Effects of Oil

The long planktonic stage of *B. nanum* suggests that dispersal of the species is likely to occur over wide distances and local adult population dynamics are expected to have no influence on the number of new recruits arriving to an area (Underwood 1975b). If a local population is decimated by an oil spill its recovery should be rapid as new recruits or immigrants arrive to populate the vacated space. Recolonisation can only be successful if a number of conditions are met. Where larvae are involved in recolonising an oil-impacted site veligers must be present in the plankton and at the 'settling' stage and must be transported to the damaged site where conditions must then be suitable for them to settle. For recolonisation by immigrants to be successful the oiling must leave pockets of minimally affected or unaffected *B. nanum* on the shore which are close enough to migrate into the impacted area. It is possible that oil may be retained at an impacted site or have altered the area in some way (e.g. by reducing epilithon growth) so that conditions are not favourable for growth of new recruits or new immigrants. If this occurs, recovery of the area is not expected or is likely to be slow. Conversely, it is also possible that light oiling will enhance the affected area in some way, perhaps by encouraging epilithon growth, thus making it more 'attractive' to *B. nanum* immigrants and settlers or in some way promoting their growth and perhaps longevity.

Usefulness as a Bioindicator

B. nanum would be an appropriate indicator of oil induced change for a number of reasons (see Table 6.2). It is abundant at study sites and the adults do not appear to travel as far as a number of other gastropod species (see Chapter 7) and so are unlikely to be able to avoid oil exposure. *B. nanum* shares some similarities in longevity and reproduction with common gastropod species and is also herbivorous like the majority of other dominant gastropods at study sites (Table 6.1). This means that it is likely to ingest and contact oil in a similar manner to other less numerous herbivorous gastropods and to show similar effects from oil contamination. The similarities in lifestyle between the dominant gastropods suggests that changes in the abundance or population variance of *B. nanum* as a result of oil exposure may also reflect changes in the other gastropod species. However, this will depend on the individual tolerances of different species to oil, their ability to recover from such exposure, and community dynamics under perturbed conditions.

The numerical dominance of *B. nanum* at selected study sites makes it ecologically important within the context of the assemblage in which it occurs, especially as it competes for food with other herbivores such as *A. constricta* and *N. atramentosa* both of which are competitively superior (Underwood 1978b). The only remaining bioindicator criteria to determine in reference to the suitability of *B. nanum* as a bioindicator are if the species shows cryptic behaviour and if it is affected by exposure to crude or refined oil. These criteria form the focus of the latter part of this chapter.

6.3.5 *B. nanum* and its Susceptibility to Oil Exposure

The literature review of the effects of oil exposure on intertidal gastropods revealed variations in their responses to oil but suggested that in a heavy crude oil spill all gastropod species are likely to be smothered. Since smothering of gastropods and other invertebrates was well documented it seemed unnecessary to directly investigate this effect experimentally.

Previous Work

To my knowledge only one (unpublished) study undertaken in Sydney in 1995 specifically investigated the effects of oil on *B. nanum*. This study involved a series of acute toxicity tests exposing *B. nanum* to the water soluble fraction (WSF) of Shell crude oil (pers. comm. Carey). The actual WSFs of oil that animals were exposed to were not directly measured but were extracted and diluted in varying proportions.

Four tests were performed (pers. comm. Carey):

1) static 96 hour exposure of animals to diluted WSFs ranging from 5-100% of that extracted,
2) 72 hour exposure of animals to 100% of the extracted WSF of crude oil, replaced daily to simulate tidal influx,
3) manipulation of aeration to investigate how this parameter affected the toxicity of the WSF,
4) manipulation of light exposure to investigate what influence this parameter had on the toxicity of the WSF of the oil.

No mortality occurred in tests 1 or 2 although the animals were 'affected', recovering gradually over the test period. Animals were observed trying to escape from the water in both of these tests, behaviour which would minimise their contact time with the oil. Problems associated with the study were that hydrocarbons would have been lost over the trial period (although this would be realistic of an oil spill in the field) and the actual WSFs the animals were exposed to were not known. The importance of aeration and light was demonstrated in the last two tests, with all animals dying after 24 hours when the water was not aerated, and lack of light increasing the toxicity of the WSF to give a 96 hour lethal concentration-50 (LC_{50}) of 58.2%.

These tests indicated that *B. nanum* was tolerant to acute exposure to the WSF of Shell crude oil but that factors such as the amount of light and aeration were capable of affecting oil toxicity. Smothering and other changes associated with being coated with crude oil were not examined in this series of tests. However, it is likely that oil present as an emulsion or slick would be more damaging to animals in the short term than exposure to the WSF of oil. Therefore, the resistance to the WSF of crude oil identified in these tests does not necessarily make the species a poor bioindicator of oil pollution, and further investigation of a relationship between crude and refined oil and *B. nanum* was warranted.

Experimental Assessment of the Effects of Oil Exposure

Two separate experiments were conducted to investigate the effects of exposing *B. nanum* to petroleum and crude oil. The oiling experiments were intended to be as realistic as possible and to that end small but realistic amounts of Mobil refined unleaded petroleum and Arabian light crude oil were used in the experiments.

Crude oil is handled at the 'Deep Ocean Point' of the Port Stanvac Refinery and if spilt is likely to be transported further and experience more weathering than would occur if a spillage occurred closer to shore (see Appendix D). The worst scenario in terms of acute damage to intertidal biota would involve crude oil rapidly grounding with very little at-sea weathering. Therefore, it was decided to investigate the effect of unweathered Arabian light crude oil on *B. nanum*. Two oiling levels were experimentally investigated; 1 ml of oil per litre of seawater (equivalent to 51.02 ml of oil per m^2 of horizontal rock surface area) and 2 ml of oil per litre of seawater (equivalent to 102.04 ml of oil per m^2 of horizontal rock surface area).

Petroleum is also handled at the refinery, both at the 'Deep Ocean Point' and the closer 'Wharf Point'. A petroleum spill is likely to have little impact on gastropods due to its high volatility unless it comes ashore rapidly, in which case it could be very toxic to all biota it encounters. However, the 'Wharf Point' is very close to shore and petroleum spilt or leaking from this point may ground in a largely unweathered state depending on the prevailing conditions. It thus seemed pertinent to investigate the effect of exposure of *B. nanum* to unweathered (leaded) 'Mobil' petroleum. The petroleum experiment involved exposing animals to the same levels of oiling used in the 'crude oil' experiment.

The September 23rd Oil Spill

The oil spill which occurred from the 'Deep Ocean Point' on the 23rd of September 1996 has been previously mentioned (Chapters 4 & 5). This spill involved crude oil reaching the eastern shore of GSV. I intended to use a Beyond-BACI analysis to investigate acute population level effects on *B. nanum* following the oil spill. However, the prevailing conditions during and following this event resulted in oil grounding high in the intertidal region well above the 'upper' zones sampled during preliminary monitoring. This meant that no pre-impact data corresponding to the perturbed areas at study sites could be extracted from the preliminary monitoring data set. This, coupled with visual assessment of the study sites and census of the abundance of *B. nanum* in the 'upper' zones following the spill (which failed to show any changes) suggested that a Beyond-BACI assessment of post-perturbation effects would not be informative. However, to avoid overlooking any acute and possibly subtle changes in intertidal assemblage structure which were coincident with this oil spill but not readily apparent, a multivariate analysis was performed.

6.4 Materials and Methods

Three separate investigations were carried out to help select appropriate indicator species. The first of these focused on the behaviour during low tide of the dominant gastropods found in the 'upper' zones at GSV sites. 'Upper' zones were targeted as the pilot and preliminary studies had revealed the access difficulties associated with sampling the 'lower' zones (see Chapters 3 & 4).

Within the context of designing a monitoring program at Port Stanvac the behaviour of interest was a tendency for animals to aggregate under mobile substrata at low tide. The pilot study had identified low tide as the most suitable time for animal census and any form of cryptic behaviour during this time could make accurate determination of animal densities difficult. The study sites used for an investigation of cryptic behaviour were Hallett Cove B (HCB), Marino Rocks (MR), Robinson Point (RP), PS2 and PS3. Other study sites were not suited to the question of cryptic behaviour as they were dominated by bedrock with minimal proportions of mobile substrata.

Regardless of the outcomes of the investigation into cryptic behaviour of dominant gastropods at GSV sites, *B. nanum* was the only animal found at most study sites and sufficiently abundant to allow a statistical analysis of population level changes in response to an oil spill. The second set of two experiments were therefore designed to investigate the effect on *B. nanum* of acute exposure to 'realistic' amounts of fresh

Arabian light crude oil and Mobil refined petroleum. This set of experiments took place on the beach at Port Stanvac to the east of PS1.

The final investigation carried out in this chapter involved using the September 23rd 1996 oil spill as an opportunistic event to assess any coincident changes in assemblage structure.

6.4.1 Cryptic Behaviour of Gastropods

It is important that an indicator species is easily and accurately sampled and by extension does not display cryptic behaviour. During initial selection of study sites in GSV (Chapter 3) and preliminary sampling (Chapter 4) it became apparent that a number of species tended to aggregate under boulders and smaller mobile substrata (which provided moist, shaded habitat) at low tide. To avoid causing intermittent sampling disturbances and to minimise sampling time it was decided not to overturn mobile substrata to census animals. However, in determining the most appropriate indicator I was interested in finding out if dominant species at GSV study sites did show a tendency to favour the undersurface of rocks. Since all study sites, including those dominated by bedrock, had varying amounts of mobile substrata (grading from gravel to boulder) it was important to investigate which species displayed the aforementioned behaviour. An animal which did not aggregate under rocks could be readily and accurately censused without disturbing the study sites while a species favouring the undersurface of rocks at low tide presented a number of sampling difficulties and was likely to give a biased estimate of its ‘true’ abundance.

The investigations into the behaviour of dominant gastropods took place in May 1995. At each of the selected study sites the $0.25m^2$ quadrat was randomly deployed 12 times within the ‘upper’ zones. All animals visible within a quadrat were censused. Then, mobile substrata with a surface area in the range of $20\text{-}40cm^2$ were overturned and the animals found underneath recorded. This size substrata was common at a number of sites and potentially afforded animals moderate shelter from exposure at low tide while still being easy to overturn without causing major disturbance to adjacent substrata and animals. During the pilot study, substrata with a surface area less than 20-40cm^2 was generally found to have few animal species associated with it and was consequently not investigated as part of this project. The number of animals found within a quadrat occupying either the exposed positions ('top') or protected positions under mobile substrata ('under') were then standardised for surface area and compared using paired *t*-tests. If the differences between the paired treatments were not normally distributed (determined using the Anderson-Darling test (Snedecor and Cochran 1989)) then a $\log_{10}(x+1)$ transformation was performed (where x=abundance of a species) and the data re-tested (see Zar 1984). If data still violated the assumption of normality then a non-parametric test, the Wilcoxon paired test was used (Wilcoxon 1945). Although 12 quadrats were assigned to census animals the number of quadrats in which particular species occurred (n) varied as some animals, particularly *Austrocochlea* spp., were present at low densities at some study sites.

Analyses were separately performed for each of the study sites to eliminate the risk of confounding the results due to observed differences in substrata characteristics between sites. Only numerically dominant animal species were investigated statistically. The *a priori* effect size of interest was a 50% difference in animal abundance (on average) between the two treatments. A two-tailed hypothesis of no difference between 'top' and 'under' positions within quadrats was addressed for each of the tested species. If a significant difference was found the direction of difference was determined. If no significant difference was found between treatments then the power of the analysis to detect a difference was calculated as described in Zar (1984, pp. 110-112 & 153) using the variance found between 'top' *versus* 'under' pairs.

6.4.2 Exposure of *B. nanum* to Oil

The two experiments investigating the acute effects of fresh crude oil and unweathered leaded Mobil petroleum on *B. nanum* were carried out on two separate days at Port Stanvac. The experiments simulated a tidal sequence of a high tide followed by a low tide. In both experiments effects at the level of the individual were investigated but it was hoped that extrapolation to the potential effects of an oil spill at the level of the population could be made.

6.4.2.1 Arabian Light Crude Oil and *B. nanum*

The first of the experiments to investigate a cause-and-effect link between *B. nanum* and crude oil commenced at Port Stanvac on the 14th of August 1996. This experiment was conducted over one day and used fresh (e.g. unweathered) Arabian light crude oil, provided by Mobil's Port Stanvac Oil Refinery.

The experiment was set up high on the beach using a randomised block design involving 5 treatments, each of which had 5 replicates (Table 6.4). Each replicate consisted of a 2 litre white icecream container into which one or two flat sun-dried rocks had been placed. Sun-dried beach rocks were used to avoid introducing the uncontrolled factor of variable amounts of epilithon into the experimental design. The size of the rocks varied (and if necessary two were used) but the surface area approximated that of the base of the icecream container which was 196cm^2. Seawater was collected from a single deep rock pool close to the low water mark and 1 litre was added to each of the containers prior to the addition of experimental animals.

An area corresponding to the 'upper' mid-eulittoral zone was selected to the north of PS1. The 0.25m^2 quadrat was randomly assigned 7 times to this area so that the average abundance of *B. nanum* could be calculated and the ratio of size classes determined. Definition of the size classes used to categorise *B. nanum* populations has been given previously (see Chapter 3). The average density of *B. nanum* was found to be equivalent to 10 animals per 196cm^2 and the ratio of size classes was found to be approximately 2 'small' : 3 'medium', with only rare appearances of larger animals. Therefore, 10 animals (consisting of 4 'small' and 6 'medium' sized *B. nanum*) were randomly assigned to each experimental container. The animals were collected from the designated area at low tide and added to containers which had been set up with the rock (or rocks) and sea water. The water was allowed to settle for 10 minutes before the animals were added, after which 30 minutes were allowed to enable animals to acclimatise to the containers. Crude oil was then added to 'oil' replicates using a syringe and the volumes indicated in Table 6.4. Additional controls to test for the procedural effects of addition of 1 or 2ml of oil (by adding the equivalent amount of distilled water) were not used as the volumes involved were small in comparison to the total volume of seawater which was added to each treatment.

Table 6.4 The treatments used in the experiment to test for the effects on *B. nanum* of acute exposure to unweathered Arabian light crude oil. There were 5 replicates in each treatment and 10 animals were randomly assigned to each of the replicates (see text for full details).

Treatment	Description
1. Control (C)	Addition of 1L of sea water only
2. 1ml (-) (1-)	As for control plus addition of 1ml of crude oil which was not allowed to contact the animals when the water was siphoned off.
3. 1ml (+) (1+)	As for control plus addition of 1ml of crude oil which was allowed to contact the animals when the water was siphoned off.
4. 2ml (-) (2-)	As for control plus addition of 2ml of crude oil which was not allowed to contact the animals when the water was siphoned off.
5. 2ml (+) (2+)	As for control plus addition of 2ml of crude oil which was allowed to contact the animals when the water was siphoned off.

In a real spill *B. nanum* were likely to directly contact pelagic oil as the tide receded and some of the oil grounded. Therefore, the amount of oil added to experimental treatments was calculated as per the area of horizontal substrata (the upper surface of the rocks plus the exposed base of the containers). This gave a crude oil concentration of 51.02ml of oil per m^2 of substrata for the 1ml treatments and 102.04ml of oil per m^2 of substrata for the 2ml treatments. Once oil was added to the appropriate treatments it was allowed to float on the surface of the water for 3 hours before being siphoned off using plastic tubing. This was done to mimic pelagic oil being carried across an intertidal region at high tide.

Within the oil treatments there were two additional treatment strategies (Table 6.4). Oil was either allowed to contact and settle on the animals as the water was siphoned off ('+' treatments), or the water was siphoned off and not allowed to contact the animals during this process ('-' treatments). Separate tubing was used to siphon water from all treatments to avoid cross contamination. The water temperature was recorded at hourly intervals in conjunction with ambient air temperature. Salinity, pH and dissolved oxygen were recorded at the start of the experiment (before oil was added) and immediately before the water was siphoned off (after 3 hours) using the YSI 3800 water-meter. The experiment continued for a further 3 hours after the water had been siphoned off.

When initially placed in containers animals were positioned upright on the rock or rocks. Their behaviour was observed at half-hourly intervals and recorded until the end of the experiment. Recognised behaviours were: dead, attached and upright, overturned with operculum open, overturned with operculum closed, actively climbing and foraging. If animals climbed out of the water or the container, this activity was recorded and the animals were returned to the container (and placed upright on the rock). In a small, localised oil spill, animals may be able to avoid or minimise contact with oil by moving away from it or out of it, but in a medium or large oil spill this is less likely. It was therefore deemed appropriate to return escapee animals to their containers. Expected animal activities were listed *a priori* and assigned a weighted subjective score (believed to reflect the 'seriousness' of the activity), with higher scores being allocated to what was postulated to be 'healthier' behaviour (Table 6.5). It was hypothesised that there would be more negative behaviour, characterised by lower 'weighted' activities, in the oiled treatments than in the control treatment.

Table 6.5 'Weighted' scores assigned to the activities of *B. nanum* within replicates in the 'crude oil' experiment. An overall activity rating was then calculated for each of the replicates so that activity differences across treatments could be examined. Higher scores were assigned to activities that were considered 'healthy' or favourable in reference to a simulated pelagic oil spill and its subsequent grounding. Refer to text for further details on methodology.

Activity	Assigned Score
Tightly adherent or actively moving on the rocks or side of container	5
Moving out of the water (through oil in oil treatments) to the rim of the container	4
Remaining in contact with the surface of the water, potentially maximising oil contact	3
Upright, but loose on the rock	3
Overturned with operculum shut	2
Overturned with operculum open	1
Dead	0

Temperature, pH, salinity and dissolved oxygen were compared at the start of the experiment (immediately before oil was added) and again immediately before the oil was siphoned off. These parameters were consistent across treatments at the start of the experiment and a statistical analysis was not performed. However, Kruskal-Wallace tests were separately performed on the water quality parameters immediately prior to water being siphoned off. This was necessary as the treatments had homogeneous variances (tested using the F_{max} test) although they were normally distributed (tested using the Anderson-Darling test) after a $\log_{10}(x+1)$ transformation.

To assess how oil affected animal behaviour the activity scores were calculated for each of the replicates at the start of the experiment, immediately prior to the water being siphoned off, and again three hours after the water was siphoned off (although half-hourly activity readings were collected). Separate ANOVAs (or Kruskal-Wallace tests) were then performed on the 'weighted' activity scores at each of the times of interest to determine if there were significant treatment effects. The non-parametric Kruskal-Wallis test was needed if the data violated the assumptions of ANOVA (Zar 1984) and a correction was made for tied ranks if necessary (Kruskal and Wallis 1952).

If significant differences in the 'weighted' activity of animals or water quality were found between treatments a Tukey test or the non-parametric equivalent (see Zar 1984) was performed to determine where the differences lay. Prior to the water being siphoned off there were, in effect, only three treatments; the control and the two groups to which oil had been added. However, results were consistent whether the data were analysed as five treatments or three.

6.4.2.2 Mobil Petroleum and *B. nanum*

The experiment to investigate the effects of exposing *B. nanum* to Mobil's unweathered refined product (leaded petroleum) was completed on the 10th of October 1996. This experiment was conducted on the shore at Port Stanvac adjacent to PS1 and was designed and analysed as previously described for the crude oil experiment apart from the following minor alterations. One extra replicate was assigned to each of the treatments, which were set up in small, commercially available aluminium containers with dimensions of 17 x 8 x 6cm. The treatments were as described in Table 6.4. However, to allow for the different horizontal surface area of the containers (136cm^2) and the altered volume of seawater used (700ml), the volume of oil added to 'oil' treatments was adjusted to achieve equivalent oil concentrations to those of the crude oil experiment (Table 6.6). Therefore, 0.7ml of petroleum was added to the 'lightly' oiled treatments (equivalent to the 1ml crude oil treatments) and 1.4ml of petroleum was added to the 'moderately' oiled treatments (equivalent to the 2ml crude oil treatments). The horizontal surface area in this experiment was less than it was for the crude oil experiment but the number of animals per replicate was increased to twelve. However, the size distributions of experimental animals were as described for the crude oil experiment. The animal densities used in these experimental treatments were slightly higher than the average densities of *B. nanum* at PS1 on the day of this experiment but were still realistic in terms of observed field densities (see Chapter 4).

Table 6.6 The treatments used in an experiment to investigate the effects on *B. nanum* of acute exposure, over one tidal cycle, to Mobil's unweathered leaded refined petroleum. Each treatment consisted of 6 replicates to which 12 animals were randomly assigned (see text for full details).

Treatment	Description
1. Control (C)	Addition of 700ml of sea water only
2. 0.7ml (-) (0.7-)	As for control plus addition of 0.7ml of petrol which was <u>not</u> allowed to contact the animals when the water was siphoned off.
3. 0.7ml (+) (0.7+)	As for control plus addition of 0.7ml of petrol which was allowed to contact the animals when the water was siphoned off.
4. 1.4ml (-) (1.4-)	As for control plus addition of 1.4ml of petrol which was <u>not</u> allowed to contact the animals when the water was siphoned off.
5. 1.4ml (+) (1.4+)	As for control plus addition of 1.4ml of petrol which was allowed to contact the animals when the water was siphoned off.

The activity ratings of animals within replicates, all water parameters and treatment protocols were assessed and handled as previously described for the crude oil experiment. The analyses were also conducted as described for the 'crude' oil experiment.

6.4.3 The Oil Spill and Intertidal Assemblage Structure

The oil spill and method of census of assemblage data have been previously described (Chapters 4 & 5). Following the spill, all animals present in the 'upper' zones at those study sites able to be accessed on the 26th of September 1996, were counted. The presence of obvious oiling (subjectively scored as described in Chapter 3: Table 3.1) was also noted. Taxa data were entered along with the previously collected 'Preliminary' data and analysed as part of the SSH MDS Ordination (see Chapter 4). A three-dimensional ordination yielded a satisfactory stress level of 0.13 and this was retained as the 'best' result to investigate any changes in the position of study sites in ordination space which coincided with the oil spill.

The only study site exposed to obvious oiling was Port Noarlunga South (PN). This site was designated as an 'impact' site. Five other study sites were not exposed to obvious oiling and were designated as 'control' sites; Kingston Park (KP), Marino Rocks (MR), and the 3 'Central' study sites (PS1, PS2 & PS3). At each sampling time, including the 26th of February 1996, the average position of the control sites was determined and plotted as a temporal data series. Data pertaining to the Port Noarlunga South site were also plotted and compared to the position of the 'control' group using various combinations of the three ordination axes. The sampling time corresponding to the post-spill positions of both 'control' and 'impact' groups was identified with an arrow. A visual assessment was then made to see if the post-impact position of PN fell within the range of data points corresponding to the pre-impact positions of this site. The same assessment was made in relation to the 'average' position of the post-impact 'control' point within the cloud of pre-impact data points.

6.5 Results

6.5.1 Cryptic Behaviour

Comparisons between the relative abundance of animals in exposed positions ('top') and protected positions under mobile substrata ('under') revealed the tendency of a number of species to favour the latter (Table 6.7). Unfortunately, it was not possible to statistically test the cryptic behaviour of all species seen at study sites. For example, *Notoacmea* spp. were generally rare at all study sites, while *A. constricta* was only present at sufficient densities to allow a statistical test in the 'upper' zone at Robinson Point (RP). However, *Notoacmea* spp. and *A. constricta* were more frequently observed under rocks, or aggregated in small areas of retained water at low tide than they were occupying more exposed positions. These taxa occurred at higher densities in the 'lower' zones at the majority of sites but since the 'upper' zone was more relevant to the monitoring program the study focus remained on this zone.

The statistical analyses of the positions occupied by dominant gastropods revealed that at the majority of study sites *B. nanum* was more likely to be found in exposed positions (Table 6.7). The exception to this trend occurred at MR, a frequently physically disturbed site with low overall abundances of all animal species. At this site, *B. nanum* still tended to be found on upper surfaces of rocks but on occasion occurred at relatively high densities on the undersurface of rocks. An estimation of the power of the analysis to detect a difference of at least 2 animals was found to be 0.92. This was calculated as described in Zar (1984, pp. 110-112 & 153) using the variance found between 'top' *versus* 'under' pairs of 3.65, 12 replicates, a critical $t_{(0.05,(2),11)}$ of 2.201 and adopting the assumption that the calculated $t_{\beta(1),11}$ (the 1 tailed t value associated with β and 11 degrees of freedom) was a normal deviate.

A. concamerata and *N. atramentosa* were significantly more numerous under rocks at all study sites where their 'favoured' positions were tested. No significant difference in the number of *A. constricta* occupying exposed positions ('top') or protected positions beneath mobile substrata ('under') could be found at RP (Table 6.7). However, a calculation of the power to detect a true difference of at least 4 animals was 0.96. This meant that the power of the analysis to detect a 50% or greater difference between 'treatments' (the desired *a priori* effect size) was satisfactory. This calculation was as described in relation to *B. nanum* at MR, with all parameter values being equivalent apart from the variance of the differences between the treatment pairs which was 12.43 in the case of *A. constricta*.

Table 6.7 Paired *t*-tests were used to determine if the relative abundances of the dominant gastropod species in the 'upper' zones at GSV sites differed between exposed surfaces (designated 'top') and protected areas underneath mobile substrata (designated 'under'). A parametric paired *t*-test was used if the differences between treatment pairs were normally distributed and a Wilcoxon paired test was chosen if the data violated the assumption of normality after transformation. The number of quadrats in which species occurred varied due to low occurrences of some species. The direction of difference (when one occurred) is shown in the last column of the table, with T='top' and U='under' positions. The results of the analyses are; **=significant at the 0.05 probability level, ***= significant at the 0.01 probability level, NS=no significant difference at the 0.05 probability level.

Site & Species Tested	Number of quadrats in which species were found (n)	Test	Probability (2 tailed)	Direction of Difference
Port Stanvac 2				
N. atramentosa	12	Parametric	0.008***	T<U
A. concamerata	10	Wilcoxon	0.001***	T<U
B. nanum	12	Parametric	0.001***	T>U
Port Stanvac 3				
N. atramentosa	12	Parametric	0.005***	T<U
A. concamerata	9	Wilcoxon	0.005***	T<U
B. nanum	12	Parametric	0.025**	T>U
Hallett Cove B				
N. atramentosa	8	Parametric	0.010***	T<U
A. concamerata	6	Parametric	0.020**	T<U
B. nanum	12	Parametric	0.020**	T>U
Marino Rocks				
N. atramentosa	10	Parametric	0.010***	T<U
A. concamerata	6	Parametric	0.005***	T<U
B. nanum	12	Parametric	0.500NS	-
Robinson Point				
A. constricta	12	Parametric	0.500NS	-
B. nanum	12	Parametric	0.010***	T>U

6.5.2 The Effect of Oil on *B. nanum*

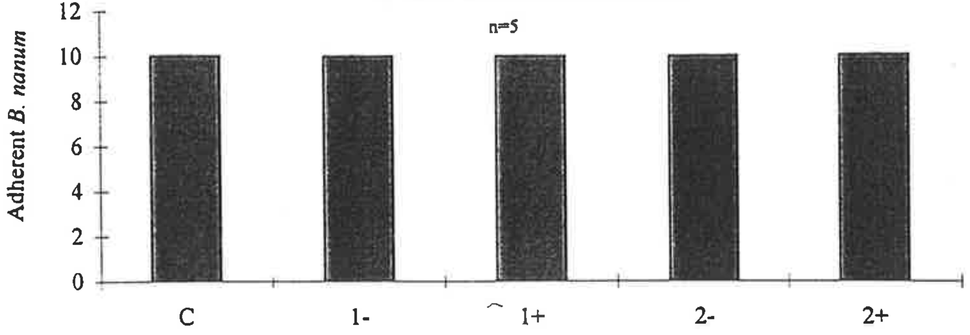
6.5.2.1 Crude Oil Exposure

Animal Behaviour

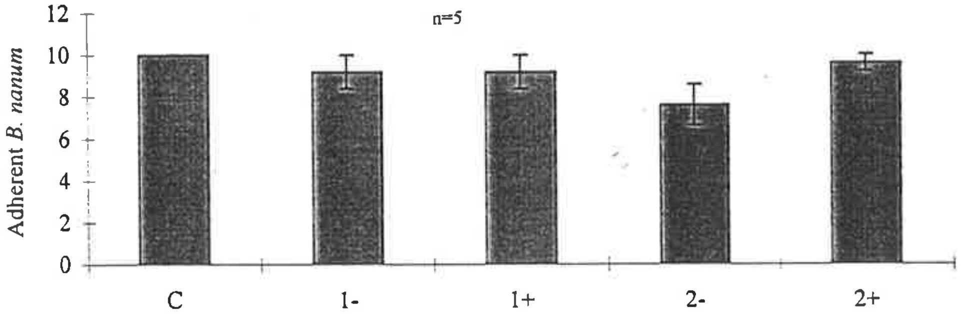
Exposure to 1ml or 2ml of Arabian light crude oil did not cause any mortality of experimental animals over the duration of this experiment. The difference between 10 and the number of adherent animals shown in Fig. 6.2 corresponds to the average number of animals overturned in experimental treatments. There is a degree of variability between replicates in terms of the number of adherent animals in 'oiled' treatments. However, it was apparent that the '2-' treatment had less adherent animals (on average) than all other treatments three hours after oil had been added (Fig. 6.2b) and three hours after the water had been siphoned off (Fig. 6.2c). The number of adherent animals in the '2-' treatment was lowest after the water had been siphoned off (Fig. 6.2c).

Similar trends were apparent when the average weighted activity scores between treatments were examined. Again, no differences between treatments existed in terms of the 'weighted' activity of experimental animals prior to the addition of crude oil to the appropriate treatments (Fig. 6.3a). A trend towards a lower activity rating in oiled treatments was seen following the addition of oil (Fig. 6.3b & c) but no obvious change in weighted activity was noted in the control treatment for the duration of this experiment (Fig. 6.3a, b & c). The only significant difference in 'weighted' activity of *B. nanum* between treatments occurred after the water had been siphoned off (Table 6.8).

a) Prior to addition of crude oil



b) Three hours after addition of crude oil



c) Three hours after removal of water

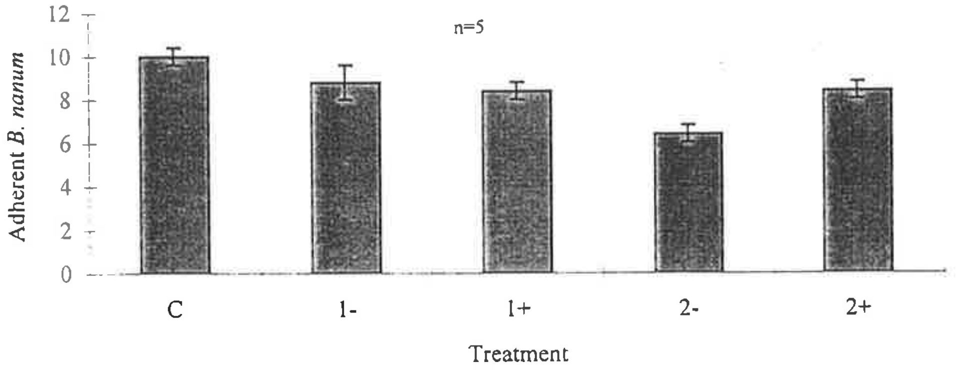
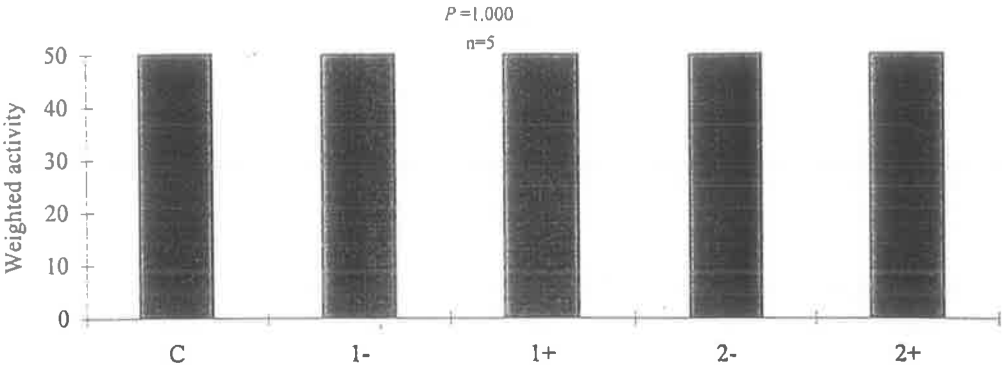
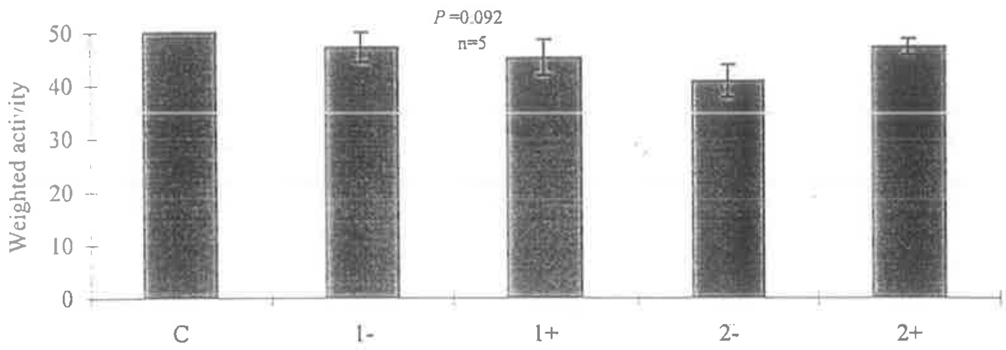


Fig. 6.2 A comparison of the average number of adherent *B. nanum* in experimental treatments; a) prior to the addition of unweathered Arabian light crude oil, b) three hours after the addition of Arabian light crude oil and c) three hours after siphoning of water from experimental treatments. Treatments are shown on the *x*-axis and are; control: no oil added (C), addition of 1 ml of oil which was not allowed to contact animals when siphoned off (1-), addition of 1 ml of oil which was allowed to contact animals when siphoned off (1+), addition of 2 ml of oil which was not allowed to contact animals (2-) and the equivalent contact treatment (2+). Full descriptions of experimental treatments can be found in Table 6.4. Ten *B. nanum* were assigned to each replicate and there were 5 replicates per treatment (n=5). Error bars represent the standard errors associated with the treatment averages.

a) Prior to addition of crude oil



b) Three hours after addition of crude oil



c) Three hours after removal of water

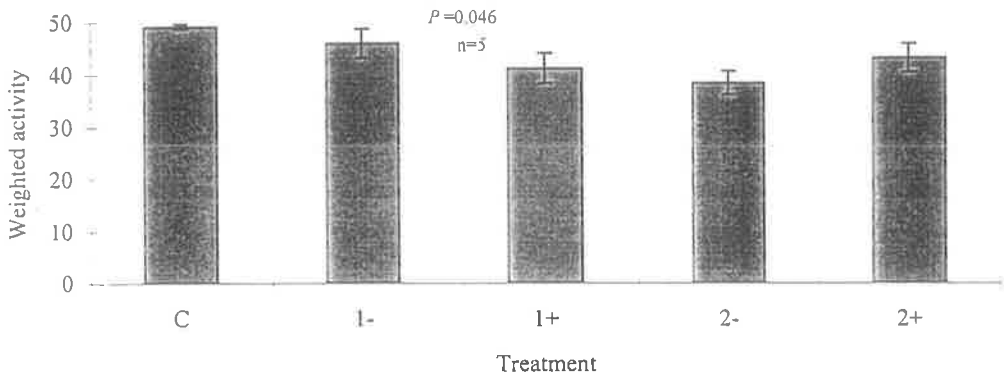


Fig. 6.3 A comparison of the average 'weighted' activity (see Table 6.5) of *B. nanum* in experimental treatments; a) prior to the addition of unweathered Arabian light crude oil, b) three hours after the addition of Arabian light crude oil and c) three hours after siphoning of water from experimental treatments. Treatments are shown on the *x*-axis and are; control: no oil added (C), addition of 1ml of oil which was not allowed to contact animals when siphoned off (1-), addition of 1ml of oil which was allowed to contact animals when siphoned off (1+), addition of 2ml of oil which was not allowed to contact animals (2-) and the equivalent contact treatment (2+). Full descriptions of experimental treatments can be found in Table 6.4. Ten *B. nanum* were assigned to each replicate and there were 5 replicates per treatment (n=5). Error bars represent the standard errors associated with the treatment averages. *P* values shown on each graph indicate the probability of significant treatment differences associated with the experiment (refer to text for details).

Table 6.8 The results of a statistical analysis on the 'weighted' activity of *B. nanum* in experimental treatments (see Table 6.5) prior to the addition of unweathered Arabian light crude oil, three hours after addition of oil and again three hours after the water had been siphoned off. The latter time corresponds to a receding tide carrying oil, with oil being allowed to directly contact animals in the '+' treatments. In effect, prior to oil being siphoned off there were three experimental treatments rather than the five shown in Table 6.5 (refer to text for details). Data were analysed using the Kruskal-Wallace Test as treatments violated the assumptions of ANOVA (Zar 1984). Bracketed values shown in the last column of the table refer to the number of treatment groups considered in the analyses, and **= probabilities which are significant at the 0.05 level.

Time	Test	Probability (*P*)
Prior to oil addition	Kruskal-Wallace	1.000 (3 gps & 5 gps)
Three hours after oil addition	Kruskal-Wallace	0.059 (3 gps) & 0.092 (5 gps)
Three hours after water siphoned off	Kruskal-Wallace	0.046**

A non-parametric multiple comparison of the treatments (with ranked sums) after the water was siphoned off was used to investigate where differences between treatments occurred. This established that the '2-' treatment was significantly different to the control treatment but no other significant treatment differences could be identified (Table 6.9). However, there was an overall tendency for more negative activities, in particular more overturned animals (Fig. 6.2), in all oiled treatments compared to the control. Differences in replicates within a treatment were apparent with one of the '2-' replicates recording 60% of its animals overturned, while another in this treatment had no overturned animals. All overturned animals had their operculum tightly shut at all times.

Table 6.9 Results of a non-parametric multiple comparison to determine where significant differences in 'weighted' activity of *B. nanum* occurred 3 hours after water had been siphoned from experimental treatments (6 hours after addition of oil) in the 'crude oil' experiment. The analysis involved using ranked sums of treatment groups (see Zar 1984, p. 199). Treatments are; C=control, 1+=1ml(+), 1-=1ml(-), 2+=2ml(+), 2-=2ml(-). Full treatment descriptions are given in Table 6.4.

Treatments ranked by ranked sums (*i*)	2-	1+	2+	1-	C
Rank sums (R*i*)	31	60	63.5	73	97.5

Comparison (B vs A)	Difference (R_B - R_A)	SE	*q*	$q_{0.05,\infty,5}$	Conclusion
C *vs* 2-	66.50	16.46	4.04	3.86	C ≠ 2-
C *vs* 1+	37.50	16.46	2.28	3.86	C= 1+
1- *vs* 2-	42.00	16.46	2.55	3.86	1- = 2-

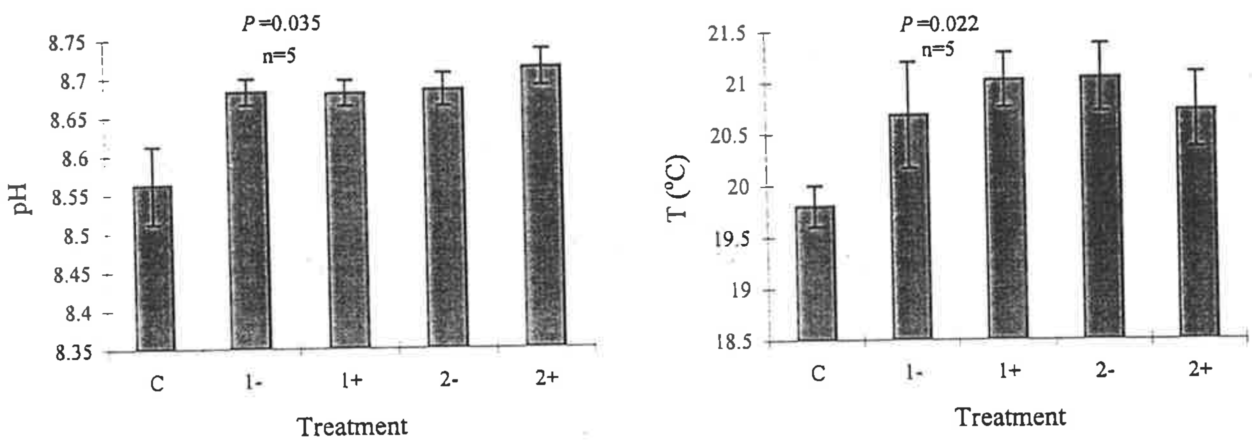
Water Quality

Comparisons of the effect of oil on assessed water parameters were made during the course of this experiment. All were within a normal range prior to the addition of the oil and it was not necessary to analyse for pre-treatment differences (Table 6.10).

Table 6.10 The range of water parameters recorded in experimental treatments immediately after the crude oil experiment had been set up and prior to addition of oil. Parameters assessed were temperature, salinity, % dissolved oxygen (DO) and pH. Experimental treatments are as shown in Table 6.4. The air temperature ranged from 15.6°C at the start of the experiment to 17.5°C at the time the water was siphoned from experimental treatments.

Treatment	T (°C)	Salinity (‰)	DO (%)	pH
Control (C)	16.11-16.57	37.28-37.46	163.0-186.8	8.06-8.34
1ml(+)	16.10-16.56	37.25-37.50	163.7-186.6	8.07-8.34
1ml(-)	16.11-16.55	37.28-37.44	163.0-186.9	8.07-8.32
2ml(+)	16.09-16.57	37.25-37.46	163.3-187.0	8.10 -8.35
2ml(-)	16.10-16.59	37.27-37.45	163.4-186.9	8.06-8.35

Three hours after the addition of oil to relevant treatments some trends in pH (Fig. 6.4a) and temperature (Fig. 6.4b) were observed but no apparent changes in salinity or DO were noted (Fig. 6.4c & d). All treatments remained supersaturated until the water was siphoned off (Fig. 6.4d). Kruskal-Wallace tests were separately performed on water quality parameters immediately prior to the removal of water from the replicates (Table 6.11).



a) pH

b) T

c) Salinity

d) DO

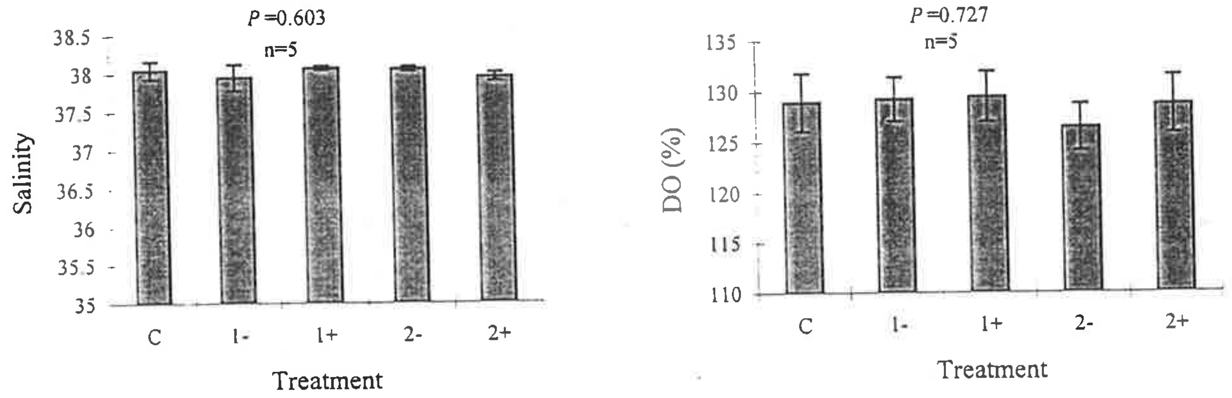


Fig. 6.4 A comparison of the average a) pH, b) temperature; T (°C), c) salinity (‰) and d) dissolved oxygen; DO (%) are presented for the 'crude oil' experiment. Treatments are shown on the *x*-axis and are; control: no oil added (C), addition of 1 ml of oil which was not allowed to contact animals when siphoned off (1-), addition of 1 ml of oil which was allowed to contact animals when siphoned off (1+), addition of 2 ml of oil which was not allowed to contact animals (2-) and the equivalent contact treatment (2+). All graphs illustrate parameters assessed 3 hours after addition of Arabian light crude oil to the appropriate treatments and were recorded immediately prior to water being siphoned off. Full descriptions of experimental treatments can be found in Table 6.4. Ten *B. nanum* were assigned to each replicate and there were 5 replicates per treatment (n=5). Error bars represent the standard errors associated with the treatment averages. *P* values shown on each graph indicate the probability of significant treatment differences associated with the experiment (refer to text for details).

Table 6.11 Kruskal-Wallace (KW) tests were used to determine if physical water parameters differed according to treatment 3 hours after addition of oil to 'oiled' treatments and immediately prior to water being siphoning from replicates in the 'crude oil' experiment. In effect, at this time there were 3 experimental treatments rather than 5, but data were analysed as though there were 5 treatments. Where treatment effects were found these was consistent whether 3 or 5 treatment groupings were used in analyses. Results which are significant at the 0.05 probability level are marked as; **.

Water Parameter	KW test statistic	Probability (*P*)
pH	10.365	0.035**
Temperature	11.424	0.022**
Salinity	2.737	0.603
Dissolved Oxygen	2.048	0.727

The KW tests revealed significant treatment effects at the 0.05 probability level in relation to water temperature and pH (Table 6.11). A non-parametric multiple comparison was used to determine where the treatment differences lay. This indicated that the control and '2-' treatments were significantly different in terms of their pH (Table 6.12) and temperature (Table 6.13). This graphical results (Fig. 6.4a & b) indicated that pH was more acidic in the control than in the oiled treatments (an average difference of approximately 0.12 or more pH units) and that the temperature was also lower in the control (a difference of at least 0.95°C). These differences were slight but indicated the direction of change in pH and temperature which would be expected in a shallow water body exposed to a high volume crude oil spill under conditions similar to those encountered in the field on the day of this experiment.

Table 6.12 Results of a non-parametric multiple comparison to determine where significant treatment differences in pH occurred 3 hours after oil had been added to the appropriate experimental treatments in the 'crude oil' experiment. The analyses used ranked sums of treatment groups (see Zar 1984, p. 199). Treatments are; C=control, 1+=1ml(+), 1-=1ml(-), 2+=2ml(+), 2-=2ml(-). Full treatment descriptions are given in Table 6.4.

Treatments ranked by ranked sums (*i*)	C	1+	1-	2+	2-
Rank sums (R*i*)	23	59	74	76.5	92

Comparison (B vs A)	Difference ($R_B - R_A$)	SE	*q*	$q_{0.05,\infty,5}$	Conclusion
2- *vs* C	69	16.46	4.19	3.86	2- ≠ C
2- *vs* 1+	33	16.46	2.00	3.86	2- = 1+
2+ *vs* C	53.5	16.46	3.25	3.86	2+ = C

Table 6.13 Results of a non-parametric multiple comparison to determine where significant treatment differences in temperature occurred 3 hours after oil had been added to the appropriate experimental treatments in the 'crude oil' experiment. The analyses used ranked sums of treatment groups (see Zar 1984, p. 199). Treatments are; C=control, 1+=1ml(+), 1-=1ml(-), 2+=2ml(+), 2-=2ml(-). Full treatment descriptions are given in Table 6.4. Ambient air temperature at the time of water monitoring was 17.5°C.

Treatments ranked by ranked sums (*i*)	C	1+	1-	2+	2-
Rank sums (R*i*)	29	51	61	84	100

Comparison (B vs A)	Difference (R_B - R_A)	SE	*q*	$q_{0.05,\infty,5}$	Conclusion
2- *vs* C	71	16.46	4.31	3.86	2- ≠ C
2- *vs* 1+	49	16.46	2.98	3.86	2- = 1+
2+ *vs* C	55	16.46	3.34	3.86	2+ = C

6.5.2.2 Petroleum Exposure

Animal Behaviour

The experiment exposing *B. nanum* to unweathered Mobil (leaded) petroleum was analysed in the same way as the previous experiment. The activity of the animals was again scored and subjectively 'weighted' as described previously (Table 6.5). The average 'weighted' activity score of experimental treatments has been presented graphically (Fig. 6.5). Analyses to determine if treatment differences at the three times of interest existed in terms of the weighted activity of *B. nanum* found significant treatment effects (*P*=0.007) three hours after removal of the water (Table 6.14). A non-parametric multiple comparison determined that the control, which had a higher weighted activity score, differed significantly from the '1.4+' and '1.4-' treatments, but the analysis lacked the power to draw further conclusions (Table 6.15).

An examination of the average activity within treatments illustrated a trend towards lower activity in the oiled treatments after the water had been removed, with the more heavily oiled treatments recording a greater depression of this parameter (Fig. 6.5c). Treatments where petroleum was allowed to contact the animals after the water was siphoned off recorded a lower average activity rating than the corresponding treatments where oil was not allowed to contact the animals (Fig. 6.5c).

Table 6.14 The results of statistical analyses investigating the effect of unweathered (leaded) Mobil petroleum on the weighted activity of *B. nanum* in experimental treatments (shown in Table 6.6); prior to addition of petroleum to appropriate treatments, three hours after addition of petroleum and three hours after water was siphoned off. The latter time simulates a receding tide carrying petroleum. Animals in the '+' treatments are allowed to directly contact oil as the water is removed. In effect, the other two times of interest correspond to three experimental treatments rather than the five shown in Table 6.6 (refer to text for further details). Data were analysed using an ANOVA or a Kruskal-Wallace (KW) Test. Results were consistent whether the data were analysed as 3 or 5 experimental treatment groups and only the results obtained for 5 groups are shown in this table. Results which are significant at the 0.01 level are marked as; ****.

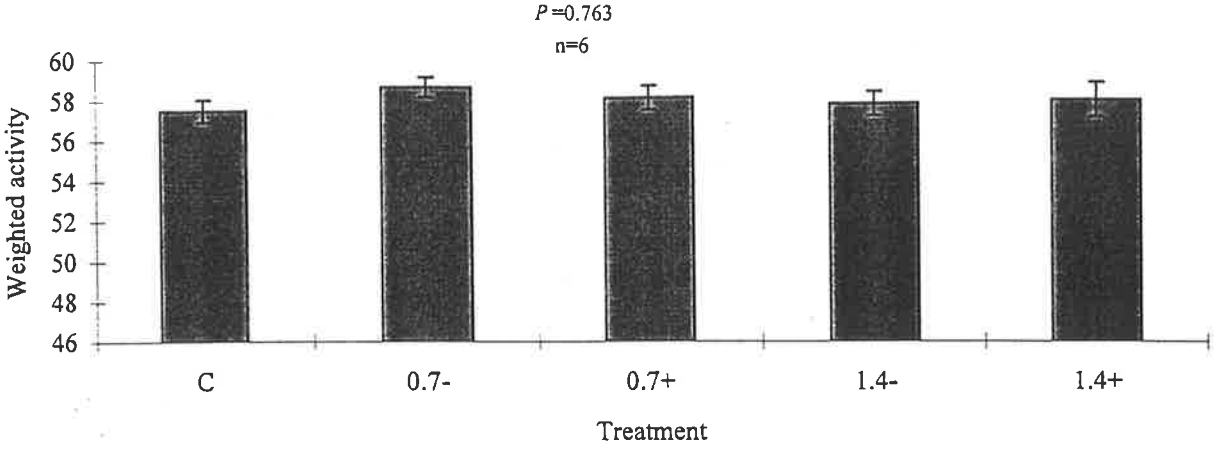
Time	Test	F or KW test statistic	Probability (*P*)
Prior to oil addition	ANOVA	0.461	0.763
Three hours after oil addition	KW	4.286	0.369
Three hours after water siphoned off	KW	13.99	0.007****

Table 6.15 Results of a non-parametric multiple comparison to determine where significant treatment differences in weighted activity of *B. nanum* occurred 3 hours after water had been siphoned from replicates in the 'refined oil' experiment. The oil used in this experiment was unweathered leaded Mobil petroleum. The analyses used ranked sums of treatment groups (see Zar 1984, p. 199). Treatments are; C=control, 0.7+=0.7ml(+), 0.7-=0.7ml(-), 1.4+=1.4ml(+), 1.4-=1.4ml(-), with treatment descriptions as shown in Table 6.6.

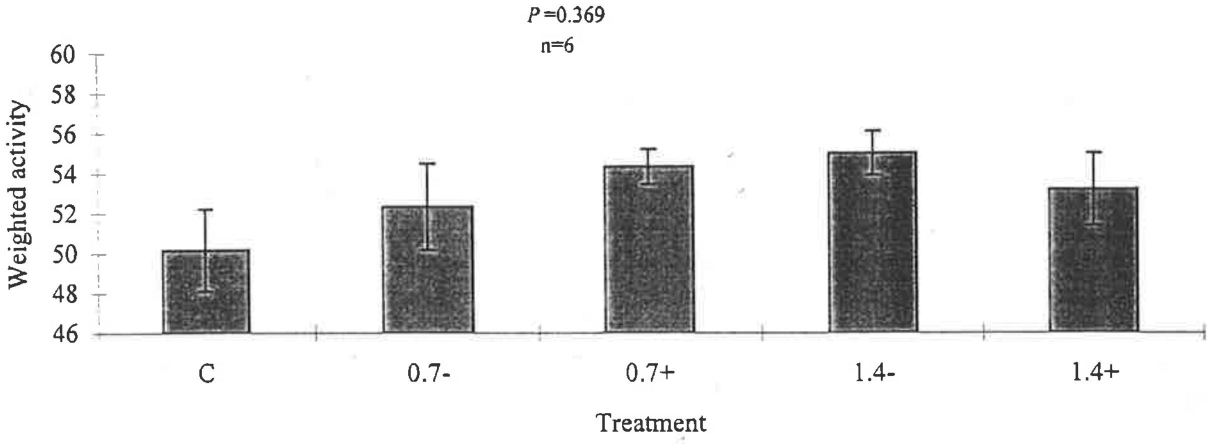
Treatments ranked by ranked sums (*i*)	1.4+	1.4-	0.7+	0.7-	C
Rank sums (R*i*)	52	64	89	110	150

Comparison (B vs A)	Difference ($R_B - R_A$)	SE	*q*	$q_{0.05,\infty,5}$	Conclusion
C *vs* 1.4+	98	21.56	4.55	3.86	C ≠ 1.4+
C *vs* 1.4-	86	21.56	3.98	3.86	C ≠ 1.4-
C *vs* 0.7+	61	21.5	2.82	3.86	C = 0.7+
0.7- *vs* 1.4-	58	21.5	2.70	3.86	0.7- = 1.4-

a) Prior to addition of petrol



b) Three hours after addition of petrol



c) Three hours after removal of petrol

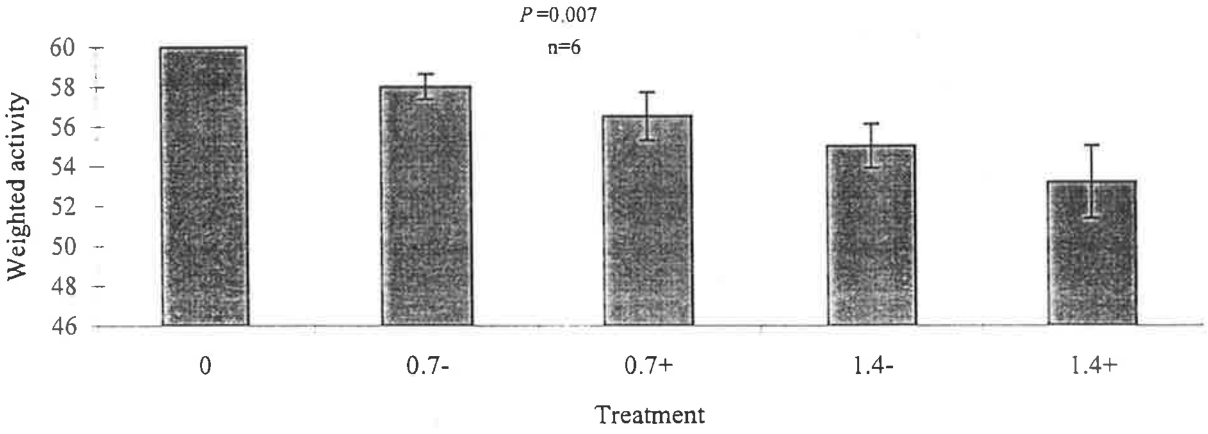


Fig. 6.5 A comparison of the average weighted activity (see Table 6.5) of *B. nanum* in experimental treatments; a) prior to the addition of unweathered leaded (Mobil) petroleum , b) three hours after the addition of Arabian light crude oil and c) three hours after siphoning of water from experimental treatments. Treatments are shown on the *x*-axis and are; C=control, 0.7+=0.7ml(+), -0.7=0.7ml(-), 1.4+=1.4ml(+), 1.4-=1.4ml(-), with treatment descriptions as shown in Table 6.6. Twelve *B. nanum* were assigned to each replicate and there were 6 replicates per treatment (n=6). Error bars represent the standard errors associated with the treatment averages. *P* values shown on each graph indicate the probability of significant treatment differences associated with the experiment (refer to text for details).

Water Quality

As was the case with the crude oil experiment some water parameters were monitored during the course of this experiment. At the start of the experiment these were consistent across experimental treatments and it was not necessary to analyse for treatment differences (Table 6.16). However, three hours after the addition of petrol to appropriate experimental treatments the average pH was lower in the more heavily oiled treatments (1.4+ & 1.4-), while the average temperature was slightly higher in oiled treatments (Fig. 6.6a & b). The average salinity was slightly lower in oiled treatments, although this effect was most obvious in the lightly oiled treatments, while dissolved oxygen tended to be less with oiling (Fig. 6.6c & d). However, none of these apparent trends represented significant treatment effects (Table 6.17).

Table 6.16 The range of water parameters recorded in experimental treatments immediately after the 'refined petroleum' experiment had been set up and prior to addition of oil. Parameters assessed were temperature, salinity, dissolved oxygen (DO) and pH. Experimental treatments are as shown in Table 6.6. The air temperature ranged from 25°C (at the start) to 30°C (when the water was siphoned from replicates).

Treatment	T (°C)	Salinity	DO (%)	pH
Control (C)	26.5-26.91	37.46-38.29	163-186.8	8.06-8.34
0.7ml(+)	26.5-27.01	37.46-38.32	165-187.8	8.07-8.35
0.7ml(-)	26.6-26.90	37.56-38.28	163-186.9	8.03-8.36
1.4ml(+)	26.4-26.84	37.49-38.31	162-187.0	8.05-8.35
1.4ml(-)	26.6-27.00	37.48-38.29	164-186.6	8.07-8.35

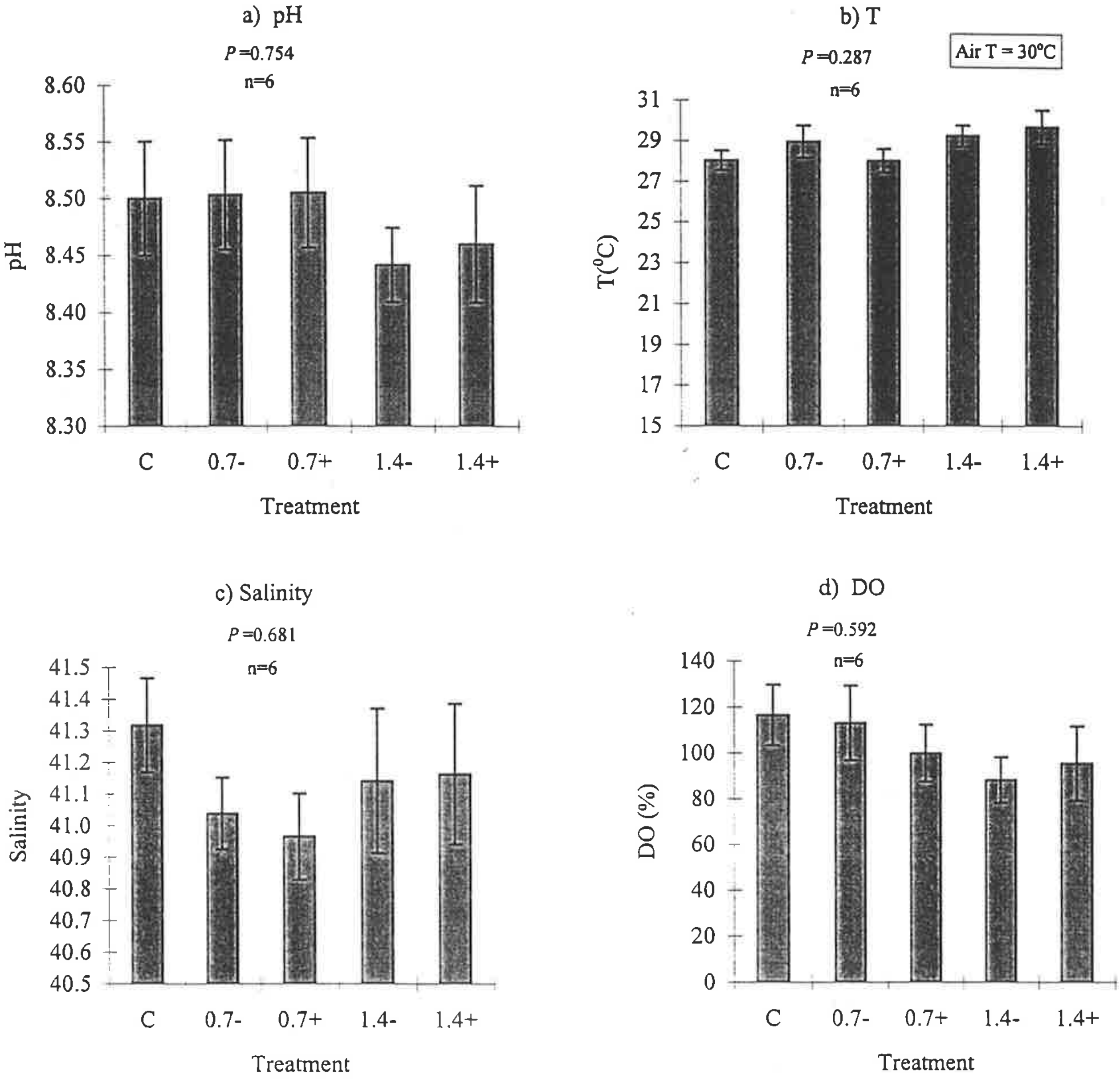


Fig. 6.6 A comparison of the average a) pH, b) temperature; T (°C), c) salinity (‰) and d) dissolved oxygen (DO); % are presented for the 'refined petroleum' experiment. Treatments are shown on the *x*-axis and are; C=control, 0.7+=0.7ml(+), -0.7=0.7ml(-), 1.4+=1.4ml(+), 1.4-=1.4ml(-), with treatment descriptions as shown in Table 6.6. All graphs illustrate parameters assessed 3 hours after addition of unweathered leaded (Mobil) petroleum to the appropriate treatments and were recorded immediately prior to water being siphoned off. Twelve *B. nanum* were assigned to each replicate and there were 6 replicates per treatment (n=6). Error bars represent the standard errors associated with the treatment averages. *P* values shown on each graph indicate the probability of significant treatment differences associated with the experiment (refer to text for details).

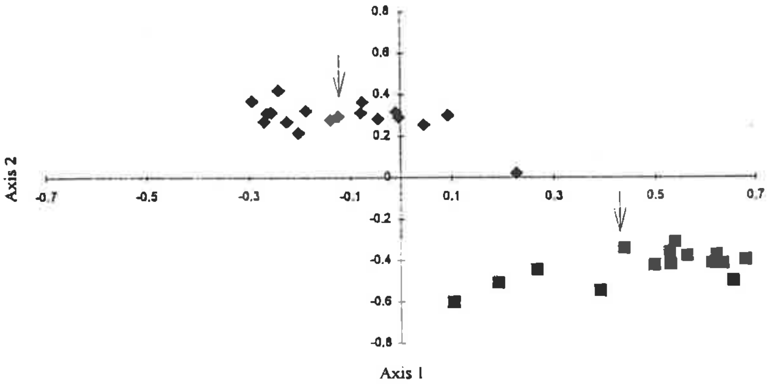
Table 6.17 Kruskal-Wallace (KW) tests or ANOVA were used to determine if physical water parameters differed according to treatment 3 hours after addition of petrol and immediately prior to water being siphoning from replicates in the 'refined petroleum' experiment. At this time there were 3 experimental treatments rather than the 5 which existed after the water had been siphoned off. Data were analysed as though there were 5 treatments but results were consistent whether 3 or 5 treatment groupings were analysed. No significant treatment effects were found at the 0.05 probability level.

Parameter	Test	F or KW test statistic	Probability (*P*)
pH	KW	1.901	0.754
Temperature	ANOVA	1.326	0.287
Salinity	ANOVA	0.578	0.681
Dissolved Oxygen	ANOVA	0.711	0.592

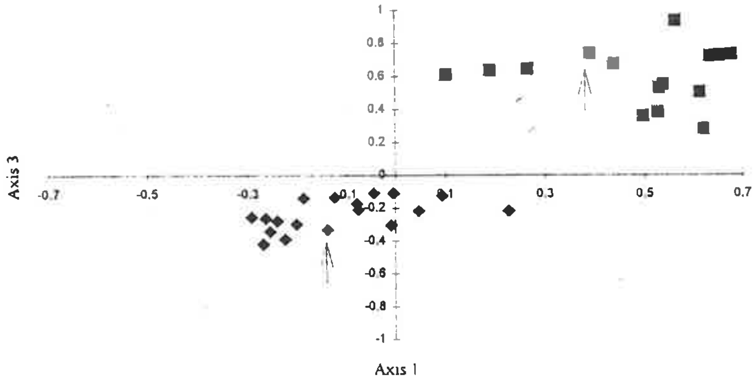
6.5.3 Oil Spill Effects

No oil was visible in the 'upper' zones at study sites, including the Port Noarlunga South site, following the oil spill. All quadrats deployed at Port Noarlunga South achieved an oil score of zero despite large amounts of oil being deposited higher on the shore by the extremely high tides which prevailed on the day of the oil spill and on subsequent days. Despite the lack of oiling at the designated 'impact' site it was still possible that acute effects of exposure to pelagic oil may have occurred. Intertidal assemblages at selected study sites were compared using a SSH MDS Ordination of sites before and after the oil spill. A satisfactory ordination (stress = 0.13) was achieved in three dimensions but when combinations of the three axes were plotted no oil related trends in assemblage structure were evident (Fig. 6.7a, b & c). For example, at Port Noarlunga South (the 'impact' site) the post-impact position of the September 26th datum point lay within the pre-impact range of positions in multivariate space.

a) Axis 1 *vs* Axis 2



b) Axis 1 *vs* Axis 3



c) Axis 2 *vs* Axis 3

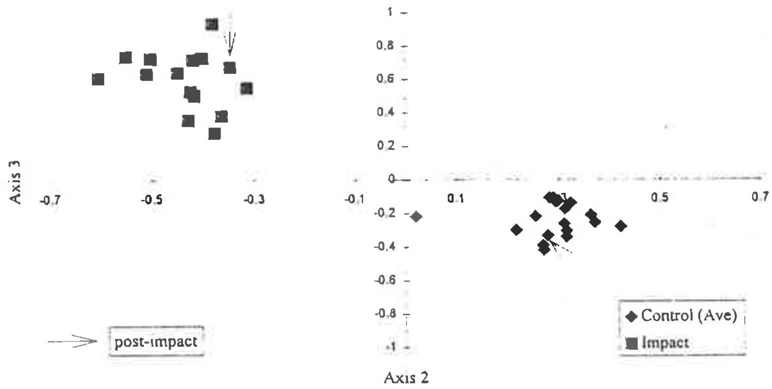


Fig. 6.7 The results of a SSH MDS Ordination of 'upper' GSV sites according to their assemblage structure prior to and a single time following an oil spill from the Port Stanvac Oil Refinery. The stress of the ordination was 0.13 (S=0.13) and combinations of the three ordination axes were plotted; a) axes 1 *vs* 2, b) axes 1 *vs* 3 and c) axes 2 *vs* 3. The 'impact' site is Port Noarlunga South, and the 'control' represents the average position of 5 sites where oil did not ground (Kingston Park, Marino Rocks, PS1, PS2 & PS3). The post-impact ordination positions of the 'control' and 'impact' sites are arrowed and lie within the range of scatter of their respective data sets. Details of the ordination methodology and the extent of the oil spill can be found in Chapters 4 & 5.

6.6 Discussion

6.6.1 Cryptic Behaviour

Clear trends in the 'preferential' occupancy of either 'top' or 'under' substrata positions at low tide were exhibited by a number of common intertidal species inhabiting the 'upper' zone at study sites with mobile substrata (Table 6.7). However, only the cryptic behaviour of *A. constricta* and *B. nanum* warrant discussion.

A. constricta

A. constricta individuals were generally not sufficiently numerous in the 'upper' zone at study sites with high proportions of mobile substrata to allow a statistical analysis of the proportion occurring on 'top' and 'under' rock. However, I observed that this species, and in particular the juveniles, appeared to be more abundant on the undersides of rocks and in areas of retained water. The latter observation is supported by Underwood (1976a & b) who demonstrated a positive relationship between *A. constricta* adults and the presence of water, including rock pools. Rock pools represent unique habitats on rocky shores (see Astles 1993) and were not designated for sampling during preliminary monitoring (see Chapter 3).

The observed aggregation of *A. constricta* in rock pools and under mobile rocks has implications to its usefulness as a potential bioindicator species. At study sites where mobile substrata and rock pools are common, the methods of animal census adopted during the pilot (Chapter 3) and preliminary (Chapter 4) phases of this project would not accurately quantify the presence of *A. constricta*. For this reason *A. constricta* was not considered a suitable bioindicator for the ongoing monitoring program.

The work of Underwood (1976a & b) led to an expectation that *A. constricta* would be relatively more numerous in the moist, shaded regions beneath rocks in areas with mobile substrata and low proportions of retained water. However, at Robinson Point no significant difference could be found between the number of animals in quadrats occupying exposed ('top') or protected ('under') positions. This could be due to the physical character of the Robinson Point site. This reef was low-lying and sheltered with a relatively short period of exposure during low tide and was characterised by areas of retained water at peak low tide (see Chapter 4). In this environment aggregative behaviour is unlikely to confer any advantage (e.g. by reducing desiccation risk). In addition, at least 50% or more of the rock at this site was embedded and stabilised by sand alone (on 'upper' sections of the reef) and *X. pulex* mussel beds and entrapped sand (on 'lower' sections of the reef). This would make a large proportion of the undersurface of rocks difficult or impossible for gastropods (including *A. constricta*) to access. The remaining substrata was semi-embedded and unlikely to be mobilised except under extreme storm conditions but was potentially more accessible to gastropods seeking positions under rocks. Reduced access to the undersurface of rocks and the high degree of water retention occurring at Robinson Point could account for the lack of a statistically significant difference in the number of *A. constricta* occupying the 'top' and 'under' positions of rocks. Since the power of the analysis was satisfactory the lack of a detectable difference between the abundance of animals occupying 'top' and 'under' positions at RP is more likely to be a 'true' result than a sampling artefact.

B. nanum

B. nanum were predominantly found on the upper surface of rocks at all study sites where their 'favoured' position was assessed (Table 6.7). This behaviour makes them easy to sample accurately without disturbing the substrata. The exception to this trend occurred at Marino Rocks, where no statistically significant difference could be found in the abundance of *B. nanum* in 'top' and 'under' positions. The lack of a detectable difference at Marino Rocks was presumably due to the nature of this site.

Marino Rocks was comprised of mobile boulder, cobble, and smaller grade substrata overlying the bedrock base. The site was also elevated with a prolonged emersion time at low tide and was frequently exposed to intermittent low to high level natural disturbance by wave and tidal action. Mobilisation of substrata and the frequency of this disturbance are likely to be the primary cause of low densities of animals at this site (see Chapter 3). The instability of the rocky substrata and its frequent mobilisation is likely to directly kill or dislodge animals. This unstable environment could also retard the growth of epilithon, resulting in negative flow-on effects to the abundance of *B. nanum* and other herbivores (Underwood 1989). The generally low numbers of *B. nanum* at Marino Rocks mean that the presence of one or two individuals under rocks (perhaps due to recent mobilisation of substrata) could obscure the general tendency of these animals to occupy exposed positions in which case the results may be a sampling artefact. However, the analysis was assessed to have a relatively high power and can be regarded with some confidence. The 'aberrant' behaviour of *B. nanum* at this unstable site highlights the importance of selecting study sites with relatively stable substrata for inclusion in the ongoing monitoring program.

6.6.2 *B. nanum* as a Bioindicator

The general tendency of *B. nanum* to occupy 'exposed' positions on the shore support its use as a bioindicator for the ongoing monitoring program. This type of behaviour facilitates accuracy in sampling and saves time, while reducing the risk of creating sampling disturbances which could arise if mobile substrata needed to be overturned to allow animal census.

Chapman and Underwood (1996) reported that careful overturning of intertidal boulders and their subsequent replacement resulted in short term disturbances that persisted for a few weeks. Although recovery was noted after this period, the act of overturning cobble and boulders, even if they were carefully replaced, would be likely to constitute an unwanted disturbance and would have an associated time cost. However, failing to overturn rocks at sites where mobile substrata dominated would introduce the risk of inaccurate census of some species. Since not all selected study sites had mobile substrata and those which did varied in their relative proportions, it was likely that overturning rocks would differentially affect the sites and introduce a confounding factor into the monitoring program. Therefore, a bioindicator that does not aggregate under mobile substrata is recommended for ongoing monitoring.

Other factors which favour *B. nanum* as an indicator species is their tendency not to be markedly contagiously distributed, their occurrence high in the mid-eulittoral zone, which facilitates ready access (see Chapter 3), and their tendency not to aggregate in pools. This species was also ubiquitous at chosen study sites (apart from Witton Bluff), is likely to contact oil in the same manner as other herbivores and was generally the most numerically dominant animal at study sites (Tables 6.1 & 6.2).

The long spawning period and longevity of *B. nanum* (Table 6.1) means that it is likely that loss of this species from an area after an oil spill will be followed by a relatively rapid recovery as new recruits and adjacent non-affected animals move into the region. Therefore, the use of this species as an indicator of oil pollution is likely to give a relatively conservative estimation of the degree of biological damage sustained by an 'impacted' site. This is advantageous as it reduces the chance of detecting a 'trivial' impact.

It is clear that *B. nanum* is the front-runner as a bioindicator species amongst the suite of animals found at study sites in GSV (Chapters 3 & 4). Its potential usefulness is well illustrated by Table 6.2. If a number of species had appeared to be appropriate bioindicators of an oil spill it would have been necessary to assess their tolerance to 'realistic' levels of oil exposure. However, since only *B. nanum* seemed suited to an oil bioindicator role this was the only species investigated in reference to its susceptibility to oil exposure.

Exposure to Oil

The quantities of oil used in both 'oiling' experiments were low in relation to horizontal substratum surface area and volume of water added. However, it was believed that they were realistic of a small operational oil spill at Port Stanvac (pers. comm. Pfennig) and this realism was considered an important aspect of these experiments.

No mortality was recorded when adult animals were exposed to crude oil or petroleum for a simulated tidal cycle. The failure to detect a short-term acute effect when *B. nanum* were exposed to the WSF of crude or refined oil was consistent with the unpublished 1995 Sydney study mentioned in section 6.3.5; "*Previous Work*". The lack of mortality associated with oil exposure does raise some concerns due to the population level focus of ongoing monitoring. This will be addressed later in the discussion. However, animals did show some behavioural responses to oil, the relative seriousness of which was quantified using the weighted activity scores (Table 6.5).

In both the 'crude' and 'petroleum' experiments the WSF of oil did not result in significant oil related treatment effects involving animal activity (Figs. 6.3b & 6.5b). This was despite the fact that the addition of crude oil did result in significant changes in water temperature (P=0.022) and pH (P=0.035), both of which were elevated in 'oiled' treatments. Similar changes were not seen when petroleum was the contaminant. Behavioural changes were apparent on exposure to both crude oil and petroleum once the water had been siphoned off (Figs 6.3c & 6.5c).

In the 'crude oil' experiment differences in animal activity were detected between the control and the 2ml(-) treatment, while in the 'petroleum' experiment differences were evident between the control and the 1.4ml oiling treatments. The most obvious effect on animal activity in the latter experiment involved the 1.4ml(+) treatment where the oil product was allowed to contact the animals as the water was siphoned off. This result was consistent with *a priori* expectations and was also expected in the 'crude oil' experiment. However, in this experiment it was the 2ml(-) treatment which appeared to have the greatest negative effect on *B. nanum* behaviour. This treatment was characterised by fewer adherent (and more overturned) animals and a lower overall 'weighted' activity score than the other treatments (Figs 6.2c & 6.3c). This may reflect the low volumes of oil added, poor siphoning technique, or varying levels of oil tolerance among *B. nanum* individuals. However, care was taken with siphoning, and randomising the animals when assigning them to treatments should have minimised the risk of the individual tolerances of animals confounding the treatments. It is more likely that the climbing behaviour exhibited by the animals maximised the contact time some of them had with oil, thus confounding the (+) and (-) oiling treatments (see Table 6.4). If the 'crude oil' experiment is repeated it is recommended that the number of treatment replicates is increased to at least six (the number used in the 'petroleum' experiment) to reduce the risk of sampling artefacts masking 'real' trends. It is also recommended that wider containers are used to minimise any procedural effects arising as a consequence of a high vertical (sides):

horizontal (mainly rock) substratum ratio which may have encouraged increased climbing in the artificial experimental systems and affected the degree of oil exposure animals encountered.

In the 'petroleum' experiment all animals were very active when covered with water, with the most commonly observed behaviour being a tendency to climb to the surface of the water and adhere where, in 'oiled' treatments, there was likely to be maximum contact with the petrol. However, this behaviour was most obvious in the control replicates (hence the low 'weighted' activity three hours after addition of oil to the other treatments) and was postulated to represent 'normal' behaviour when contained artificially during hot weather in containers with a high vertical : horizontal substrata ratio.

The 'oiled' treatments in the 'petroleum' experiment were characterised by low activity scores once the water was siphoned off. This trend was significant (P=0.007) and was due to higher incidences of dislodged and overturned animals in the 'oiled' treatments compared to the control. A similar result was found with the 'crude' oil experiment (P=0.046). It is possible that the increased tendency of animals to lose adherence on exposure to crude or refined oil could be a narcotic effect induced by the contaminant. This has been reported in some gastropods on exposure to hydrocarbons, which can trigger tight ostial closure and subsequent loss of adherence (see Suchanek 1993). However, if this was the cause for the increased dislodgment incidence on exposure to oil and petroleum it occurred three hours after the water was siphoned off and not when the oil was pelagic.

In an actual oil spill loss of adherence may be advantageous as animals are removed from immediate contact with the oil, but it could also result in transport to a less favourable position (Suchanek 1993). The experimental findings suggest that a spill of fresh petroleum or crude oil could result in an initial decrease in abundance of *B. nanum* due to dislodgment. A severe crude oil spill could also smother most shore invertebrates (Baker 1991, Suchanek 1993). If large numbers of *B. nanum* individuals are dislodged and displaced from the affected shore or smothered by an influx of oil, population level changes should be detectable with a Beyond-BACI monitoring program provided the magnitude of change is sufficiently high. The expected effect in such a situation would be an initial decrease in abundance at the 'impacted' site(s) compared to 'control' (unoiled) sites. The lack of acute experimental mortality of *B. nanum* on exposure to small amounts of unweathered Arabian light crude oil and leaded Mobil petroleum indicates that the species is not extremely sensitive to these particular oils.

Both 'oil' experiments investigated only the immediate short-term effects of exposure of *B. nanum* to oil. It is likely that sublethal changes could occur in this species even on exposure to small amounts of oil and that these changes may in the future affect the survivorship of exposed animals or their fecundity and so have potential flow-on effects at the population level. Such effects were not investigated in this thesis but have been found to occur in the herbivorous gastropod *Nerita atramentosa* (an animal with a similar lifestyle to *B. nanum*) on exposure to crude oil (see Battershill and Bergquist 1982). If oil exposure results in lowered fecundity this is likely to impact on future *B. nanum* populations but may not correlate strongly with the levels of oiling at sites due to the planktonic method of dispersal and the extended planktonic phase of this species (see Underwood 1975b). Population level effects could also occur in other herbivores with a similar lifestyle if they are exposed to oil (Table 6.1). This implies that *B. nanum* will potentially show trends expected in other herbivores at GSV sites, important since herbivores are the most frequent functional feeding group found in 'upper' zones at the majority of these sites (personal observation).

Clearly *B. nanum* emerges as the only possible bioindicator for a Beyond-BACI monitoring program in the selected section of GSV (see Fig. 6.1 & Tables 6.1, 6.2 & 6.3). The choice of this species as a bioindicator is further strengthened by its altered behaviour in response to experimental exposure to small amounts of fresh oil (either crude or refined product), behaviour which could manifest as population level changes in abundance.

If the choice of a bioindicator was not clear and a number of species were ubiquitous and present at high enough densities for use in a statistical analysis, a multivariate analysis could be used to identify which species best satisfied the bioindicator criteria. The ability of each species to meet each bioindicator criterion (section 6.3.2) could be subjectively assessed (using a scoring system) and the matrix generated fed into "PATN" and subjected to an agglomerative hierarchical clustering using flexible UPGMA and a Semi-Strong Hybrid (SSH) Multi-Dimensional Scaling (MDS) Ordination (Belbin 1991). The resultant dendrogram would allow determination of which species group together most closely in terms of the bioindicator criteria. If the order of the input matrix was reversed the dendrogram could be used to determine how closely linked the bioindicator criteria were in terms of the species (and assigned scores) they had in common. This may help to identify the most 'important' criteria. Plotting the species in 'bioindicator criteria' multidimensional space could assist in determining species patterns in relation to the criteria, further facilitating the choice of a bioindicator. A regression of species against the MDS result using a Principle Canonical Correlation (PCC) may also prove useful (see Belbin 1992). The species selected by this process could then be tested experimentally for a relationship with oil.

A simpler method to select an indicator from a suite of species could be to rate the importance of the criteria (some such as ubiquity are essential and must be met) and score how well each species met the criteria (perhaps weighting the scores depending on their perceived importance). The resultant scores could then be summed and the species with the highest aggregate score chosen. Fortunately *B. nanum* does appear a realistic bioindicator of oil pollution and an elaborate selection process was not necessary.

The Oil Spill and Assemblage Structure

The multivariate assessment of intertidal assemblages at study sites following the refinery oil spill failed to detect any oil related trends. This was not surprising as the extreme wave and wind conditions and the high tidal regimes which prevailed at the time of the oil spill and over the next few days acted to protect the 'upper' zones from exposure to large quantities of oil. Any long term effects on the animals at the 'impact' site (Port Noarlunga South) were not investigated although it was possible that changes may have occurred on a longer temporal scale following exposure to pelagic oil as it was carried across the site and deposited higher on the shore.

6.6.3 Implications for the Ongoing Monitoring Program

The outcomes of this chapter have some implications to the design of the ongoing monitoring program. *B. nanum* is recommended as the bioindicator of choice primarily due to its behaviour (which facilitates accurate animal census without disturbing sites), its relatively high densities and presence at all sites apart from Witton Bluff. It was also found to have a similar lifestyle, including reproduction and feeding strategies, to the majority of gastropods dominating the 'upper' zones at study sites. This makes it a good representative of more general changes which are likely to occur in other herbivore populations at oil affected sites. In addition, *B. nanum* responded to low level oil exposure by behavioural changes, which were postulated to result in population level changes under certain conditions (although this was not demonstrated). Another benefit of using this species as a bioindicator of oil exposure is its relative robustness and lack of extreme sensitivity to oil. This means that the species is unlikely to respond to a 'trivial' oil spill.

A *B. nanum* population impacted by oil is also likely to make a relatively rapid recovery, unless other species opportunistically occupy the vacated area or it is not suitable for settlement. This is expected due to the long planktonic phase of this species and the lack of correlation between adult population dynamics and recruitment. Therefore, any persistent change indicated by a Beyond-BACI analysis based on the abundance of *B. nanum* following an oil spill is likely to represent serious effects rather than more trivial change (refer to Keough and Mapstone 1995).

This chapter in conjunction with Chapter 4 highlights the importance of selecting study sites for ongoing monitoring which are 'stable' and less likely to be perturbed by confounding physical factors such as storm mobilisation of substrata. For this reason, the selected area at Marino Rock is not suitable for ongoing monitoring (see Table 6.7) and it is recommended that all sites used in preliminary monitoring (Chapter 4) are reassessed prior to inclusion as sites for ongoing monitoring.

Chapter 7. The Impact of Trampling on Rocky Intertidal Animals

7.1 Introduction

The potential for anthropogenic driven change has grown as the density of human populations around coastal areas has increased (Olivia and Castilla 1986, Keough *et al.* 1993, Brosnan and Crumrine 1994). In the last decade this has resulted in burgeoning interest in the impact of human activities on intertidal areas (Brosnan and Crumrine 1994). This interest is fuelled by the realisation that human disturbances constitute an important ecological force that is capable of modifying the natural structure and dynamics of intertidal communities (Moreno *et al.* 1984, Castilla and Durán 1985, Moreno *et al.* 1986, Castilla and Bustamante 1989).

A range of human activities may constitute pulse, press or combination disturbances (Underwood 1989) and can result in differing levels of impact to susceptible coastal biota (see Addessi 1994). The most common anthropogenic disturbances affecting coastal areas are industrial and sewage outfalls, commercial and recreational fish and food collection, and recreational trampling and related activities (Underwood and Kennelly 1990, Underwood 1991, Keough *et al.* 1993). In rocky intertidal regions natural patterns and processes are altered as boulders are overturned (Addessi 1994); animals and plants are collected for food, bait, aquaria or scientific purposes; or trampling crushes, chips or dislodges animals and removes plant biomass (Povey and Keough 1991, Keough *et al.* 1993).

The scientific literature details the importance of natural predation (e.g. Underwood and Denley 1984, Fairweather 1990) and natural physical disturbance (e.g. Connell and Keough 1985, Sousa 1985) in structuring intertidal systems. However, it is only recently that scientific interest in the effects of human collection, which can be considered as predation, and recreational trampling, which acts as a physical disturbance, has grown (Povey and Keough 1991). It is important to bear in mind that both predation and trampling are likely to be acting over spatial and temporal scales which are different to the 'normal' scales experienced by the organisms within an evolutionary context (Povey and Keough 1991, Keough *et al.* 1993).

Trampling and human collection of intertidal animals were expected to differentially impact on intertidal assemblages at study sites in Gulf St Vincent (GSV) but the effects they were likely to elicit and the implications for the ongoing monitoring program were not known. It was beyond the scope of this thesis to directly investigate animal collection and its seriousness as a confounding influence in ongoing monitoring (but see 'Recreational Use of Study Sites' for indirect effects). However, the enforced restrictions on legal collection of intertidal animals (Appendix M) were expected to reduce the possibility of confounding an ongoing monitoring program.

The focus of this chapter was on the intensity and type of recreational use of study sites in GSV and to more specifically investigate the effect of trampling on the biota of 'bare' rock habitats (defined by their lack of macroalgal cover) which characterised the majority of the sites. Previous studies had found that species occupying 'bare' rock tended to be more resistant to the effects of trampling than biota in more 'sensitive' habitats (Beauchamp and Gowing 1982, Povey and Keough 1991). A series of experiments, which closely followed the study by Povey and Keough (1991), were used to investigate the immediate effects of trampling on intertidal biota at a number of relevant intensities. Since dislodgment of gastropods was a possible effect of trampling, the distances travelled by dislodged animals were also investigated. This investigation was also thought to be helpful in predicting the consequences of an oil spill as dislodgment of motile intertidal animals has been reported in response to oil exposure (Chapter 2).

7.2 Aims

This chapter aimed to investigate some of the patterns of human usage of study sites in GSV. This was needed as it was likely that differences would be evident between sites which were protected from public access (the Port Stanvac sites), sites where the public were not permitted to remove animals (initially Witton Bluff only) and the remaining sites which, for various reasons such as ease of access, were likely to be exposed to differing intensities of recreational use. A detailed survey of the type used by Underwood and Kennelly (1990) and Kingsford *et al.* (1991) was not intended rather, this study aimed to gain a broad understanding of the patterns of human use of the study sites.

Trampling was noted to be an important recreational pressure placed on intertidal areas and the trampling associated with sampling biota during ongoing monitoring was also of some concern. Therefore, this chapter aimed to investigate the short-term effects of acute trampling on intertidal biota. As dislodgment of gastropods was a possible result of trampling, I also aimed to determine the distances over which dislodged animals were displaced over one tidal cycle.

This chapter specifically addressed the following questions:

1. What are the patterns of recreational shore use at study sites in GSV?
2. How does a single footstep affect *Xenostrobus pulex* mussels and dominant gastropods in the 'bare' rock mid-eulittoral zone?
3. Are dislodged and overturned gastropods more likely to travel further or more likely to be lost from an area over one tidal cycle than control (non-dislodged) gastropods?
4. What short-term effects does the intensity of trampling seen on a weekend have on intertidal animals?
5. What short-term effects does the intensity of trampling seen over a two-week school holiday period have on intertidal animals?

Question 1 was examined using a survey of recreational shore use, while the remaining questions were addressed with a series of experiments. Question 2 was studied with a set of 'footstep' experiments which simulated a single 'footstep' and which categorised the effects of this activity on dominant intertidal biota. Question 3 was examined using 'dislodgment' experiments which involved overturning gastropods which were susceptible to displacement by trampling and assessing how far they were transported over a tidal cycle compared to the distance travelled by animals which were not overturned. Question 4 was investigated with a simulated 'weekend' trampling experiment involving three trampling intensities, while question 5 involved a similar experiment which was conducted over two weeks and which simulated a 'school holiday' trampling perturbation.

7.3 Site Descriptions

Recreational visitation was assessed at all sites but did not occur at Port Stanvac sites where public access was denied. The study sites have been described in detail in Chapter 3. The experimental component of this chapter was conducted at some of the study sites used for preliminary monitoring but care was taken to use areas not designated for preliminary sampling.

The experiments to investigate the effect of a single 'footstep' on intertidal animals were carried out in areas which were equivalent to, but situated to the south of, the 'upper' and 'lower' zones at Kingston Park, and the 'lower' zone at PS1. The experimental areas at these study sites generally corresponded to the defined areas used for preliminary monitoring in terms of their biota and dominant substrata types (see Chapter 3).

The 'experimental' 'upper' zone at Kingston Park was dominated by flat bedrock with minimal elevation. The 'lower' zone at this site consisted of bedrock with increased fissuring and some areas of slight elevation interspersed by cobble and boulder towards the low water mark. *Bembicium nanum* heavily dominated the mainly gastropod biota found in the 'upper' zone at Kingston Park. The 'lower' zone at this site also supported large numbers of *B. nanum* but was characterised by patchy but often dense pockets of the small mussel *Xenostrobus pulex*, and increased densities of *Austrocochlea constricta*, *Nerita atramentosa* and *Lepsiella vinosa*. The 'footstep' experiments took place at Port Stanvac in an area adjacent to PS1. The experimental site was dominated by bedrock strata (some of which was elevated) which was interspersed with variable amounts of mobile substrata of different sizes. The assemblage found in the latter experimental area included *Cellana tramoserica*, *Siphonaria diemenensis*, *Austrocochlea* spp., *B. nanum*, *N. atramentosa*, *X. pulex* and *Chthamalus antennatus*.

The 'dislodgment' experiments were set up in the 'upper' zone at Kingston Park in the area used for a subset of the 'footstep' experiments, and also in the 'upper' zone at Port Stanvac (slightly to the south of PS1). The latter site had a more complex topography and substrata mix than Kingston Park. The biota were as described for PS1 (see Chapter 3).

The 'weekend' trampling experiment was conducted at Kingston Park, slightly to the north of the area used for preliminary sampling. The biota and substrata were as described in relation to the 'upper' zone used in the 'footstep' experiment. The 'school-holiday' trampling experiment was carried out in the 'upper' region at Port Stanvac, adjacent to study site PS1 (in the same region as a subset of the 'dislodgment' experiments). All survey work and experimental manipulations and assessments took place at low tide when maximum access to sites and animals was possible.

7.4 Materials and Methods

7.4.1 Recreational Use of Study Sites

At each sampling time (during low tide) recreational visitation to all study sites was scored and the activities of people present recorded. The time and day were also recorded and a comparison between weekend, public holiday, school holiday and weekday visitation to all sites was made. To standardise use of the sites by visitors all observations were made over a one-hour period during the main low tide of the day. The survey period commenced in January 1995 and continued until November 1996 but only the data from January 1995 to February 1996 has been included in this chapter.

The visitation data were standardised to give a weighted visitation score. Older children (3-12 years), teenagers (13-19 years) and adults (20 plus years) were given a weighting factor of two, whereas dogs and toddlers (1-2 years) were unweighted. This weighting was used, as it appeared that the activity of adults, teenagers and children caused more impact than the minimal perturbation induced by the other two groups of visitors. Similarly, recreational site usage was assessed in terms of its local impact potential. This was subjectively scored at each census time against a scale of 0-3; with 0 representing no impact, 1 representing minimal impact, 2 representing moderate impact and 3 representing severe impact. Activities such as fishing from the edge of a 'zone' or surfing were given a zero impact score, while severe disruption to a site was assigned to activities such as overturning large numbers of rocks and collecting animals. Data were pooled across sites to compare recreational use between different times such as public holidays, school holidays and weekends, and the results presented graphically.

7.4.2 The Effect of Trampling on Intertidal Animals

The effect of trampling on the most common animals found at the majority of study sites was investigated with a series of small experiments carried out during days when suitable low tides occurred. Unless otherwise stated all data to be statistically analysed underwent preliminary testing for normality and homoscedasity using the Anderson-Darling test (Snedecor and Cochran 1989) and the F_{max} test (Zar 1984) respectively. If the data failed either of these tests it was $\log_{10}(x+1)$ transformed and reassessed for normality and homoscedascity. If the data still did not meet the assumptions of normality and homogeneity of variances a nonparametric equivalent of the test was used. All analyses in this chapter used a significance level of 0.05.

7.4.2.1 A 'Footstep' Disturbance

A preliminary examination of the study sites suggested that the small mussels which were frequently found in 'lower' regions may be prone to damage as a direct consequence of trampling, and that gastropods could be dislodged or crushed by the same activity. I therefore used a series of experiments to investigate the effect of a single footstep on beds of the mussel *X. pulex* and on gastropods that occupied the 'bare' rock mid-eulittoral zone. An additional experiment investigated the effect of directly stepping on adult *C. tramoserica* limpets. These animals were generally tightly adherent to rocks and not easily dislodged by trampling.

The Effect of a Single 'Footstep' on Dominant Gastropods

The first of the 'footstep' experiments took place in the 'upper' zone at Kingston Park in May 1995. A rectangular foot-sized quadrat (with dimensions of 14 x 32 cm and an area of 0.045m^2) was randomly deployed 30 times, and assignation of treatments ('control' and 'footstep') were determined by the toss of a coin to give 15 treatment replicates. The 'footstep' treatments involved me placing a single footstep in the centre of the quadrat while walking normally, while the control quadrats were not stepped into. I wore rubber-soled size 9 sandshoes and weighed approximately 61 kg at the time these experiments were undertaken. Animals within quadrats were censused for 'orientation' (upright *versus* dislodged or overturned) and 'health' (chipped or crushed *versus* intact).

Statistical comparisons were made between the two treatment groups based on the number of unaffected animals in quadrats. A parametric *t*-test was used (if the data were normally distributed and had homogeneous variances) or it's non-parametric equivalent, the Mann-Whitney test (if the data violated the assumptions of normality or homoscedasity of variances) (see Zar 1984). The analyses were separately performed on the three most common intertidal gastropods found at Kingston Park, namely; *B. nanum, A. constricta* and *N. atramentosa.* The appropriate tests were one-tailed as the alternative hypothesis was that more animals would be unaffected (e.g. intact and undisplaced) in the controls than in the 'footstep' treatments.

The Effect of a Single 'Footstep' on *Xenostrobus pulex*

It was suspected that the small mussel *Xenostrobus pulex* would be damaged by trampling and a repeated measures experiment was used to investigate the effect of a single 'footstep' on beds of these animals. This experiment took place in the 'lower' zone at Kingston Park in May 1995. Heavy beds of the mussel were selected and the small quadrat used previously was randomly deployed a total of six times. The number of intact and damaged animals in each quadrat were censused prior to and following a 'footstep', administered as previously described. Small 16cm^2 sub-quadrats were used to assist in counting the mussels, with all *X. pulex* being counted apart from those which had pre-existing damage (such as holes drilled in their shell by *L. vinosa*) and which were identified by a dot of nail polish before the 'footstep' was applied. The alternative hypothesis was that more *X. pulex* would be intact prior to the 'footstep' being applied. The parametric paired *t*-test or the non-parametric equivalent was the statistical analysis of choice for this experiment.

As an adjunct to this experiment I was interested in determining if the densities of the carnivorous gastropod *L. vinosa*, which is known to prey on *X. pulex* mussels (Ward and Quinn 1988), were different in 'footstep' quadrats compared to undisturbed 'control' quadrats. To investigate this the location of the 'footstep' treatments and 6 control 'non-footstep' treatments (randomly assigned) were marked with paint so they could be relocated the following day at low tide when the number of *L. vinosa* in each of the quadrats were censused. It was thought that even if mussels were not obviously damaged they may be affected in some way which could 'attract' carnivores to the area.. This experiment was analysed using a parametric students-*t*-test after first subjecting the data to a test for homoscedasity and normality as previously described.

The Effect of a Single 'Footstep' on Cellana tramoserica

The limpet *Cellana tramoserica* was observed to be very difficult to dislodge by trampling but could potentially be damaged by a direct 'footstep'. Povey and Keough (1991) reported seeing adolescent beachgoers kicking the animal during their study but since this was not observed during the course of this study it was not investigated. However, an experiment was designed to test the hypothesis that limpets which had been stepped on would be more likely to move from their original position over one full tidal cycle (e.g. the next equivalent daytime low tide) than limpets not subjected to this treatment. This experiment was similar to that of Povey and Keough (1991) who hypothesised that limpets which had been kicked or stepped on would be more likely to be lost on subsequent high tides than control animals.

Thirty limpets at PS1 were marked with a number (using a permanent marker) and randomly assigned (using a coin toss) to 'control' or 'footstep' treatments. The control animals were marked and left otherwise untouched while the 15 remaining animals were marked and stepped on a single time by myself walking normally as described in relation to the 'footstep' experiment at Kingston Park. The position of the numbered animals were mapped in reference to landmarks including Mobil's effluent pipeline, large beached boulders and small-scale topographical features so that they could be relocated the following day. At low tide the next day the animals were relocated and a determination of how far they had moved from their original positions made. The distance of each animal from their original position within the two treatment groups was the parameter of interest and a parametric student's *t*-test or the nonparametric equivalent was the *a priori* analysis of choice.

7.4.2.2 Dislodgment of Dominant Gastropods

As noted by Povey and Keough (1991) it appeared that trampling was more likely to dislodge gastropods (apart from limpets) than it was to crush or otherwise damage them. Therefore, I was interested in determining if animals which were dislodged at low tide (for example by a trampling disturbance) were more likely to be displaced further by the incoming tide than control (undisturbed) animals.

The three gastropod species selected for this examination were *B. nanum*, *N. atramentosa* and *A. constricta*. The experiment involved 7-10 paired treatments (the number being dependant on time constraints associated with the tidal regime). Each treatment 'pair' consisting of 20 animals, 10 of which were marked and otherwise left undisturbed, and the remainder of which were marked and overturned. The effects of overturning the animals were investigated separately at Kingston Park and Port Stanvac in August 1995. Only one species was marked on any one day at low tide, with the recovery and assessment being carried out the following day again during low tide.

A 'tagging' pilot study revealed that marking the hand-dried shells of gastropods with liquid paper, allowing this to dry and then writing on it with a permanent marker, was a satisfactory method to use in a short term study of this type. The liquid paper made it easier to relocate marked animals, and the use of a numbering system allowed individual animals and their groups to be identified no matter how far they had travelled when recovered.

Animals to be marked were randomly selected but those within a treatment 'group' were in close proximity. The central position of treatment groups were recorded (in reference to appropriate landmarks) and further defined using paint. The following day at low tide the sites were again visited and as many animals as possible relocated and the linear distance from their original (group) position was recorded. This represented the minimum distance travelled by recovered animals between equivalent daytime low tides.

The dependent variables used in this experiment were the number of animals recovered in each group and the average 'group' distances travelled by animals in each of the treatments. These variables were separately analysed using a paired-sample *t*-test if the differences between treatment pairs were normally distributed or a Wilcoxin paired sample test if data violated the assumption of normality (Zar 1984).

The Unreplicated 'Overturning ' Experiment

In addition to the main ‘dislodgment’ experiments described previously, an unreplicated experiment was performed at Port Stanvac in August 1995 to again assess the effect of overturning gastropods in the mid-eulittoral zone. Ten individuals each of *B. nanum*, *A. constricta* and *N. atramentosa* were overturned on wet rock and observed for 30 minutes to see what strategies they adopted and how long they took to right themselves. The same experiment was then repeated on dry rock using different individuals belonging to the three species of interest. The animals were not moved from their original positions and were overturned where they were found. Due to the unreplicated nature of this experiment the results were not conclusive and could not be statistically analysed.

7.4.2.3 A ‘Weekend’ Trampling Disturbance

The results of a literature review on trampling in intertidal regions, particularly in Australia (Chapter 2), and the survey of study sites in GSV were used to determine a realistic trampling intensity in terms of weekend recreational use. The three trampling intensities used were equivalent to those investigated by Povey and Keough (1991) except that due to generally low recreational use of GSV study sites their high intensity treatment of 25 trampling passages was reduced to 20.

The experiment commenced on the 10th of November 1995 at the Kingston Park site. The treatment levels used were zero (control), two passages (low trampling intensity) and twenty passages (high trampling intensity). Trampling was carried out on both days of the weekend at low tide as described by Povey and Keough (1991). Six replicates (or plots) separated by 5 metres were established and the three trampling treatments were interspersed within each, giving a randomised block design. This was necessary, as it was possible that patterns of spatial differences might exist and confound the experimental treatments. Treatment areas within plots consisted of 2m x 3m wide strips marked using small dobs of paint and separated by a 1m wide strip (which was not trampled).

All animals were counted (and their size classes recorded (refer to Chapter 3)) prior to trampling, one day after trampling, and again six days later. This time sequence allowed investigation of the pre-impact state of the biota, any immediate changes following the trampling disturbance and the degree of recovery after six days. Under 'real' conditions another 'weekend' trampling perturbation is likely to occur after this time so the recovery time was realistic in this sense.

The abundances of all animals were estimated using a $0.25m^2$ wooden quadrat that was randomly deployed from east to west three times within each treatment at each sampling time. Once an area had been sampled it was marked with small dobs of paint to ensure it was not subsequently resampled. Three quadrats were used within treatments, the minimum number recommended for intertidal monitoring during the procedural pilot study phase (Chapter 3). Deployment of seven quadrats per treatment would have meant greater sampling precision but would have increased the sampling time (not desirable due to tide-related access restrictions). It was decided to pool the abundances of all animals obtained using the three quadrats giving an overall number of animals per $0.75m^2$, a decision which eliminated within-plot treatment replication. However, averaging the data from the three quadrats yielded similar graphical trends to the summed comparisons and using the quadrats as within-treatment replicates did not alter the outcomes of the statistical analyses.

Community data were analysed as a pre-impact and immediately post-impact (1 day after cessation of trampling) cluster analysis and SSH MDS Ordination using the "PATN" software package (Belbin 1992). Taxa were identified as far as possible (generally to species) for input into a treatment plot x taxa matrix. A multiple regression was also performed on the main species again using PATN and the significant vectors (after alpha had been adjusted according to the number of simultaneous regressions) plotted on the MDS ordination axes. In addition, Pearson multiple correlations were carried out using Bonferroni probabilities. The analyses were handled as described in relation to the mulivariate analyses in Chapter 4. Univariate community measures were also generated from the data using the "PRIMER: V 3.1b" Program (Clarke and Warwick 1994b) (again as described in Chapter 4). Comparisons were then made between treatments in reference to the number of taxa, species richness (d), Shannon-Wiener diversity (H') and Pielou's Evenness (J').

In their literature review Keough and Quinn (1991) found that in many instances the use of community indices failed to indicate changes which were apparent at population level. This, in association with the fact that the 'bare' mid-eulittoral area at the majority of GSV sites was dominated by one or a few species, usually *B. nanum*, encouraged the use of a univariate analysis of population level change. To this end, the total abundance of *B. nanum* per $0.75m^2$ was used as the dependant variable in separate statistical analyses performed prior to trampling, immediately post-trampling and again after the recovery phase.

Data were subjected to tests for normality and homoscedasity as previously described and analysed with a randomised block parametric ANOVA, or the nonparametric equivalent, the Friedman's test (Friedman 1937). A randomised block design assumes there is no interaction between the fixed factor of interest (treatments) and the block factor (plots); this was tested for prior to accepting the outcomes of analyses. If a significant effect of the main (fixed-effects) factor was found a multiple comparison as described by Zar (1984, pp. 230-231) was used to determine where the differences lay.

7.4.2.4 A 'School-Holiday' Trampling Disturbance

The 'school-holiday' trampling experiment was designed to simulate the intensities of trampling seen under school-holiday conditions. This experiment was set up at Port Stanvac between sites PS1 and PS2 and commenced on the 20th of March 1996. The experimental design was identical to that used in the 'weekend' trampling experiment except that the trampling continued over a two week period on each day that the tidal regime allowed access (10 days in total). The trampling intensities were the same as those used in the 'weekend' trampling experiment except that the high intensity treatment was replaced by a medium intensity treatment consisting of 5 passages a day. This was thought to be realistic of the type of trampling occurring within a small section of a popular intertidal GSV site during school holidays.

Animals were censused as described previously pre-impact, one day after completion of trampling and again one week later. Data were analysed as for the 'weekend' trampling experiment except that summary statistics were not generated from the community data due to the lack of any clear univariate or community trends.

7.5 Results

7.5.1 Recreational Use of Study Sites

The most common activities observed at study sites were walking across reefs (either to exercise dogs or for personal enjoyment / exercise) and overturning rocks to inspect animals (without collecting them) (Table 7.1). Although only 8.96% of the total people recorded making recreational use of sites were engaged in collecting intertidal animals, this activity and overturning rocks were likely to be having the greatest recreational impact. Many visitors seen at sites were regular beachgoers who were repeatedly censused carrying out the same activities on a number of occasions during 1995 and 1996.

Table 7.1 The range of recreational activities people were seen engaging in at study sites in GSV during 1995 and 1996. The activities have been pooled for all study sites and ranked in order of the frequency with which they were observed. The percentage of people engaging in each activity has also been calculated. Some activities (such as overturning rocks and collecting animals) were likely to be having a greater impact on intertidal areas than other more common activities such as walking a dog.

Recreational Activity	% of People Engaged in the Activity
Walking for exercise or enjoyment	32.37
Overturning rocks to examine animals	23.41
Walking a dog	19.65
Fishing from the edge of a rocky reef	11.56
Collecting animals (e.g. crabs and gastropods)	8.96
Surfing	4.05

Port Stanvac sites were protected from recreational use by their private ownership and I was generally the only person present at these sites during this study. Therefore, weighted visitation and scored recreational impact have only been graphed for study sites outside the confines of the refinery. These sites were subjected to variable visitation pressure and recreational 'impact' for the duration of preliminary monitoring, with most found to have low visitation rates during 1995 and 1996 (Fig. 7.1). The highest recorded visitation pressure occurred at Kingston Park between November and December 1995 when a school group were examining the intertidal assemblage (Fig. 7.1a). In general, this site received a higher 'weighted' visitation score than the remaining sites. Marino Rocks was found to have low visitation rates throughout the study period apart from a single visitation peak that occurred in February 1996 (Fig. 7.1b). Hallett Cove (HCA) was consistently exposed to recreational use throughout the year and achieved peak weighted visitation scores above 18 on three occasions (Fig. 7.1c). However, no visitors were seen at the site from late April through to July when high tides and heavy sand influx occurred (refer to Chapter 4). The remaining 'Southern' sites were generally found to have lower visitation pressure than their 'Northern' counterparts, with the Port Noarlunga South site being the most heavily visited (Fig. 7.1e). Generally, I assessed local 'impact' as a result of recreational shore use to be low at all study sites.

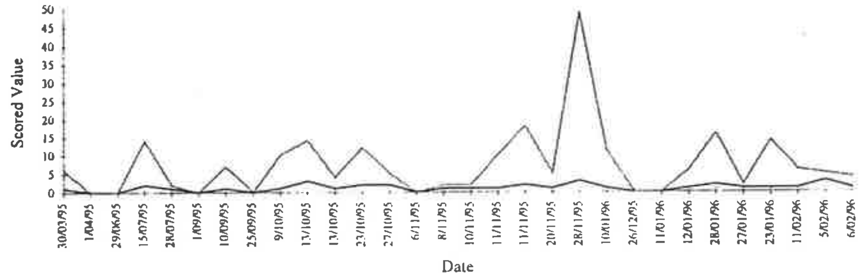
Severe 'impacts' (assigned the maximum score of 3) were associated with fossickers collecting gastropods on two occasions in October and November 1995 at Kingston Park (Fig. 7.1a), and on the 28th of January 1996 at Hallett Cove (Fig. 7.1c). The animals being collected at these times were *N. atramentosa* and *Austrocochlea* spp., and in each case approximately one 7 litre bucket had been filled with these animals which were destined for bait or table purposes. Researchers from Flinders University were responsible for peak 'impact' scores at Robinson Point in September and late October 1995 when they removed intertidal crabs and their gastropod prey for experimental purposes(Fig. 7.1f). At all other times at all sites the visitation 'impact' score was moderate or less, with the majority of sites receiving an impact rating of minimal or nil. Witton Bluff (7.1d) and Port Noarlunga South (7.1e) only scored zero or 'minimal' impact ratings due to low visitation rates (particularly in the case of Witton Bluff) and a predominance of low perturbation activities such as surfing (at the former) and fishing.

Data used to generate the graphs for individual site use (Fig. 7.1) were pooled across study sites for all 1995 and 1996 data to produce an 'impact' and 'weighted visitation' profile for the primary visitation times (Fig. 7.2). Times of visitation were divided into four categories; weekday, public holiday, school holiday, weekend (non-holiday) and weekends falling on a school holiday. The 'impact' and 'weighted visitation' scores were consistent, with greater visitation and impact pressure being recorded on weekends and school holidays (Fig. 7.2a & b respectively). The large variation in public holiday 'impact' and 'weighted visitation' scores was a function of the small number of occasions when public holidays occurred compared to the other categories, and so these results are probably not as informative or reliable as those in the other categories.

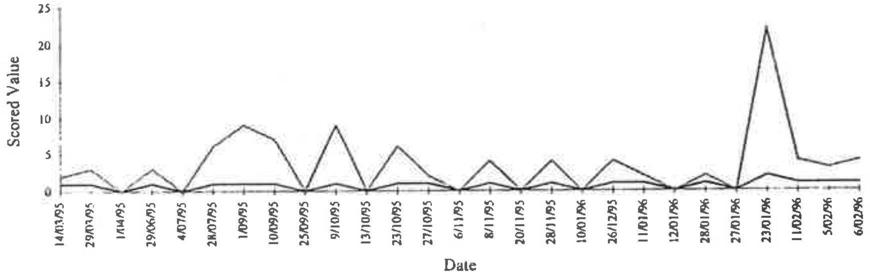
(opposite page)

Fig. 7.1 Comparison of recreational visitation (V) and scored recreational impact (I) experienced in the mid-eulittoral zone at GSV sites over a 12 month period (from February 1995 to February 1996). The sites examined were Kingston Park (a), Marino Rocks (b), Hallett Cove (c), Witton Bluff (d), Port Noarlunga South (e) and Robinson Point (f). Visitation was weighted with older children, teenagers and adults being assigned twice the score of very small children and dogs (each given a score of 1). Recreational impact was subjectively assessed on a scale of 0-3 (0=no impact, 1=minimal impact, 2=moderate impact, 3=severe impact) and involved considering the amount of visitation as well as the recreational activities being carried out at a site. The sampling dates on the x-axes were irregularly spaced but have been graphed at regular intervals. Note the different scales associated with the scored value of 'V' and 'I' shown on the *y*-axes.

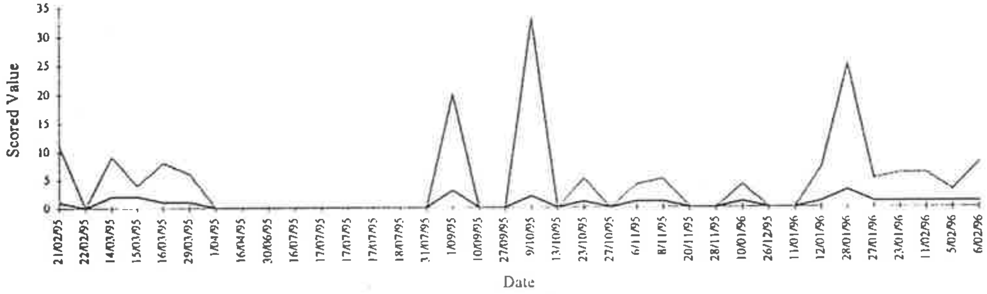
a) Kingston Park



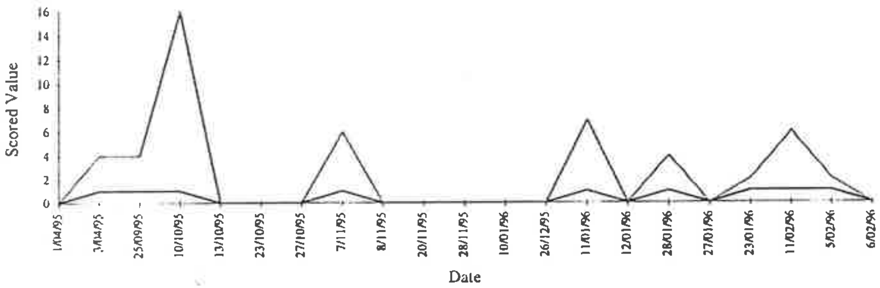
b) Marino Rocks



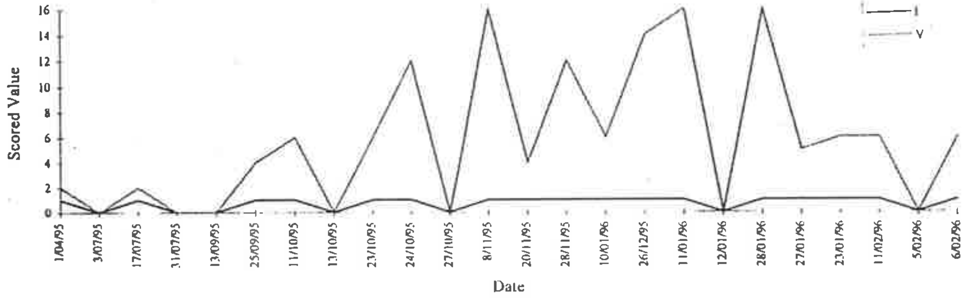
c) Hallett Cove



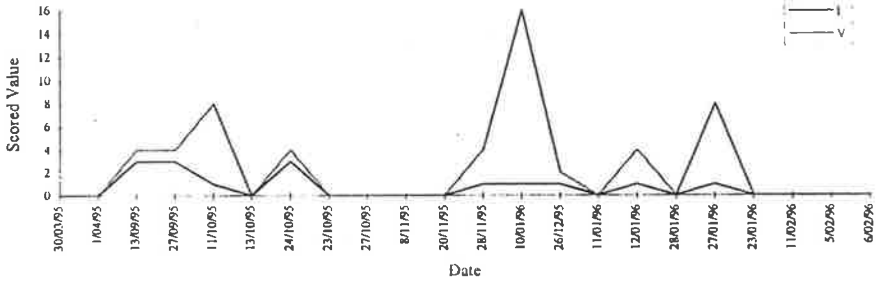
d) Witton Bluff



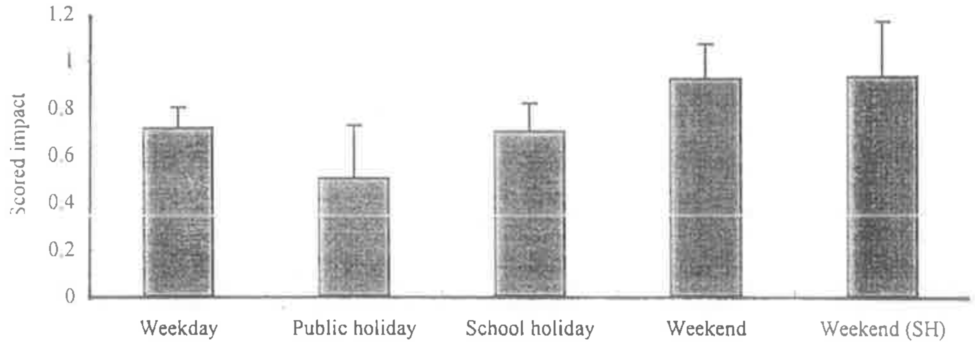
e) Port Noarlunga South



f) Robinson Point



a) Recreational Impact



b) Weighted Visitation

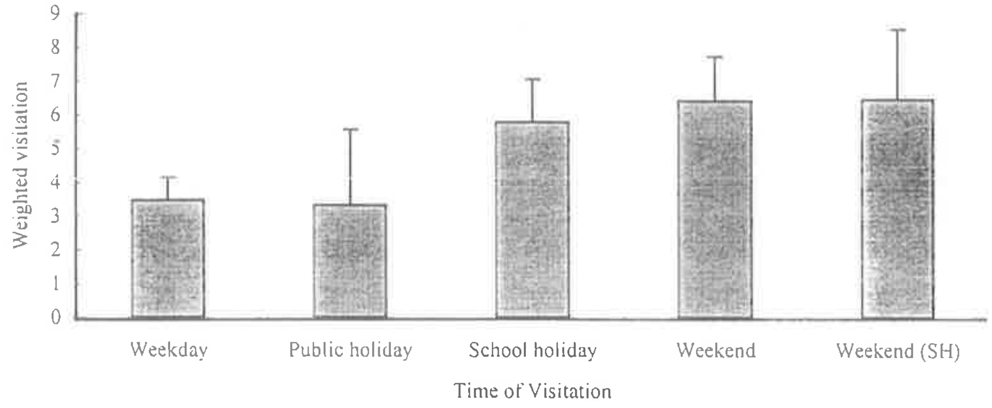


Fig. 7.2 Scored recreational impact and weighted visitation profiles for each of the sites shown in Fig. 7.1 have been averaged to enable broad comparisons between different times of visitation (shown on the *x*-axis). The time categories used were; 'weekday', 'public holiday', 'school-holiday', 'weekend' (weekend non-holiday) and 'weekend (SH)' (a weekend coinciding with a school-holiday or public holiday). A breakdown of recreational use according to time of day was not made during this study. The average scored recreational impact is shown in (a) and the average weighted visitation is shown in (b). The error bars represent the standard error associated with sampling.

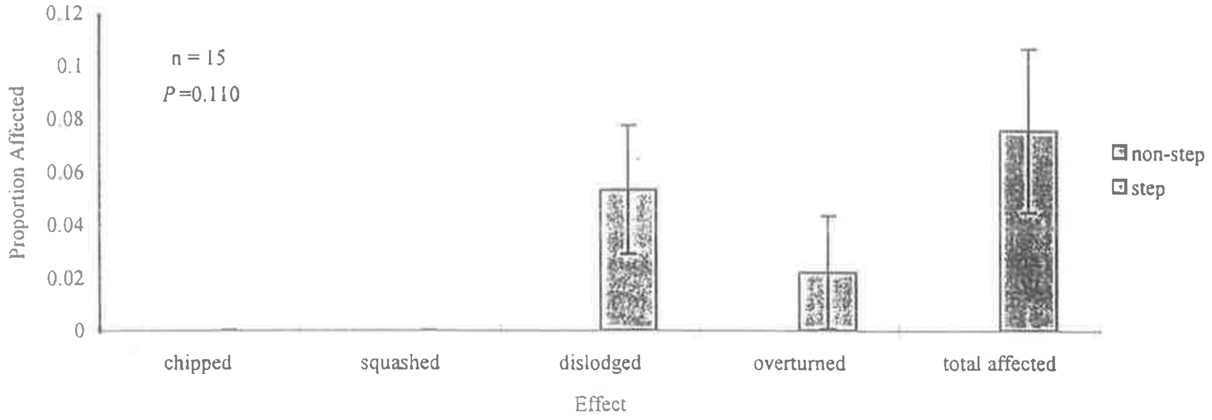
7.5.2 A 'Footstep' Disturbance

7.5.2.1 Effects on Dominant Gastropods

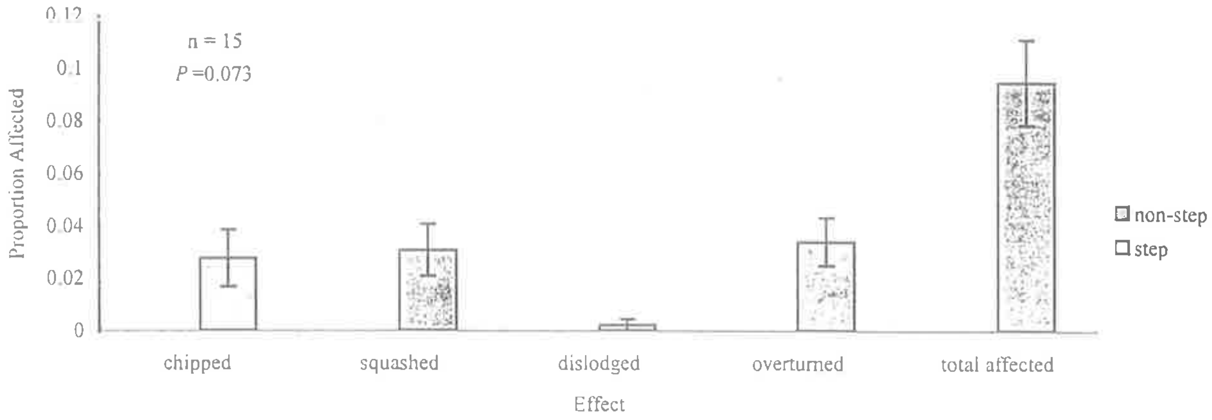
The 'footstep' experiment investigated the small-scale effects of a single 'footstep' on three herbivorous gastropods; *B. nanum*, *A. constricta* and *N. atramentosa*. Only small proportions of gastropods were affected by the 'footstep' treatment, and no animals were damaged in any of the 'control' quadrats. The average proportion of animals affected by the 'footstep' treatments ranged from 0.08 for *A. constricta* to 0.17 for *N. atramentosa*, while 0.01 *B. nanum* were affected (Fig. 7.3). The main effects seen in response to a 'footstep' were either dislodgment (where the animal was no longer tightly adherent to the rock but maintained its upright position) or overturning. The only species that suffered physical damage was *B. nanum*, which was chipped in 0.025 cases (on average) and squashed in 0.03 cases (Fig. 7.3b).

Statistical analyses were separately performed for the three gastropod species using the total unaffected animals in treatment and control quadrats as the dependant variable. No significant differences were found between the 'control' and 'footstep' treatments (Table 7.2), a result which was also evident graphically (Fig. 7.3).

a) *A. constricta*



b) *B. nanum*



c) *N. atramentosa*

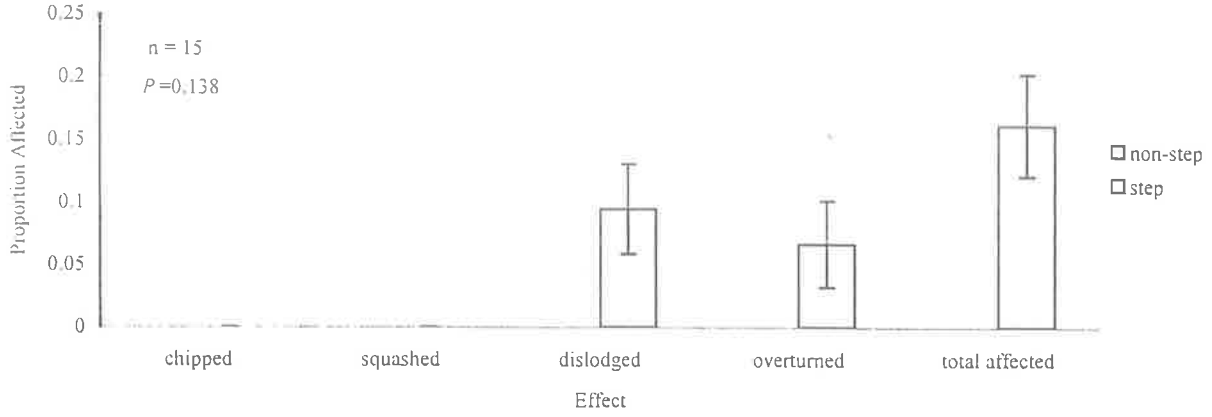


Fig. 7.3 The effect of a single 'footstep' on a) *A. constricta*, b) *B. nanum* and c) *N. atramentosa* was investigated at Kingston Park. The proportions of animals affected by a footstep ('step') were compared to the proportion of affected animals in experimental controls ('non-step'), shown on the *y*-axis, while the recognised effects (chipped, squashed, dislodged & overturned) and the total proportion of censused animals affected are shown on the *x*-axis. N=15 for each of the two treatments and the significance of treatment effects on the proportion of unaffected animals were examined using the analyses shown in Table 7.2. The resultant treatment probabilities (*P*) were not significant at the 0.05 level. Error bars represent the standard error associated with sampling.

Table 7.2 Analyses of the effects of a single 'footstep' on three gastropod species inhabiting 'bare' rock at Kingston Park. All data were $\log_{10}(x+1)$ transformed prior to testing for normality (using the Anderson-Darling statistic) and homoscedasity (using the F_{max} test). The dependant variable used in the analyses was the number of intact 'unaffected' animals. None of the results were significant at the 0.05 probability level.

Species	Normality	Homoscedasity	Analysis	Probability
A. constricta	No	not tested	Mann-Whitney	0.110
B. nanum	Yes	yes (P>0.5)	Student's t-test	0.073
N. atramentosa	Yes	yes (P>0.5)	Student's t-test	0.138

7.5.2.2 Effects on *Xenostrobus pulex* and *Lepsiella vinosa*

There was no obvious damage or change in the abundance of *X. pulex* in mussel beds which had been subjected to a 'footstep' treatment, either immediately following the treatment or when rechecked the following day (Fig. 7.4). Therefore, it was not necessary to subject the data to a repeated measures statistical analysis.

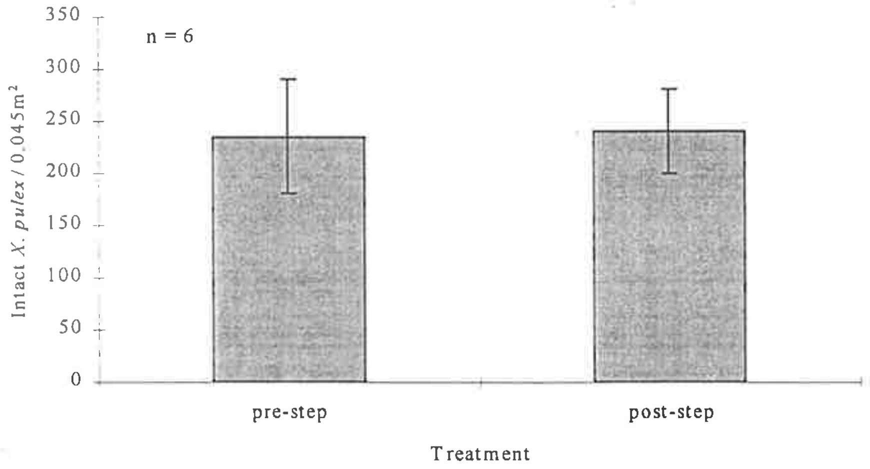


Fig. 7.4 Comparison of the average abundance of intact *X. pulex* mussels prior to (pre-step) and following (post-step) a single footstep into designated mussel dominated plots established at Kingston Park. Animals showing signs of previous damage unrelated to the experiment were not included in the census. There were 6 replicates (n=6) in each of the two treatments, shown on the x-axis, while the average number of intact *X pulex* per 0.045m^2 quadrat (intact *X. pulex*/0.045m^2) are shown on the y-axis. The clear lack of a treatment effect meant that a statistical analysis was not necessary. Error bars represent the standard error associated with the treatments.

The second part of this experiment involved comparing the 'footstep' quadrats used in the *X. pulex* experiment with six undisturbed ('non-footstep') controls and censusing them the following day to see if the abundance of the carnivore *L. vinosa* differed between the two treatments (Fig. 7.5). The data did not require transformation and no differences were found at the 0.05 probability level using a two-tailed Student's *t*-test (P=0.84). The average abundance of *L. vinosa* present in both the control and 'footstep' treatments was less than 2 animals per quadrat, meaning that the results should be interpreted with caution (Fig. 7.5).

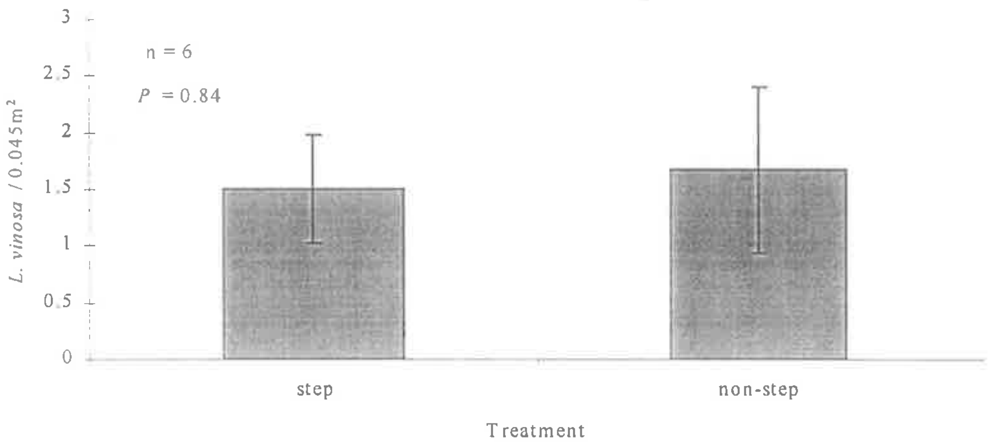


Fig. 7.5 Comparison of the average number of *L. vinosa* found in 0.045m^2 quadrats deployed in *X pulex* beds which had been subjected to a 'footstep' (step) and those which had not been exposed to this treatment (non-step). Treatment effects were assessed one day after the 'footstep' had been applied to the relevant treatment and are shown on the *y*-axis as the average number of *L. vinosa* per 0.045m^2 quadrat (*L. vinosa*/0.045m^2). Error bars represent the standard error associated with the treatments and there were 6 treatment replicates (n=6). There was no significant treatment effect at the 0.05 level of probability (P=0.84).

7.5.2.3 Effects on *Cellana tramoserica*

There were no immediate effects of a single 'footstep' on the limpet *C. tramoserica* other than the dislodgment of one limpet from its rock. However, when I returned to Port Stanvac to census the animals one tidal cycle later, all limpets were found in their original 'home' positions (Fig. 7.6). It was apparent that stepping on the animals had not resulted in their loss from the area. The results of this experiment were conclusive and no statistical analysis was required.

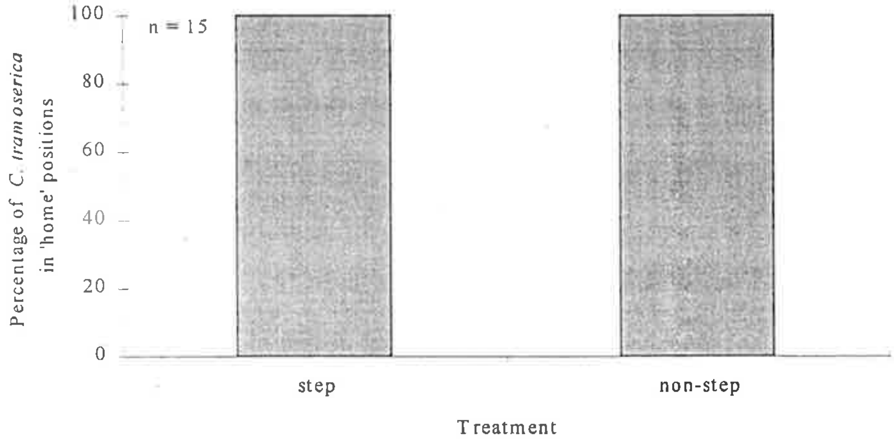


Fig. 7.6 Comparison of the percentage of *C. tramoserica* animals remaining in their original 'home' positions (shown on the *y*-axis) in the two treatments (shown on the *x*-axis) one day after the treatments had been established. Each treatment consisted of 15 adult animals (n=15) which had been randomly chosen and stepped on ('step') or left undisturbed ('non-step'). All animals were found in their original positions and a statistical analysis was not needed.

7.5.3 Overturning Dominant Gastropods

The results of the small scale 'footstep' experiment involving gastropods on 'bare' rock indicated that the most likely impact arising from a single 'footstep' was dislodgment of animals (Fig. 7.3a, b & c). Dislodgment in association with overturning was the most serious outcome and was found to be more common than dislodgment alone in the case of *B. nanum* (Fig. 7.3b). Accordingly, it was appropriate to experimentally investigate if the percentage of overturned animals recovered after one tidal cycle differed from the percentage of recovered control (non-overturned) animals. Comparisons were also made between the two treatment groups to assess if overturned animals (which were recovered) had travelled further than their control counterparts.

Paired *t*-tests, or the non-parametric equivalent (the Wilcoxon paired sample test) were used to separately test the following one-tailed alternative hypotheses;

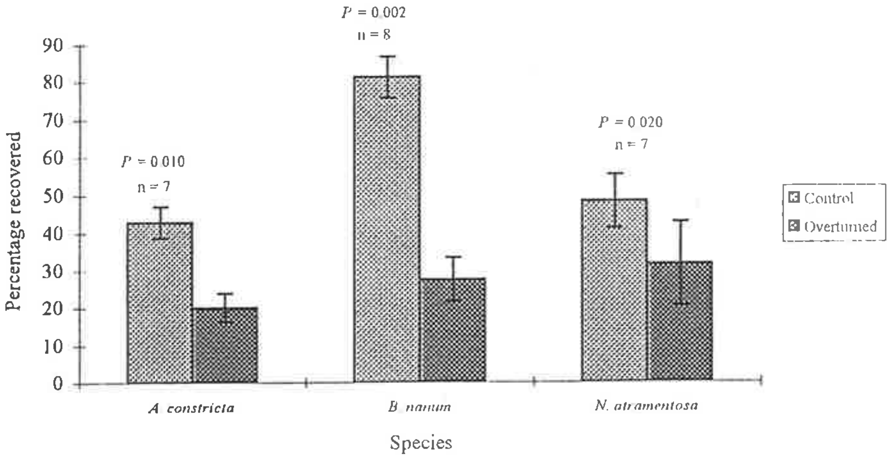
1. Less animals were recovered in 'overturned' treatments than in the equivalent 'controls', and
2. Of the animals recovered, the overturned animals were transported further (on average) over one tidal cycle than the control animals.

Some differences in the assessed parameters were found according to site and the species being investigated (Fig. 7.7, Tables 7.3 & 7.4).

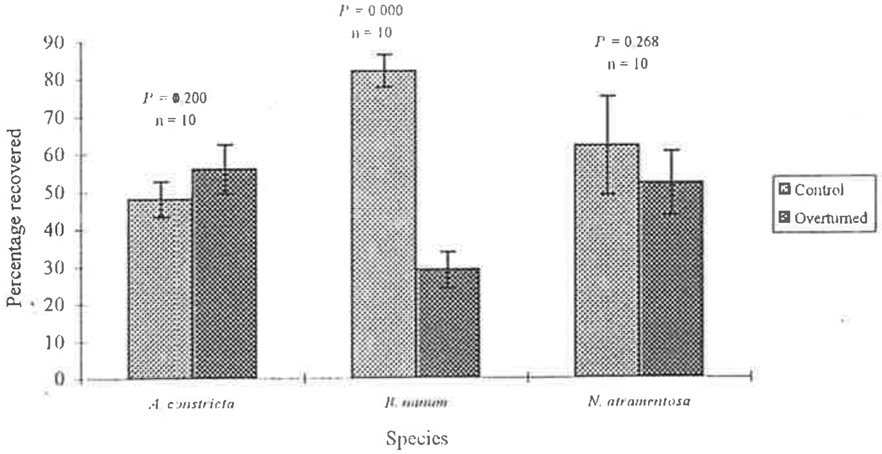
(opposite page)

Fig. 7.7 The percentages (shown on the *y*-axes) of three species of mollusc (shown on the *x*-axis) recovered at Kingston Park (a) and Port Stanvac (b) after being marked and overturned or marked and left upright and *in situ* (control) (refer to legend) have been compared. The distances (in metres) travelled by the recovered animals (shown on the *y*-axis) have also been plotted for Kingston Park (c) and Port Stanvac (d). The graphed results were obtained one day after the treatments had been applied. The number of replicates within treatment groups (n) varied due to time constraints, but there were 10 animals in each replicate. The treatment probabilities (*P*) obtained after paired comparisons were made at a significance level of 0.05 have been plotted for each species. See text and Tables 7.3 & 7.4 for further details.

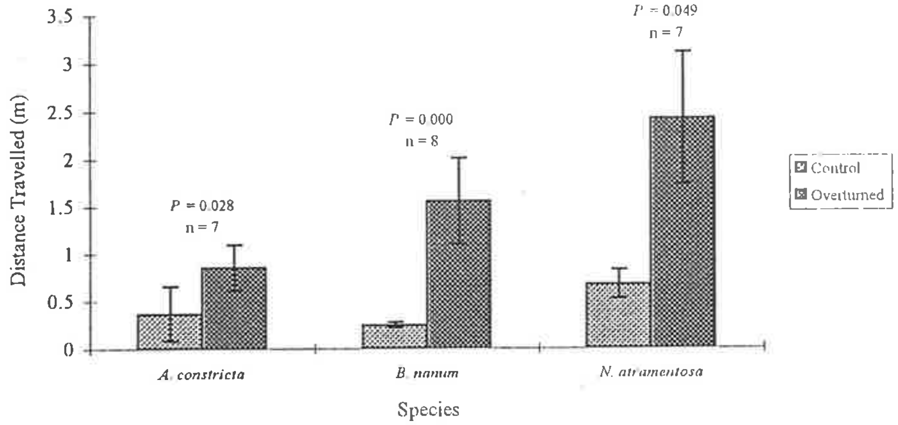
a) Recovered molluscs at Kingston Park



b) Recovered molluscs at Port Stanvac



c) Distance travelled by recovered molluscs at Kingston Park



d) Distance travelled by recovered molluscs at Port Stanvac

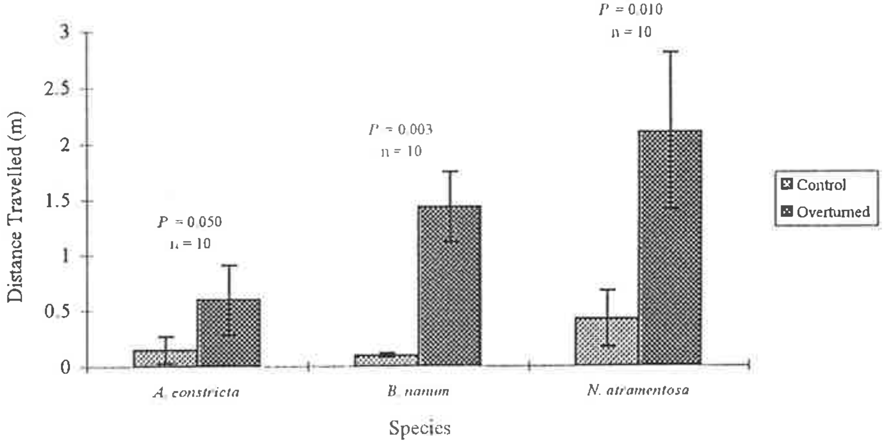


Table 7.3 Analysis of the effect of overturning dominant gastropods on the proportion of animals recovered in treatments after one tidal cycle. The treatments were paired and consisted of an 'overturned' and a companion 'control' group. The experiments were conducted at a) Kingston Park and b) Port Stanvac, and involved three gastropod species; *A. constricta*, *B. nanum* and *N. atramentosa*. The differences between treatment pairs were tested for normality and the appropriate statistical test applied separately for each species. Results which were significant at the 0.05 level are marked as **, while those which were significant at the 0.01 level are marked as ***.

a) Kingston Park

Species	Normality	Analysis	Probability
A. constricta	No	Wilcoxin	0.010***
B. nanum	Yes	paired *t*-test	0.002***
N. atramentosa	Yes	paired *t*-test	0.020**

b) Port Stanvac

Species	Normality	Analysis	Probability
A. constricta	No	Wilcoxin	0.200
B. nanum	Yes	paired *t*-test	0.000***
N. atramentosa	Yes	paired *t*-test	0.268

Table 7.4 Analysis of the effect of overturning dominant gastropods on the distance travelled by recaptured animals in treatments after one tidal cycle. The treatments were paired and consisted of an 'overturned' and a companion 'control' group. The experiments were conducted at a) Kingston Park and b) Port Stanvac, and involved three gastropod species; *A. constricta*, *B. nanum* and *N. atramentosa*. The differences between treatment pairs were tested for normality and the appropriate statistical test applied separately for each species. Results which were significant at the 0.05 level are marked as **, while those which were significant at the 0.01 level are marked as ***.

a) Kingston Park

Species	Normality	Analysis	Probability
A. constricta	Yes	paired *t*-test	0.028**
B. nanum	Yes	paired *t*-test	0.000***
N. atramentosa	Yes	paired *t*-test	0.049**

b) Port Stanvac

Species	Normality	Analysis	Probability
A. constricta	No	Wilcoxin	0.050**
B. nanum	No	Wilcoxin	0.000***
N. atramentosa	Yes	paired *t*-test	0.010***

Significantly less animals belonging to all three species were recovered from overturned treatments at Kingston Park (Fig. 7.7a and Table 7.3a), but at Port Stanvac a significant result was found only with *B. nanum* (Fig. 7.7b and Table 7.3b). When the average distances travelled by recovered animals within groups were compared it was apparent that in all cases (at both sites) the overturned animals had been displaced further than their control counterparts (Fig. 7.7c & d and Table 7.4a & b).

The Unreplicated 'Overturning' Experiment

The experiment where 10 individuals of *B. nanum*, *A. constricta* and *N. atramentosa* were overturned on 'bare' dry rock and also in shallow water at Port Stanvac was unreplicated and the results could not be statistically analysed. The most definitive finding was that overturned *B. nanum* individuals failed to right themselves over the observation period (Table 7.5). Results were less clear for the other species, but generally more animals righted themselves when overturned on 'bare' rock in shallow water than individuals of the same species which were overturned on dry rock (Table 7.5). *A. constricta* individuals which were overturned in shallow water were more likely to right themselves over a 30 minute observation period than the other species investigated.

Very few of the animals overturned on dry rock righted themselves over 30 minutes, and those that remained overturned kept their operculum tightly closed. Therefore, it was hypothesised that if these animals where exposed to an incoming tide, they would be displaced further than animals which had not been overturned and which remained adherent to substrata. This supports the findings of the main 'overturning' experiments which were performed at low tide when the rock in the mid-eulittoral zone was basically dry, and which established that overturned animals had travelled further over one tidal cycle than equivalent non-overturned control animals.

Table 7.5 The behaviour of three species of gastropods overturned at Port Stanvac are compared. The animals were divided into two groups of 10 for each species. Animals were overturned in their 'original' position on either wet or dry 'bare' rock and then observed for 30 minutes. Different individuals were used in the examination of the behaviour of the animals on wet and dry substrata.

Species	Overturned in 'shallow' water	Overturned on 'dry' rock
A. constricta	7 righted by 19 minutes	1 righted by two minutes
	3 overturned after 30 minutes	9 overturned after 30 minutes
B. nanum	10 overturned after 30 minutes	10 overturned after 30 minutes
N. atramentosa	4 righted by 10 minutes	2 righted by 2.45 minutes
	6 overturned after 30 minutes	8 overturned after 30 minutes

7.5.4 The 'Weekend' Trampling Experiment

7.5.4.1 Effects on the Intertidal Assemblage

Due to the similarity of the two post-trampling data sets and to simplify interpretation of the effects of acute 'weekend' trampling on the intertidal assemblage only the pre-impact and immediately post-impact trampling times were examined with multivariate techniques. The dendrogram revealed 7 groupings (Fig. 7.8) the members of which are described in Table 7.6. Dendrogram groups 1-5 shared 65% (Bray-Curtis) similarity, while groups 6 and 7 shared less than 57% similarity with the other dendrogram groups and had only one member each. In general, all 'before' (not yet treated) plots were spread widely through dendrogram groups 1-6, while the 'after' (treated) plots had a more aggregated presence in the groups.

Dendrogram groups 1 and 4 each accounted for a third of the 'before' plots destined to be heavily trampled, while group 4 also accounted for two-thirds of the 'before' plots awaiting 'light' trampling and one third of the 'before-control' plots (Table 7.6). The 'after-control' plots were primarily found in groups 2 and 4 which accounted for 50% and 33% of these plots respectively, while the remaining 'control' plots were found in dendrogram group 3 (Table 7.6). This group accounted for 50% of the 'after-light' and 'after-heavy' trampled plots. The remaining 'after-light' trampled plots were evenly spread between dendrogram groups 1, 4 and 5. The rest of the 'after-heavy' trampled plots were primarily found in dendrogram group 2, and the single member of group 7 also belonged to this category.

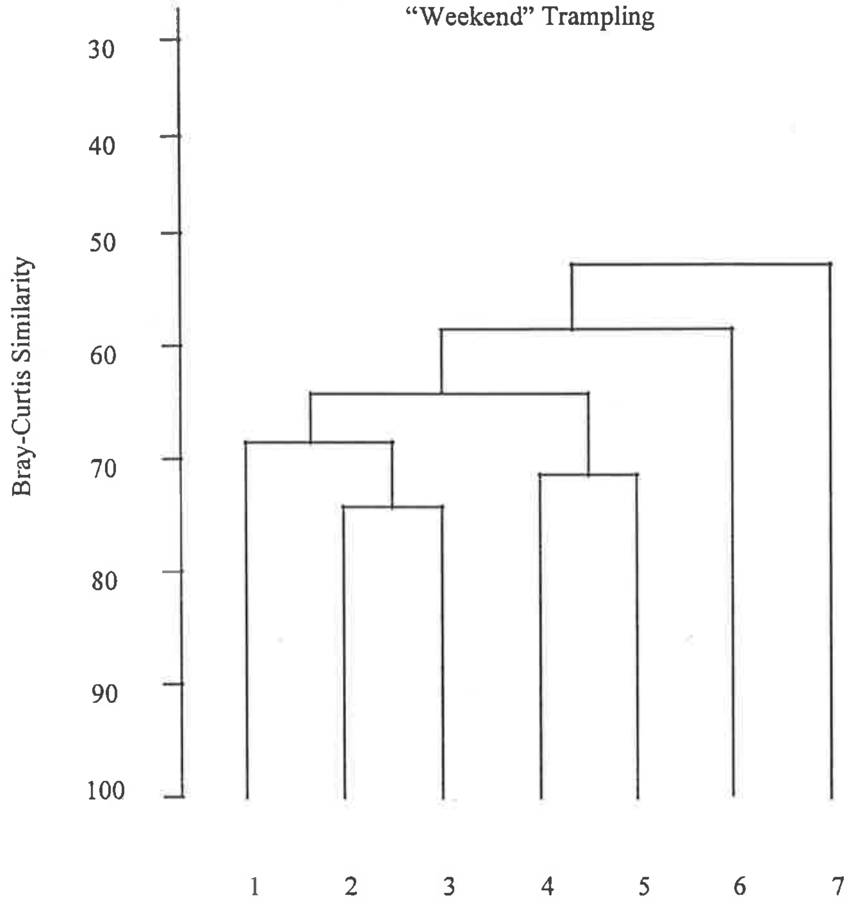


Fig. 7.8 The dendrogram was generated from the 'weekend' trampling experiment which involved 3 experimental treatments ('control', 'light' and 'heavy' trampling) established as a blocked design in 6 experimental plots which were assessed prior to the commencement of trampling ('before) and one day after trampling was completed ('after'). The dendrogram groups are numbered 1-7 and are based on Bray-Curtis similarities computed for double square root-transformed species abundances. Members of each dendrogram group are shown in Table 7.6.

Table 7.6 A breakdown of the members of dendrogram groups 1-7 (see Fig. 7.8) identified in the analysis of the 'weekend' trampling experiment. The number of members within dendrogram groups are shown as well as the percentage of the 'before' ('B') (not yet treated) and 'after' ('A') (treated) plots, subjected to three levels of trampling over a weekend. The trampling levels used in the experiment were: control (C) (no trampling), lightly trampled (L) (2 trampling passages) and heavily trampled (H) (20 trampling passages). See section 7.4.2.3 for further experimental details.

	Dendrogram Group						
Treatment	1	2	3	4	5	6	7
BC	16.67%	16.67%	16.67%	33.33%	16.67%	00.00%	00.00%
BL	16.67%	00.00%	00.00%	66.67%	00.00%	16.67%	00.00%
BH	33.33%	00.00%	16.67%	33.33%	16.67%	00.00%	00.00%
AC	00.00%	50.00%	16.67%	33.33%	00.00%	00.00%	00.00%
AL	16.67%	00.00%	50.00%	16.67%	16.67%	00.00%	00.00%
AH	00.00%	33.33%	50.00%	00.00%	00.00%	00.00%	16.67%
No. in group	**5**	**6**	**9**	**11**	**3**	**1**	**1**

The SSH MDS Ordination generated from the raw abundances of species per $0.75m^2$ was more useful than the dendrogram in revealing assemblage changes in association with the level of trampling (Fig. 7.9). Although ordination stress was relatively high (S=0.17) a useful interpretation of the data was obtained in two dimensions. The majority of treatment plots (apart from two pre-impact control plots) were positioned negatively with respect to Axis 2 before the trampling treatments were applied. All 'after' plots (irrespective of treatment) were positive with respect to Axis 2 except for one of the 'light' plots. Multiple taxa regressions against the MDS ordination, revealed that three taxa shared significant relationships with the ordination scores. These taxa were *B. nanum* ($0.002<P<0.005$), *A. constricta* ($P<0.001$), and *Notoacmea* spp. ($P<0.001$), and all were acting within Quadrat 4 of the ordination plot (see Fig. 7.9). A Pearson correlation with a Bonferroni correction failed to reveal significant relationships between the ordination scores and the dominant species (Table 7.7).

To simplify any treatment trends the ordination scores were averaged across treatments prior to trampling and again one day after trampling and the positions corresponding to these times linked (Fig. 7.10). The resultant vectors represent the direction and magnitude of change under the three trampling regimes. Changes were evident in all treatments (including the 'control'), but the 'light' vector changed in a direction that was approximately midway between the other two vectors. Changes occurring under 'heavy' trampling resided in Quadrat 1, while the vectors of change associated with the remaining treatments were within the area defined by Quadrat 4 (Fig. 7.10). The changes seen in the 'control' and 'light' treatments regressed significantly with *B. nanum*, *A. constricta* and *Notoacmea* spp. However, no significant relationships between taxa and the changes occurring under 'heavy' trampling could be found (Figs 7.9 & 7.10).

Fig. 7.9 SSH MDS Ordination based on double square root transformed taxa abundance pre-impact and one day after impact in the 'weekend' trampling experiment at Kingston Park. Three trampling treatments were established in each of 6 plots; control (no trampling), lightly trampled (2 trampling passages), and heavily trampled (20 trampling passages). Trampling levels are; C=control, L=light, and H=heavy. Pre-impact treatments are prefixed with a P, and all other treatments represent post-impact data points. The stress associated with this two-dimensional ordination was 0.17 (S=0.17). The significant PCC taxa vectors associated with the ordination are shown with their probability levels (*P*) and are; *Bemb.=B. nanum*, *Aust. cons.=Austrocochlea constricta* and *Noto.* spp.=*Notoacmea* spp. The plotted area has been divided into four quadrats (Q1-4) delineated by Axes 1 & 2.

"Weekend" Trampling Experiment:
SSH MDS Ordination

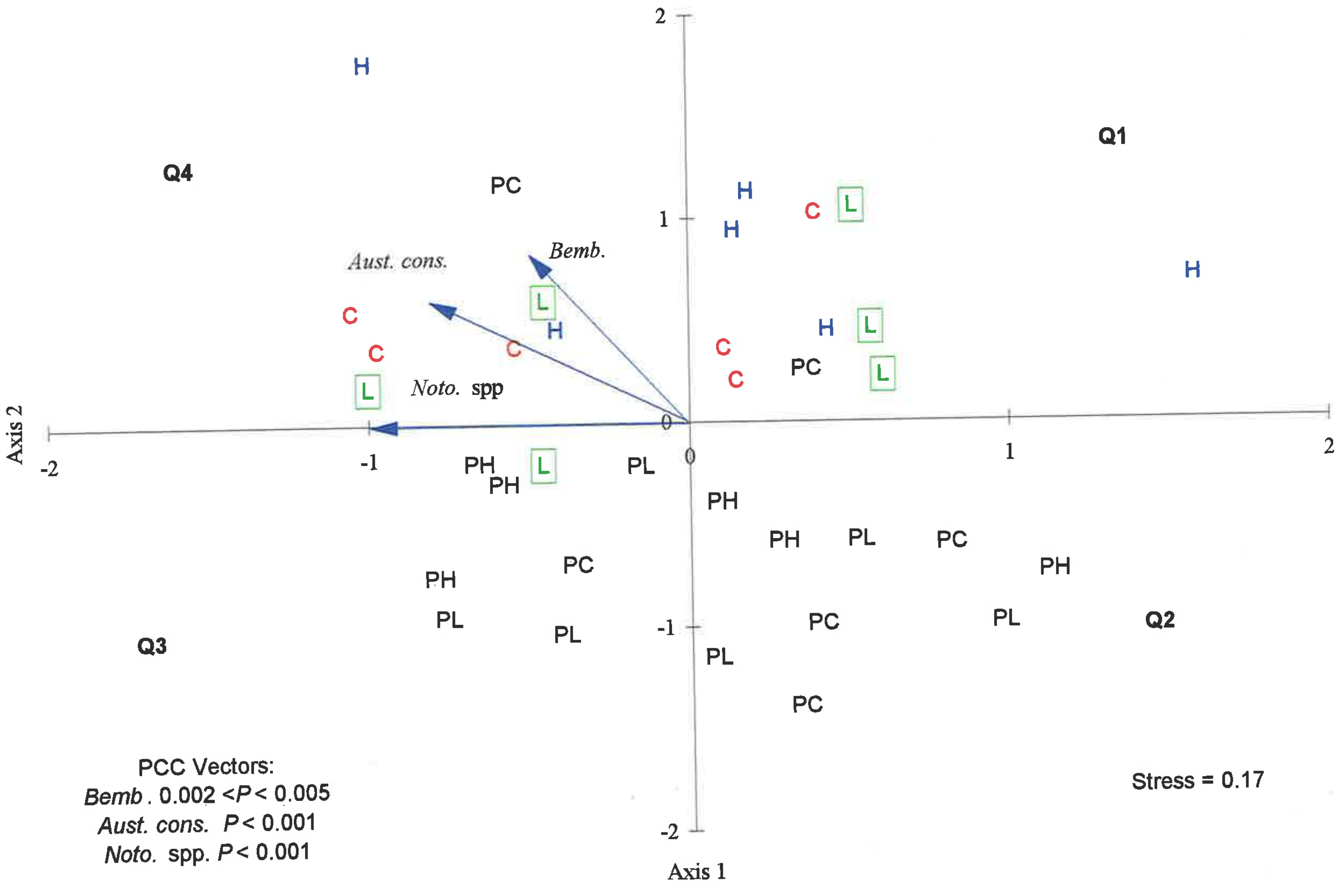
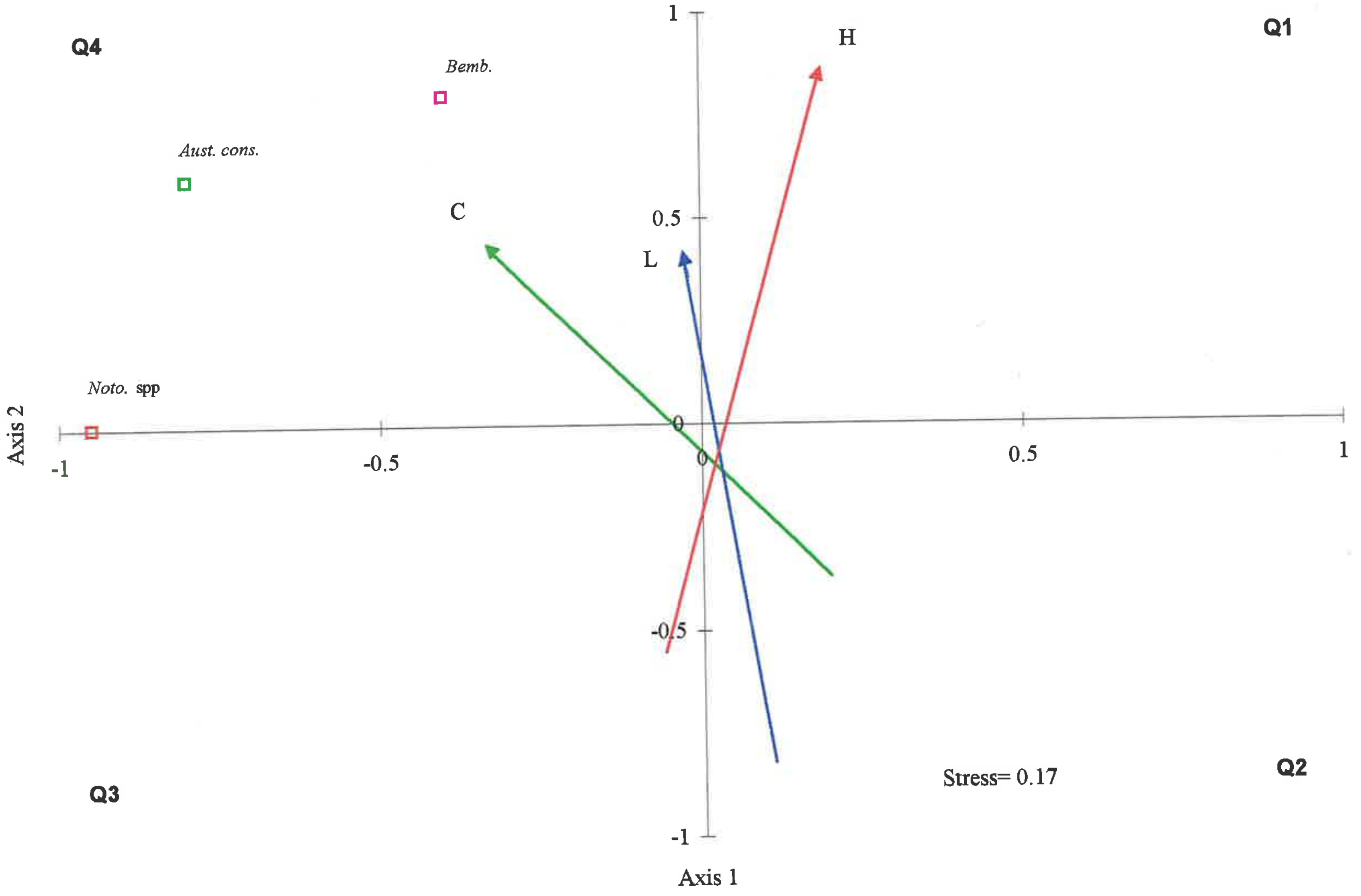


Fig. 7.10 SSH MDS Ordination based on double square root transformed taxa abundance pre-impact and one day after impact in the 'weekend' trampling experiment at Kingston Park. The vectors correspond to the average change in ordination position between the pre-trampling and one day post-trampling times for each treatment (see Fig. 7.9). Trampling levels are C=control (no trampling), L=light (2 trampling passages), and H=heavy (20 trampling passages). The stress associated with this two-dimensional ordination was 0.17 (S=0.17). The plotted area has been divided into four quadrats (Q1-4) delineated by Axes 1 & 2. Taxa that regress significantly with the ordination lie within Q4, and are as shown in Fig. 7.9. To avoid confusion the regression vectors have not been shown for each of the significant taxa on this figure but their end points have been represented as open-squares that would arise from the origin of the plot.



"Weekend" Trampling Experiment:
SSH MDS Ordination Treatment Effects

Table 7.7 Pearson matrix of Bonferroni probabilities; MDS axes *vs* dominant taxa for the 'weekend' trampling data set. Bartlett's chi-squared statistic: 213.91, *P*=0.000. Bold numbers represent significant probabilities at the 0.05 level, and negative values indicate a negative correlation. Species abbreviations are: *Nerita*=*Nerita atramentosa*, *A. conc.*=*Austrocochlea concamerata*, *A. cons.*=*Austrocochlea constricta*, *Lit. u.*=*Littorina unifasciata*, *Bemb.*=*Bembicium nanum*, *Lep.*=*Lepsiella vinosa*, *Cell.*=*Cellana tramoserica*, *Noto.* spp.=*Notoacmea* spp.

Variable	Axis 1	Axis 2	*Nerita*	*A. conc.*	*A. cons.*	*Lit. u.*	*Bemb.*	*Lep.*	*Cell.*	Noto. spp.
Axis 1	**0.000**									
Axis 2	-1.000	**0.000**								
Nerita	1.000	-1.000	**0.000**							
A. conc.	1.000	-1.000	-1.000	**0.000**						
A. cons.	1.000	-1.000	1.000	-1.000	**0.000**					
Lit. u.	1.000	-1.000	1.000	1.000	-1.000	**0.000**				
Bemb.	1.000	-1.000	-1.000	1.000	-1.000	1.000	**0.000**			
Lep.	1.000	-1.000	-1.000	1.000	1.000	-1.000	-1.000	**0.000**		
Cell.	1.000	-1.000	-1.000	1.000	1.000	1.000	-1.000	**0.000**	**0.000**	
Noto. spp	1.000	-0.599	-1.000	0.062	-1.000	1.000	1.000	-1.000	1.000	**0.000**

7.5.4.2 Effects on Summary Statistics

All assessed summary statistics decreased following trampling but the changes occurred irrespective of treatment (Fig. 7.11). The number of taxa (Fig. 7.11a), Species Richness (Fig. 7.11b), Shannon-Wiener Diversity (Fig. 7.11c) and Pielou's Evenness (Fig. 7.11d) all declined between the pre-impact and the immediate post-trampling times. All changes were definitive (as indicated by the non-overlapping standard error bars) apart from Pielou's Evenness where the error bars overlapped between the two sampling times in the lightly trampled treatment (Fig. 7.11d). No pre-impact differences in the assessed summary statistics were apparent between trampling categories and no differences between treatments were evident post-impact (Fig. 7.11). Therefore, statistical analyses of treatment effects were not performed.

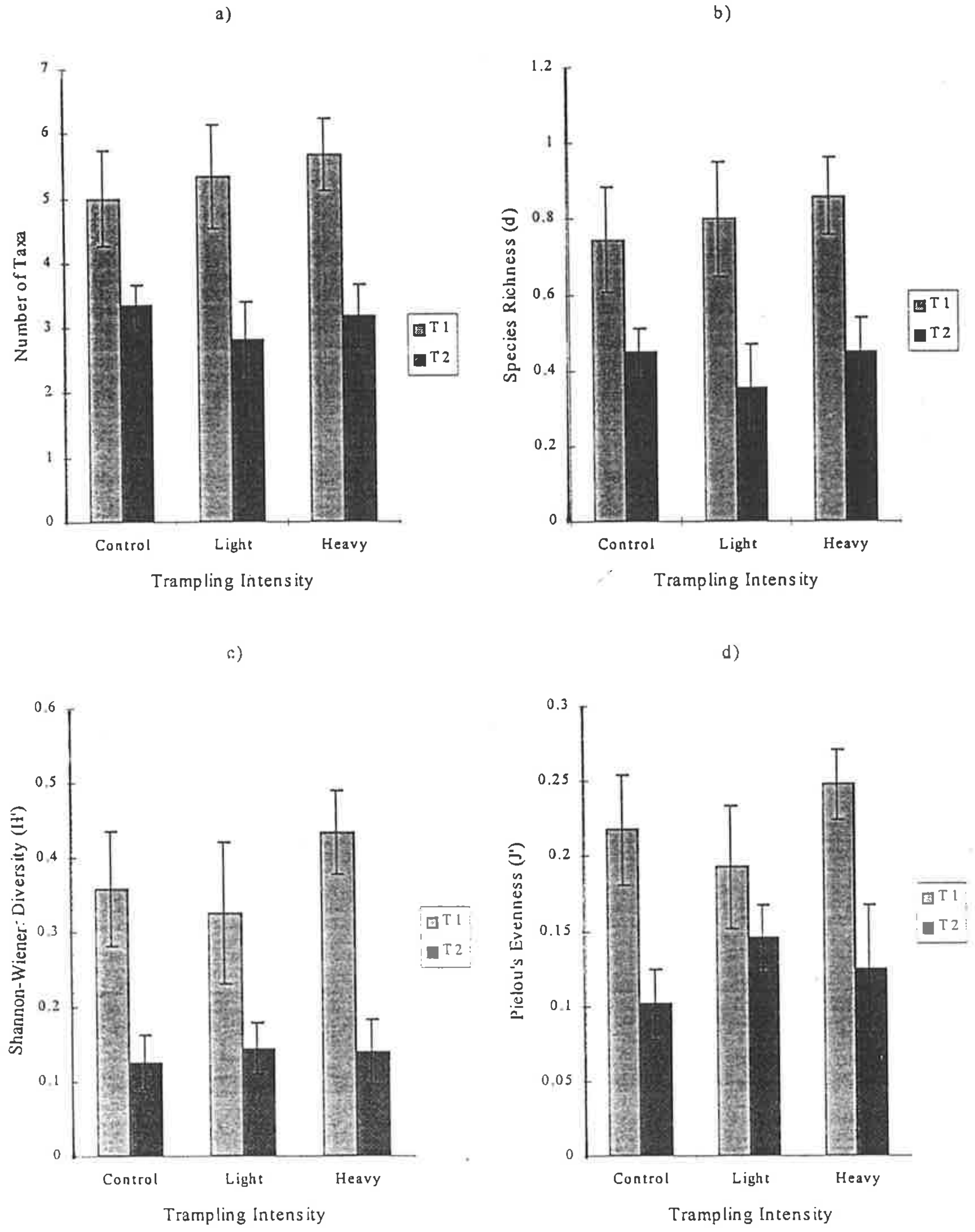


Fig. 7.11 Summary statistics were calculated from assemblage data and generated from the 'weekend' trampling experiment. Assessed parameters are: a) number of taxa, b) Species Richness, c) Shannon-Wiener Diversity and d) Pielou's Evenness. The trampling treatments are shown on the *x*-axis and are; control (no trampling), light (2 trampling passages), and heavy (20 trampling passages). Data are compared prior to trampling (T1) and one day after completion of trampling (T2). Error bars represent the standard error associated with sampling.

7.5.4.3 Effects on *B. nanum*

The Total Abundance of B. nanum

The total abundance of *B. nanum* had decreased in all treatments by the first post-impact trampling time (T2), a trend which was most marked in the heavily trampled treatment (Fig. 7.12). The decrease in abundance occurring in the control treatment suggested that this trend was (in part) independent of trampling. There was no evidence of a return to pre-impact *B. nanum* numbers after the recovery period (T3) had elapsed, and identical trends were observed whether quadrats used in each treatment plot were summed (Fig. 7.12a) or averaged (Fig. 7.12b).

All statistical analyses were performed on data that were averaged for the three plot 'replicates' for each of the three census times. The total abundances of *B. nanum* in treatments were normally distributed and displayed homoscedastic variances pre-impact so a randomised block ANOVA was performed using "SYSTAT", Version 5.0 (Wilkinson 1990) to assess if treatments (the fixed factor) differed by chance. No significant differences in the total abundance of *B. nanum* were found between plots or treatments at the start of the experiment (Table 7.8).

Total *B. nanum* abundance data collected at the other two times of interest (immediately post-impact (T2) and post-recovery (T3)) displayed non-normal distributions even after $\log_{10}(x+1)$ transformations and were analysed using the Friedman's Test (Freidman 1937) as described in Zar (1984, pg 229), again using "SYSTAT", Version 5.0. No significant differences were found between treatments either immediately post-impact or after a 6 day recovery period (Friedman's test statistic=0.333, P=0.846). The statistical results were identical at both post-impact sampling times (T2 & T3) due to identical within-plot treatment rankings.

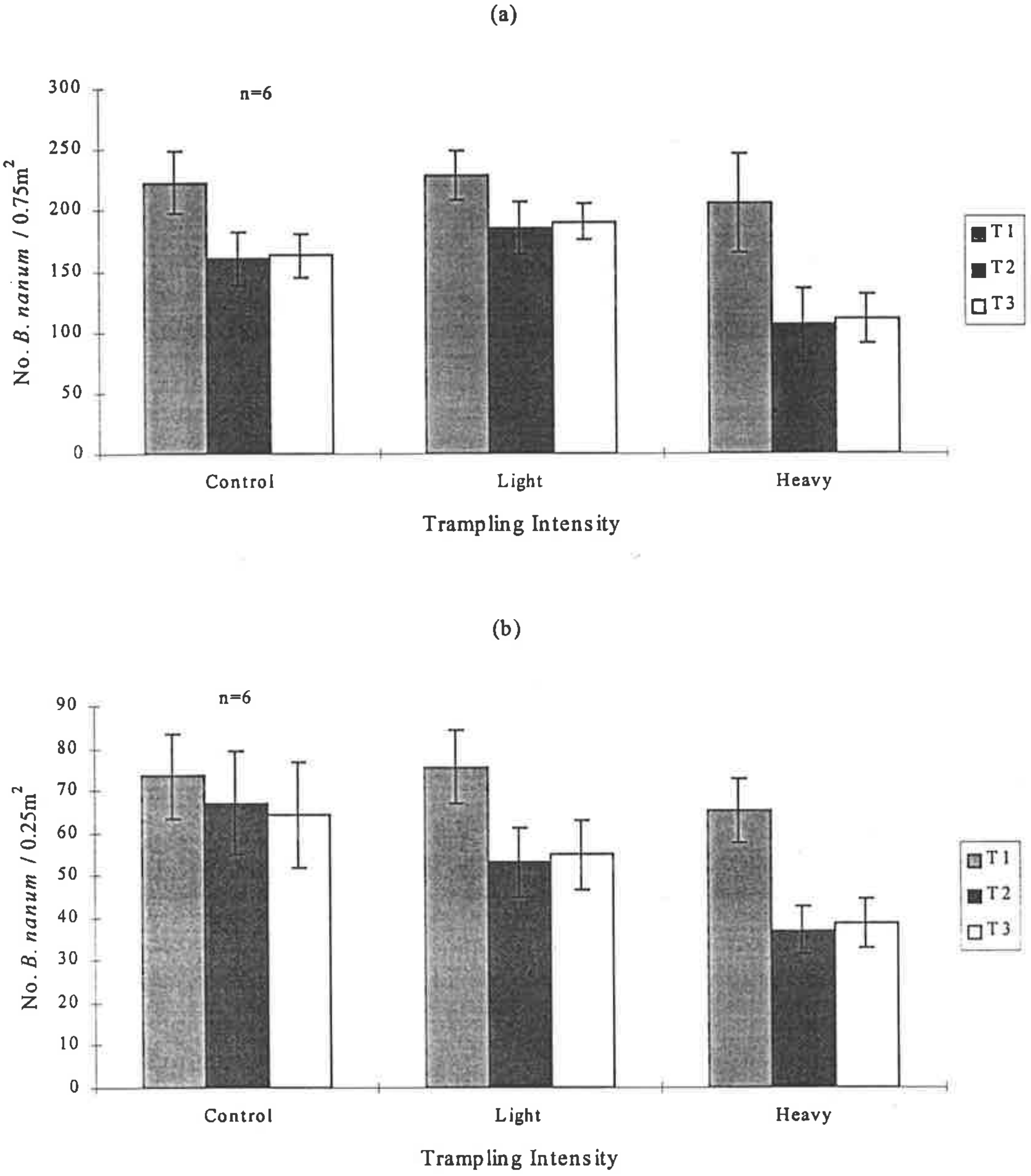


Fig. 7.12 Comparison of the abundance of *B. nanum* (a) per 0.75m^2 and (b) per 0.25m^2 in the 'weekend' trampling experiment. The trampling treatments investigated are shown on the *x*-axis and are; control (no trampling), light (2 trampling passages) and heavy (20 trampling passages). Abundances were averaged across the six experimental plots (n=6) and are shown on the *y*-axis as the number of animals per specified surface area of the shore. The three census times shown in the legend are; pre-impact (T1), one day after trampling (T2) and six days after trampling (T3). Error bars represent the standard error associated with sampling.

Table 7.8 A pre-impact randomised Block ANOVA was used to compare the average abundance of *B. nanum*/0.25m^2 (incorporating all size classes) between trampling treatments in the 'weekend' trampling experiment. 'Plots' were the random factor and 'trampling' treatments were the fixed factor in the analysis. Data were normal and homoscedastic and did not require transformation prior to analysis. The resultant analysis probabilities (*P*) are shown in the last column of the table. **=significant at the 0.05 level.

Source	Sum-of-squares	df	Mean-Square	F-Ratio	*P*
Plot	3118.083	5	623.617	1.616	0.242
Treatment	357.501	2	178.751	0.463	0.642
Error	3858.321	10	385.832		

'Large' *B. nanum* were rare at Kingston Park and the censused animals were categorised into two size classes ('medium-large', and 'small') and subjected to separate size-specific analyses. The sizes are as specified in Chapter 3, with the 'medium-large' size class consisting of both 'medium' and 'large' animals.

The Abundance of 'Medium-Large' *B. nanum*

No pre-trampling treatment differences in the average abundance of 'medium-large' *B. nanum* were apparent (Fig. 7.13a & Table 7.9). The Friedman's test was used to analyse treatment differences following trampling. No significant differences could be found between treatments immediately following trampling or after the recovery phase (Friedman's test statistic=2.33, *P*=0.311). Slight decreases in the abundance of 'medium-large' *B. nanum* were apparent under 'light' and 'heavy' trampling but these were more pronounced in the latter and persisting through the recovery phase of the experiment (Fig. 7.13a).

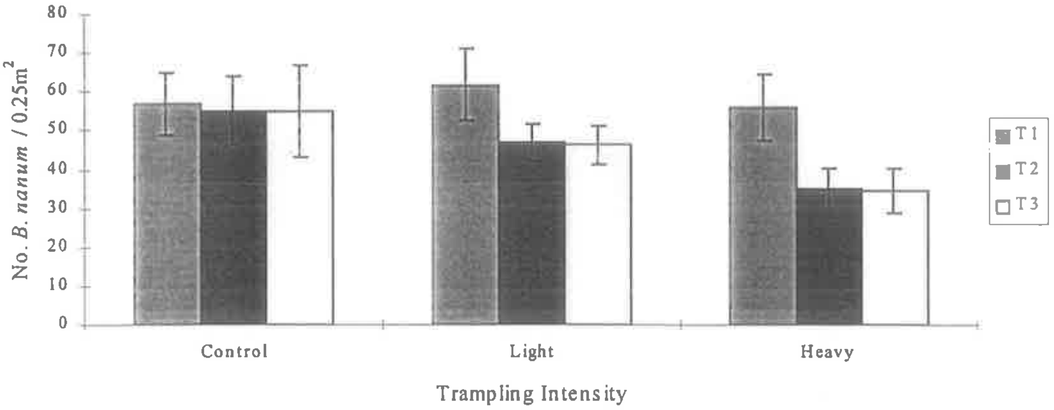
Table 7.9 A pre-impact randomised Block ANOVA was used to compare the average abundance of 'medium-large' *B. nanum*/0.25m^2 between trampling treatments in the 'weekend' trampling experiment. 'Plots' were the random factor and 'trampling' treatments were the fixed factor in the analysis. Data were normal and homoscedastic and did not require transformation prior to analysis. The resultant analysis probabilities (*P*) are shown in the last column of the table. **=significant at the 0.05 level.

Source	Sum-of-squares	df	Mean-Square	F-Ratio	*P*
Plot	3856.248	5	771.250	2.721	0.084
Treatment	111.302	2	55.651	0.196	0.825
Error	2833.990	10	283.399		

The Abundance of 'Small' B. nanum

Data pertaining to the abundance of 'small' *B. nanum* in 'trampling' treatments were not normally distributed even after transformation and Friedman's tests were used to analyse for treatment differences. The abundances of 'small' animals were observed to decline in all treatments after trampling commenced but clear decreases (supported by non-overlapping standard error bars) were only evident under 'heavy' trampling (Fig. 7.13b). The statistical analyses revealed no significant differences between treatments prior to trampling (Friedman's test statistic=4.75, *P*=0.093), but significant post-trampling effects (Friedman's test statistic=7.583, *P*=0.023). As explained previously, due to the within plot ranking used in the Friedman's test the probability values obtained for the two post-trampling times were identical. A *post hoc* multiple non-parametric comparison established that the 'control' and 'heavy' trampled treatments were different following trampling (at both post-trampling times), with the latter treatment supporting lower densities of 'small' *B. nanum* (Table 7.10 & Fig. 7.13b).

(a) "Medium/large" *B. nanum*



(b) "Small" *B. nanum*

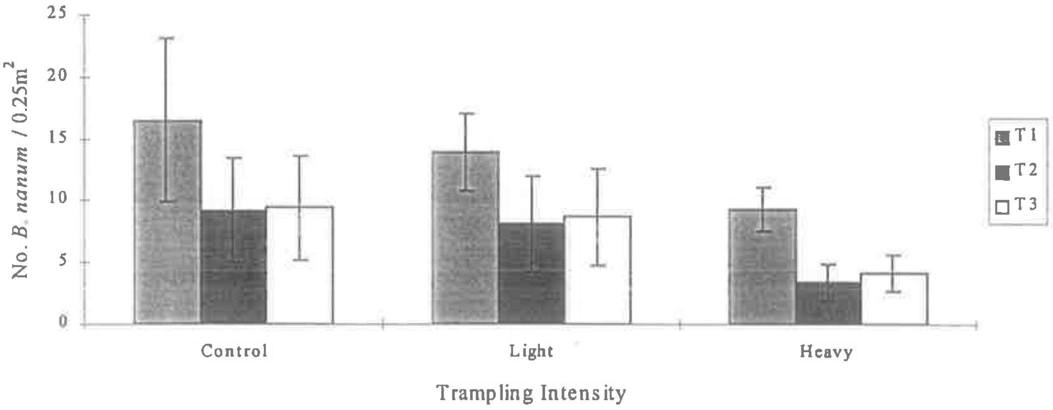


Fig. 7.13 Comparison of the abundance of a) 'medium/large' *B. nanum* and b) 'small' *B. nanum* per $0.25m^2$ in the 'weekend' trampling experiment. The trampling treatments (shown on the *x*-axis) and the sampling times (depicted in the legend) are as described for Fig. 7.12. Abundances were averaged across the six experimental plots (n=6) and are shown on the *y*-axis as the number of animals per $0.25m^2$. Error bars represent the standard error associated with sampling.

Table 7.10 A *Post hoc* multiple comparison following the Friedman's analysis of the average abundance of 'small' *B. nanum* per 0.25m^2 one day after completion of trampling in the 'weekend' trampling experiment. The trampling intensities investigated were; C='control' (0 trampling passages), L='light' (2 trampling passages), H='heavy' (20 trampling passages). The multiple comparison was performed as described by Zar (1984, pp. 230-231) using the rank sums (R_i) for treatments. The standard error (SE) used in the calculations was 2.45, and the differences between rank sums are represented in the table by R_A-R_B (where R_A is the ranked sum calculated for treatment A, and R_B is the ranked sum calculated for treatment B). An unbroken line links treatment groups if no *post hoc* differences could be determined. Note that the probability of a type I error is less than the stated alpha, actually 0.017 (see Bernhardson 1975); in which case the adjusted critical value of q is estimated to be 3.79, which does not alter the outcome of the analysis.

Samples ranked by rank sums	H	L	C
Rank sums (R_i)	7.5	11.5	17.0

Comparison (B *vs* A)	Difference (R_A-R_B)	SE	q	$q_{0.05,10,3}$	*Conclusion*
C *vs* H	9.5	2.45	3.887	3.314	Reject H_0: R_C=R_H
C *vs* L	5.5	2.45	2.24	3.314	Accept H_0: R_C=R_L

7.5.5 The 'School-Holiday' Trampling Experiment

The 'school-holiday' trampling data were analysed and graphed in the same way as the 'weekend' trampling data set but data pertaining to all three sampling times have been included in all analyses and graphs. The sampling times have been abbreviated as; 'B' (before trampling commenced), 'A1' (1 day after trampling was completed) and 'A2' (the recovery phase, two weeks after trampling was completed). The trampling treatments are abbreviated as; 'C' (control, untrampled), 'L' (light, 2 trampling passages) and 'M' (medium, 5 trampling passages).

7.5.5.1 Effects on the Intertidal Assemblage

The dendrogram generated from hierarchical clustering of 'school-holiday' assemblage data could be subdivided into 7 dendrogram groups (Fig. 7.14 & Table 7.11). All dendrogram groups shared greater than 55% taxa similarity apart from group 7 (with only one member) which was 10% less similar (Fig. 7.14). Group 4 contained 23 members and accounted for 50% of all 'BC' and 'BL' plots and 33% of the other 'B' treatment (Table 7.11). The remaining 'B' treatments were found in groups 1, 2 and 5. Dendrogram group 4 accounted for 50% of the 'A1C' plots and 50% or more of all 'A2' treatment plots (Table 7.11). 'A1' treatment plots were generally widely dispersed between dendrogram groups, apart from the 'A1C' plots which were equally divided between groups 2 and 4. However, dendrogram groups 2 and 6 jointly accounted for 66.67% of all 'A1L' plots, while group 2 also contained 50% of all 'A1M' plots (Table 7.11).

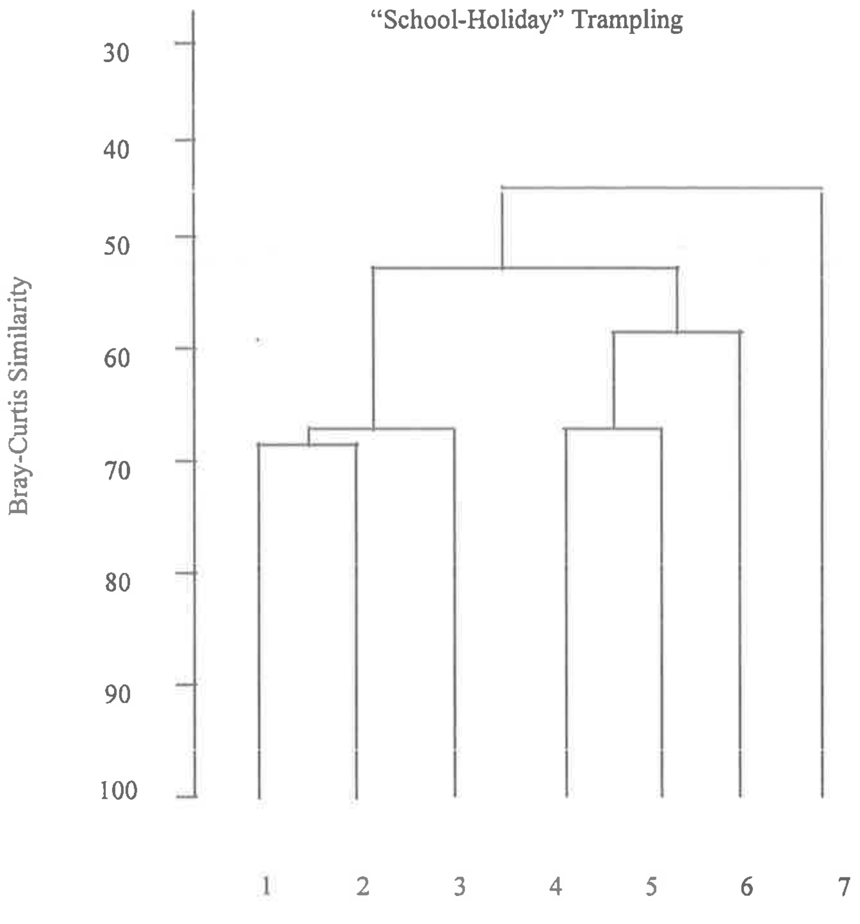


Fig. 7.14 The dendrogram generated from the 'school-holiday' trampling experiment. Bray-Curtis similarities were computed for double square root transformed taxa abundances per $0.75m^2$ for each of 6 plots which had been subjected to three trampling intensities over a two-week period. The trampling intensities used were; 'control' (no trampling), 'light' (2 trampling passages) and 'medium' (5 trampling passages). The plots were censused prior to trampling ('B'), one day after trampling was completed ('A1') and two weeks after trampling had ceased ('A2'). The dendrogram groups are numbered 1-7 and their members can be found in Table 7.11.

Table 7.11 A breakdown of the members of dendrogram groups 1-7 (see Fig. 7.14), identified by hierarchical clustering, in the 'school-holiday' trampling experiment. The dendrogram groups have been classified according to the percentage of the total 'before' (not yet treated) and 'after' (treated) plots they account for, the trampling intensities plots were subjected to, and the three census times. Treatments were: 'C' = control (no trampling), 'L' = light (2 trampling passages), and 'M'= medium (5 trampling passages). Census times were as described for Fig. 7.14, 'B' = before trampling, 'A1' = first sampling time after trampling commenced and 'A2' = second sampling time after trampling commenced.

	Dendrogram Group						
Treatment	**1**	**2**	**3**	**4**	**5**	**6**	**7**
BC	33.33%	00.00%	16.67%	50.00%	00.00%	00.00%	00.00%
BL	33.33%	00.00%	00.00%	50.00%	16.67%	16.67%	00.00%
BM	16.67%	33.33%	00.00%	33.33%	16.67%	00.00%	00.00%
A1C	00.00%	50.00%	00.00%	50.00%	00.00%	00.00%	00.00%
A1L	16.67%	33.33%	00.00%	16.67%	00.00%	33.33%	00.00%
A1M	00.00%	50.00%	16.67%	16.67%	00.00%	16.67%	00.00%
A2C	00.00%	16.67%	00.00%	66.67%	00.00%	00.00%	16.67%
A2L	16.67%	16.67%	00.00%	50.00%	00.00%	16.67%	00.00%
A2M	00.00%	50.00%	00.00%	50.00%	00.00%	00.00%	00.00%
No. in group	7	15	2	23	2	4	1

The SSH MDS Ordination was performed on the raw abundances of taxa which were summed across 'replicates' within plots to generate the taxa abundance per $0.75m^2$ for each of the three sampling times. The stress of the ordination was high (0.18) but a three dimensional ordination did not yield a clearer picture and so the two dimensional ordination was retained and graphed (Fig. 7.15a). When the spread of treatments was examined within the two dimensional ordination it was difficult to determine any definite trends due to wide data scatter within treatments and between sampling times (Fig. 7.15a).

A PCC multiple regression of taxa against ordination scores revealed significant relationships in seven cases (after alpha had been adjusted for the number of multiple regressions). *N. atramentosa, Littorina unifasciata, B. nanum, C. antennatus* and *Notoacmea* spp. all scored significant probability values of less than 0.001, while *A. constricta* and *A. concamerata* scored slightly higher probabilities (Fig. 7.15a). The majority of significant taxa regressions were found in Quadrat 4 of the ordination plot, a trend which also occurred in the 'weekend' trampling ordination (Fig. 7.9). However, more taxa made significant contributions to the placement of treatments within 'school-holiday' ordination space than in the equivalent 'weekend' trampling ordination.

As an adjunct to the multiple regressions of species against ordination scores a Pearson Correlation (with Bonferroni correction) was performed on taxa *versus* axes scores (Table 7.12). Three species (*N. atramentosa, A. constricta* and *B. nanum*) were significantly correlated with Axis 1, no species were correlated with Axis 2, and *N. atramentosa* showed significant positive correlations with the presence of *A. constricta* and *C. antennatus.*

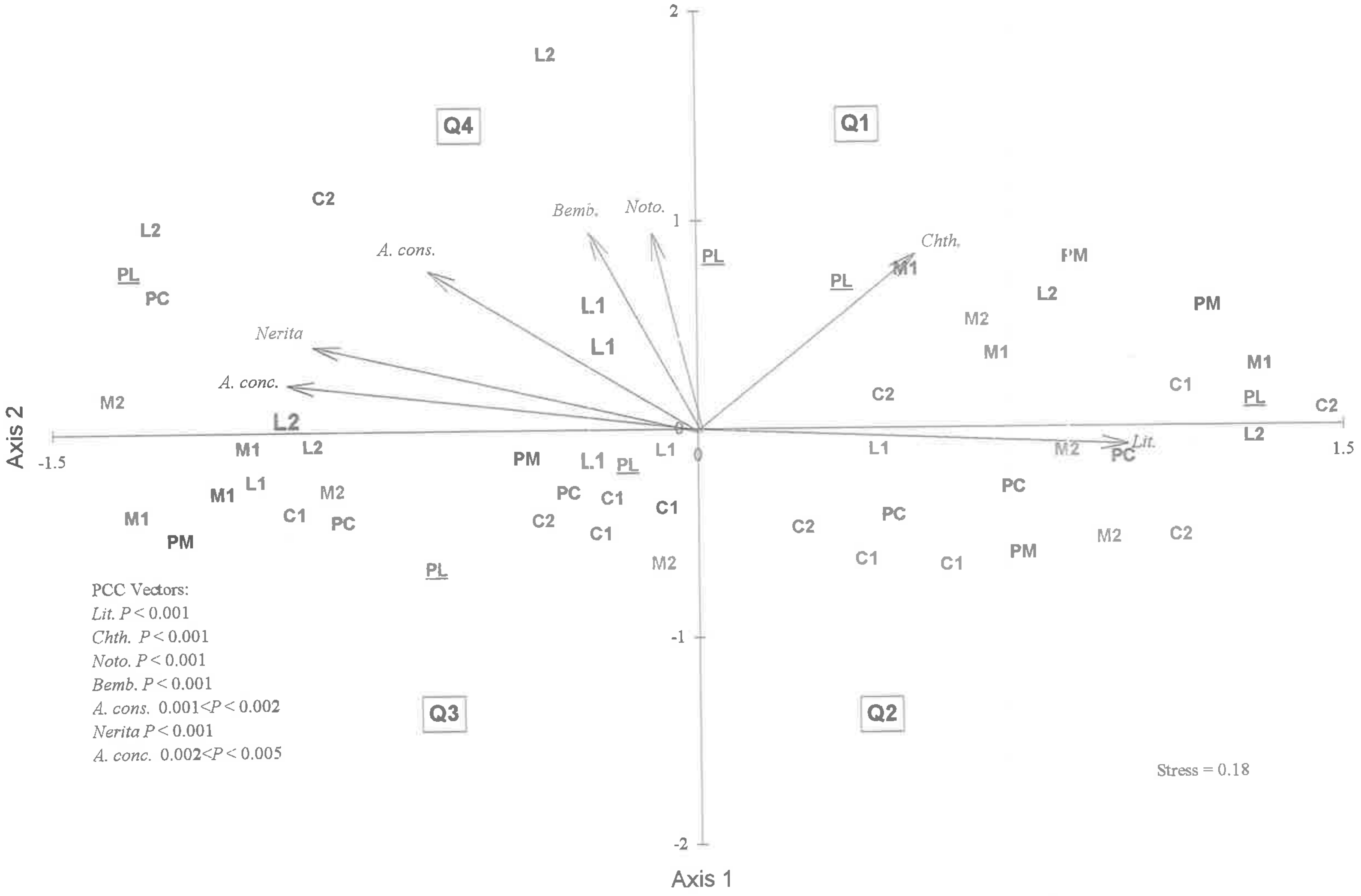
Averaging the ordination positions of the three treatments in an attempt to simplify the ordination picture did not reveal any obvious trends associated with treatments (Fig. 7.15b). All treatments changed during the experiment but clear patterns between treatments and times were not readily apparent. The only similar trajectories of change were found with the 'control' treatment vector (between the pre-impact sampling and the first post-impact sampling) and the 'medium' trampling treatment (between the two post-impact sampling times) (Fig. 7.15b).

The overall conclusion from the MDS ordination was that plots showed a high degree of ordination separation and that the low trampling intensities investigated in the 'school-holiday' trampling experiment did not appear to trigger any treatment driven assemblage based trends.

(next two pages)

Fig. 7.15 SSH MDS Ordination based on double square root transformed taxa abundance per $0.75m^2$ in the 'school-holiday' trampling experiment at Port Stanvac. The stress associated with this two-dimensional ordination was 0.18 (S=0.18). (a) The full ordination plot revealing the spread of data points for each treatment at each of the three sampling times. The plotted area has been divided into four quadrats (Q1-4) defined by the two axes. The taxa which regress significantly with the ordination are; *Nerita (Nerita atramentosa)*, *A. conc.* (*Austrocochlea concamerata)*, *A. cons.* (*Austrocochlea constricta)*, *Lit.* (*Littorina unifasciata)*, *Bemb.* (*Bembicium nanum)*, *Noto.* spp. (*Notoacmea* spp.) and *Chth.* (*Chthamalus antennatus)*. The associated regression probabilities (*P*) are shown on the plot. (b) The average treatment positions for each of the three sampling times were calculated and joined by arrows to indicate the trajectories of change under the three trampling intensities. Trampling occurred once a day over a two week period when access to the six experimental plots was possible. Plots were censused prior to trampling, one day after trampling was completed and two weeks after trampling had ceased. Trampling levels shown in both (a) and (b) are; 'C'=control (no trampling), 'L'=light (2 trampling passages) and 'M'=medium (5 trampling passages). The sampling times have been abbreviated as 'P'=pre-impact, '1'=first post-impact sampling, and '2'=second post-impact sampling.

(a) "School-Holiday" Trampling:
SSH MDS Ordination



PCC Vectors:
Lit. $P < 0.001$
Chth. $P < 0.001$
Noto. $P < 0.001$
Bemb. $P < 0.001$
A. cons. $0.001 < P < 0.002$
Nerita $P < 0.001$
A. conc. $0.002 < P < 0.005$

Stress = 0.18

(b) "School-Holiday" Treatment Change:
SSH MDS Ordination

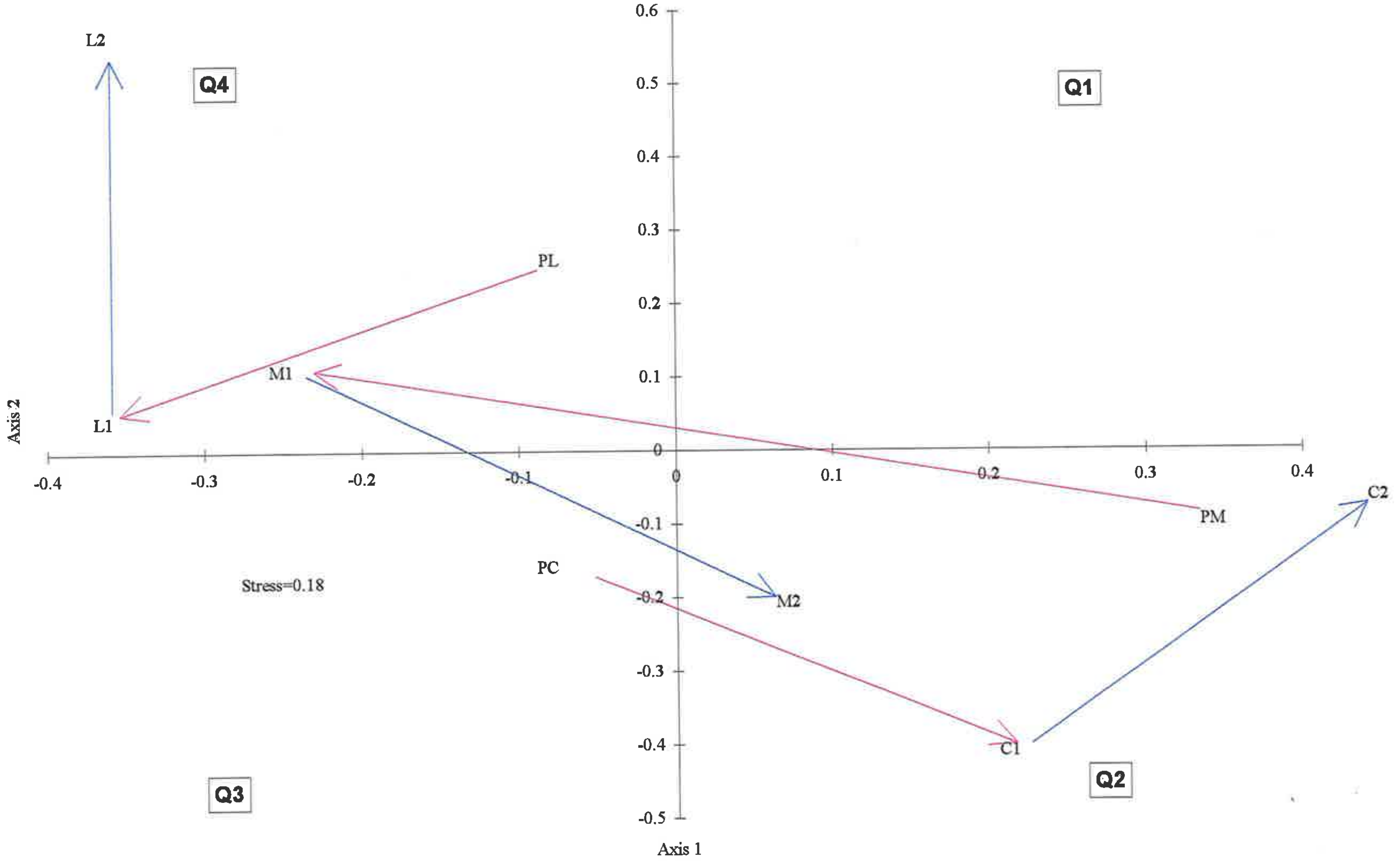


Table 7.12 Pearson matrix of Bonferroni Probabilities; MDS axes *vs* dominant taxa for the 'school-holiday' trampling experiment data set. Bartlett's chi-squared statistic: 206.71, $P = 0.000$. Bold numbers represent significant probabilities at the 0.05 level and negative values indicate a negative correlation. Species abbreviations are: *Nerita*=*Nerita atramentosa*, *A. conc.*=*Austrocochlea concamerata*, *A. cons.*=*Austrocochlea constricta*, *Lit. u.*=*Littorina unifasciata*, *Bemb.*=*Bembicium nanum*, *Cell.*=*Cellana tramoserica*, *Noto.* spp.=*Notoacmea* spp., *Chth.*=*Chthamalus antennatus*.

Variable	Axis 1	Axis 2	*Nerita*	*A. conc.*	*A. cons.*	*Lit. u.*	*Bemb.*	*Cell.*	*Noto.* spp.	*Chth.*
Axis 1	**0.000**									
Axis 2	-1.000	**0.000**								
Nerita	**0.015**	1.000	**0.000**							
A. conc.	1.000	1.000	**0.000**	**0.000**						
A. cons.	**0.014**	-1.000	**0.008**	0.227	**0.000**					
Lit. u.	1.000	-0.244	-1.000	-1.000	-1.000	**0.000**				
Bemb.	**0.000**	-1.000	0.076	1.000	0.280	1.000	**0.000**			
Cell	-1.000	-1.000	-1.000	-1.000	-1.000	1.000	-1.000	**0.000**		
Noto. spp	1.000	1.000	1.000	1.000	1.000	-1.000	0.074	-1.000	**0.000**	
Chth.	1.000	-1.000	**0.042**	0.325	**0.000**	1.000	**0.000**	-1.000	0.414	**0.000**

7.5.5.2 Effects on Summary Statistics

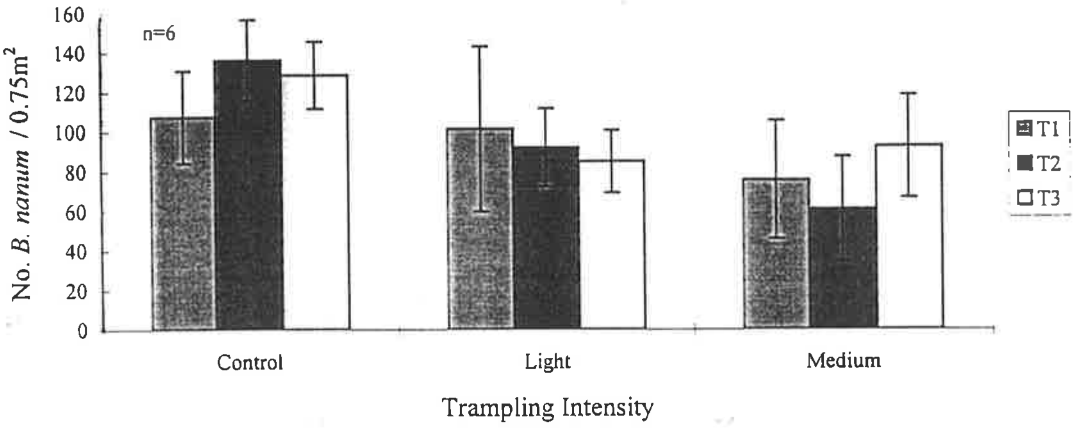
The lack of clear trampling driven patterns in the 'school-holiday' ordination and dendrogram was matched by the lack of treatment related changes in summary statistics. Summary statistics generated from community data (as shown in Fig. 7.11 for the 'weekend' trampling experiment) were not informative and have not been included in this thesis. However, an examination of *B. nanum* abundance under the three trampling intensities was used to test for treatment related trends.

7.5.5.3 Effects on the Abundance of *B. nanum*

The Total Abundance of B. nanum

B. nanum was the most abundant gastropod found in the mid-eulittoral zone at Port Stanvac, showed less variability in its distribution than other common intertidal species and was the only animal suitable for use in a univariate analysis. Consideration of the total abundance of *B. nanum* (combining all three size classes) revealed differences before trampling commenced and trampling did not result in any treatment driven changes (Fig. 7.16). Results were consistent whether the data were summed within treatments prior to averaging across plots (Fig. 7.16a) or were averaged within treatment plots (to generate an abundance per $0.25m^2$) prior to being averaged across plots (Fig. 7.16b).

(a)



(b)

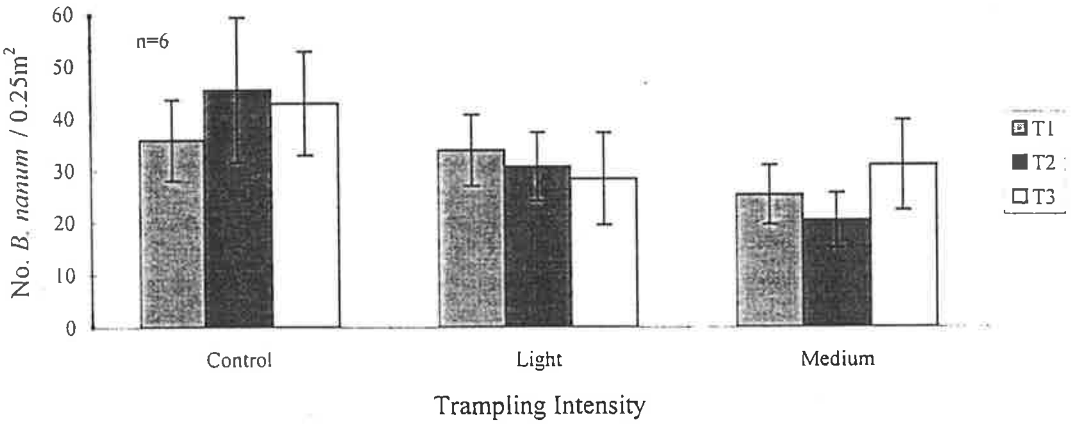


Fig. 7.16 Comparison of the abundance of *B. nanum* per $0.75m^2$ (a) and per $0.25m^2$ (b) in the 'school-holiday' trampling experiment. The trampling treatments investigated are shown on the *x*-axis and are; control (no trampling), light (2 trampling passages) and medium (5 trampling passages). Abundances were averaged across the six experimental plots (n=6) and are shown on the *y*-axis as the number of animals per specified surface area of the shore. The three census times shown in the legend are; pre-impact (T1), one day after trampling was completed (T2) and two weeks after trampling had ceased (T3). Error bars represent the standard error associated with sampling.

Statistical analyses were performed as described for the 'weekend' trampling experiment. A randomised block ANOVA was used to test for treatment effects where data was normally distributed and displayed homogeneous variances, and the Friedman's test was substituted if data violated these assumptions. The pre-impact total abundance data were found to satisfy the basic assumptions of ANOVA and were subjected to a randomised block ANOVA which revealed significant pre-existing differences between plots and between treatments (Table 7.13).

Table 7.13 Randomised Block ANOVA comparing the abundance of *B. nanum*/0.25m^2 prior to commencement of the 'school-holiday' trampling regime. The average abundance of all *B. nanum* (combining size classes) was used as the dependent variable and abundances were averaged across the three quadrats deployed in each treatment plot. Data were normal and homoscedastic and did not require transformation. Significant F-ratios are marked *** if significant at the 0.01 probability (*P*) level and ** if significant at the 0.05 probability level.

Source	Sum-of-squares	df	Mean-Square	F-Ratio	*P*
Plot	3920.751	5	784.150	83.678***	0.000
Treatment	532.130	2	266.065	28.393***	0.000
Error	93.709	10	9.371		

All post-impact data sets violated the assumptions of ANOVA (particularly equal variances between treatment groups), even after a $\log_{10}(x+1)$ transformation. Therefore, Friedman's tests were used to examine data for treatment effects one day after the completion of trampling and again after the two week recovery period. At both these times significant treatment effects were found to exist (Friedman's test statistic=9.33, *P*=0.009 immediately post-impact, and Friedman's test statistic=6.33, *P*=0.042 after the recovery period). The pre-existing treatment effect negated the significance of these results and to adjust for this the differences between the pre-impact and post-impact treatment abundances and the pre-impact and post-recovery treatment abundances were calculated and analysed as previously described. The differences were not normally distributed and a Friedman's test revealed non-significant treatment effects immediately after trampling (Friedman's test statistic=2.58, *P*=0.275) and after the recovery period had elapsed (Friedman's test statistic=4.33, *P*=0.115).

As with the 'weekend' trampling experiment, I was interested in determining the effect of trampling on different sized *B. nanum*. Two size classes ('small' and a combined 'medium-large' class) were considered statistically and graphically (Fig. 7.17). The data violated the underlying assumptions of ANOVA necessitating the use of Friedman's analyses as described for the combined size class data.

The Abundance of 'medium-large' *B. nanum*

The average abundance of 'medium-large' *B. nanum* within treatments did not appear to differ prior to commencement of trampling (Fig. 7.17a). This graphical finding was supported by the results of the Friedman's analysis which returned a non-significant treatment effect (Friedman's test statistic=2.33, *P*=0.311). The abundance of 'medium-large' *B. nanum* was not significantly altered by the trampling intensities investigated (Fig. 7.17a) and non-significant treatment effects were detected post-impact (Friedman's test statistic=3.25, *P*=0.197) and following the recovery period (Friedman's test statistic=2.33, *P*=0.311).

The Abundance of 'small' *B. nanum*

Non-significant treatment differences (Friedman's test statistic=5.33, *P*=0.069) in the average abundance of 'small' *B. nanum* were found prior to commencement of trampling (Fig. 7.17b). Therefore, the statistical results obtained from direct analyses of post-impact and post-recovery 'school-holiday' data could be regarded with confidence. A treatment effect was detected immediately after trampling (Friedman's test statistic=6.33, *P*=0.042) but this was not apparent after the recovery period had elapsed (Friedman's test statistic=5.25, *P*=0.072). A *post hoc* multiple comparison failed to establish a significant treatment effect one day after trampling was completed (Table 7.14).

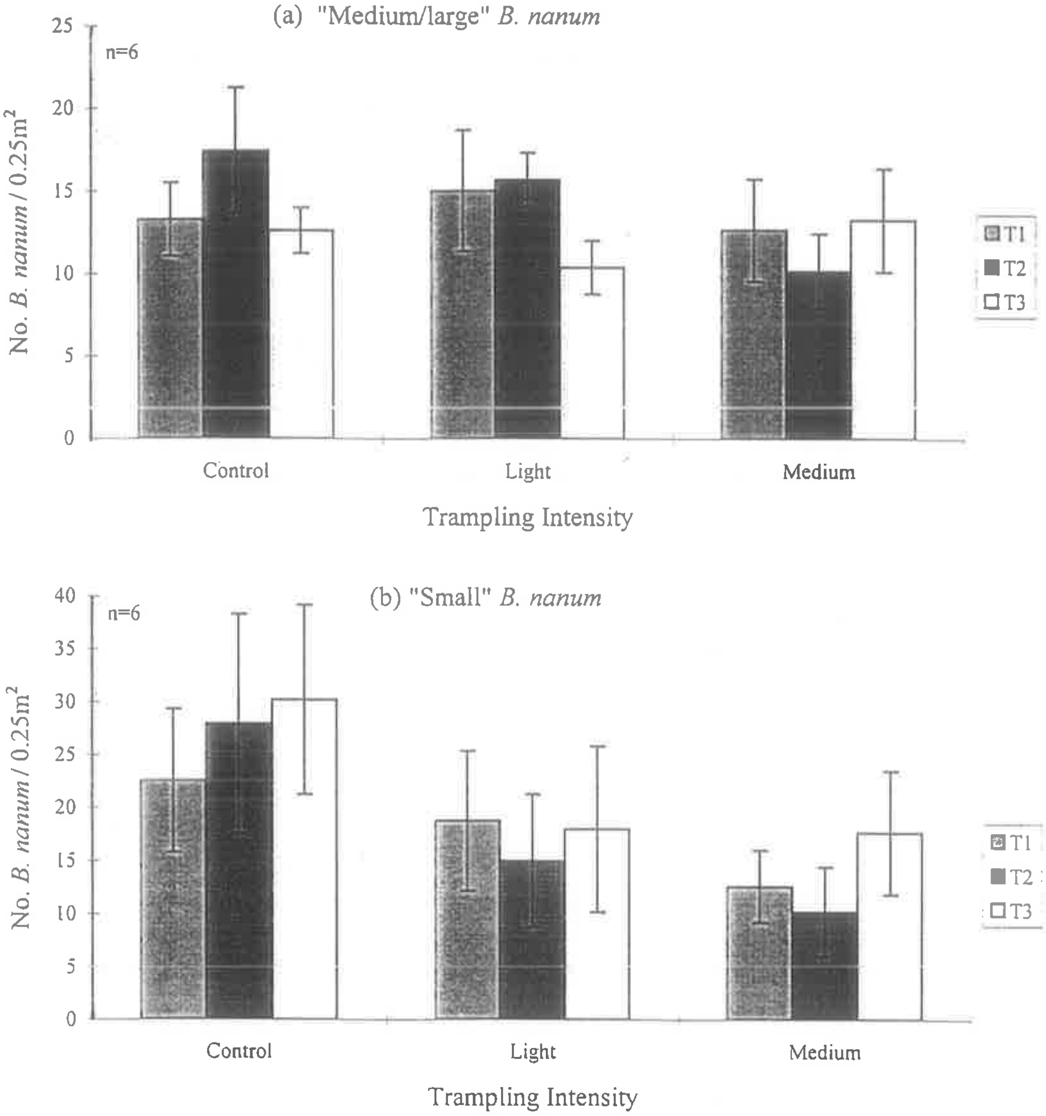


Fig. 7.17 Comparison of the abundance of a) 'medium/large' *B. nanum* and b) 'small' *B. nanum* per $0.25m^2$ in the 'school-holiday' trampling experiment. The trampling treatments (shown on the *x*-axis) and the sampling times (depicted in the legend) are as described for Fig. 7.16. Abundances were averaged across the six experimental plots (n=6) and are shown on the *y*-axis as the number of animals per $0.25m^2$. Error bars represent the standard error associated with sampling.

Table 7.14 A *Post hoc* multiple comparison following the Friedman's analysis of the average abundance of 'small' *B. nanum* one day after completion of trampling in the 'school-holiday' trampling experiment. The trampling intensities investigated were; C='control' (0 trampling passages), L='light' (2 trampling passages), M='medium' (5 trampling passages). The rank sums (R_i) calculated for treatments (ranked from low to high) were used to locate where treatment differences occurred. The multiple comparison was performed as described by Zar (1984, pp. 230-231). The standard error (SE) used in the calculations was 2.45 and the differences between rank sums are represented in the table by R_A- R_B (where R_A is the ranked sum calculated for treatment A and R_B is the ranked sum calculated for treatment B). Treatment groups C, L and M are linked by an unbroken line, meaning that no *post hoc* differences could be determined. Note that the probability of a type I error is less than the stated alpha, actually 0.017 (see Bernhardson 1975), in which case the adjusted critical value of q is estimated to be 3.79.

Samples ranked by rank sums	M	L	C
Rank sums (R_i)	7	14	15

Comparison (B *vs* A)	Difference (R_A- R_B)	SE	q	$q_{0.05,10,3}$	Conclusion
C *vs* M	8.0	2.45	3.27	3.314	Accept H_0: R_C=R_H
C *vs* L	1.0	2.45	0.40	3.314	Accept H_0: R_C=R_L

The univariate results of the 'school-holiday' trampling experiment were consistent with the 'weekend' trampling experiment with 'small' *B. nanum* proving more susceptible to a trampling perturbation than larger animals. The numbers of 'small' *B. nanum* increased for the duration of the experiment in 'C' plots but decreased slightly in 'L' and 'H' plots immediately following completion of trampling (Fig. 7.17b). At the first post-impact sampling time (A1) 'C' plots supported an average increase in 'small' *B. nanum* abundance of about 18% while the abundance declined by 7% under 'light' trampling and by approximately 10% under 'medium' trampling (Fig. 7.17b). However, a *post-hoc* comparison of the trialed intensities of trampling failed to determine where the treatment differences lay. Following the recovery period the decline in *B. nanum* abundance was reversed, with the 'lightly' trampled plots (L) almost reaching their pre-impact level and the 'medium' plots (M) exceeding their average pre-impact numbers of 'small' *B. nanum.* When the 'A1' abundance of 'small' *B. nanum* was used as a baseline the 'A2' numbers represented an average increase of 7% in 'C' plots, 16% in 'L' plots and 60% in 'M' plots (Fig. 7.17b).

7.6 Discussion

7.6.1 Recreational Visitation

Trampling

The low visitation rates observed at GSV sites implied that the intensities of trampling investigated in the 'trampling' experiments were likely to realistically simulate the range of trampling pressure experienced by mid-eulittoral assemblages. Under 'favourable' weather conditions and 'favoured' times of the year (specific to a particular recreational activity) it is possible that large numbers of people may visit a reef (see Underwood and Kennelly 1990, Kingsford *et al.* 1991) and greatly exceed the numbers seen during this study. However, it is unlikely that they would all trample a particular part of the reef. The exception to this would occur if natural 'paths' were followed as a consequence of the topography of an area in order to access a particular point. This could result in heavily trampled tracts within sites otherwise subjected to low or moderate visitation pressure. However, due to the relative homogeneity of substrata within the designated sites it was predicted that the intensity of trampling at any one spot should be considerably less than the sum of people visiting a reef during a day.

The 'light' and 'medium' trampling intensities used experimentally were thought to closely reflect the 'real' trampling pressure at work within the intertidal zone at GSV study sites. The 'heavy' trampling treatment would equate to a very large number of recreational users but was considered the upper extreme of a 'realistic' trampling intensity under favourable conditions in a recreationally attractive section of a popular reef. Hallett Cove and Kingston Park were the most frequently visited study sites (Fig. 7.1) and it is possible that on a weekend (particularly during summer) they could sustain a trampling load equivalent to the 'heavy' trampling pressure investigated in the 'weekend' trampling experiment.

Collection of Intertidal Animals

Underwood (1993b) found that human harvesting of rocky intertidal species resulted in significant population level changes to targeted species and flow-on community effects at high harvesting intensities (refer to Durán *et al.* 1987). A possible population level effect arising as a consequence of collection of intertidal animals is a change in their size distribution. This would have been interesting to examine but was not directly tested during the course of this project. However, some comments on the size distribution of gastropods at study sites in GSV and the observed activity of fossickers can be made.

In 1995 and 1996 fossickers were observed collecting gastropods, mainly *N. atramentosa* and *A. constricta*, from Hallett Cove and Kingston Park. This practice would presumably occur at some of the other study sites and could affect the abundance and size structure of these species. In the 'upper' mid-eulittoral region at Hallett Cove *N. atramentosa* and *A. constricta* were rarely found but if present tended to be very small, while at the Port Stanvac sites (where animal collection was prohibited) *N. atramentosa* and *A. constricta* tended to be larger and more abundant.

This could reflect the opportunity for large animals to become established at Port Stanvac where collection pressure is not a primary structuring force. However, *A. constricta* animals were abundant and large at the Port Noarlunga South and Robinson Point sites which suggests that factors other than animal collection could be operating on their population dynamics. These factors could well be interacting and are likely to include the availability of algae, intra- and inter-specific competition, the degree and extent of exposure of the reef and seasonal criteria (see Underwood 1975a & b, 1978a & b and 1984a, b & c). Port Noarlunga South and Robinson Point were low-lying, sheltered sites with stable substrata. This scenario is likely to enhance the availability of epilithon and increase the ability of these sites to support high herbivore loads. It is also postulated to enable individuals within a species to potentially attain greater sizes than they would achieve under more physically 'stressed' conditions.

7.6.2 The Small-Scale Experiments

Gastropods

The results of the small-scale trampling experiments agreed with the findings of Povey and Keough (1991), namely that a single 'footstep' had very little impact on animals inhabiting 'bare' intertidal rock. *B. nanum* was the only gastropod found to be susceptible to crushing (3%) and it was also observed to be chipped by a 'footstep' in 2.5% of cases. Povey and Keough (1991) reported similarly low levels of crushing (4%) and even lower levels of chipping (1.5%) when *B. nanum* animals were exposed to a single 'footstep'. *N. atramentosa* and *A. constricta* were not physically damaged by a single 'footstep' possibly because they were generally larger and had thicker shells than the majority of *B. nanum* individuals found within the experimental area.

Despite the low levels of damage observed in response to a 'footstep' it is predicted that newly recruited gastropods and species which are small at maturity would be most susceptible to crushing or chipping. However, physical factors such as substrata complexity could affect the levels of damage occurring in response to a 'footstep'. For example, a small animal may find a refuge and physical protection from 'footstep' damage if it inhabits fissured, or in some other way complex, rock.

X. pulex

It was predicted *a priori* that *X. pulex* would be damaged by a single 'footstep' but no obvious damage to beds of this small mussel were observed in the 'footstep' experiment. This could be due to the cushioning effect of retained sand within the mussel beds and the close proximity of individual mussels, two factors that would minimise and spread the trampling force being felt by individual mussels. It is also possible that individual mussels may have sustained damage that was not evident immediately after application of the 'footstep'. However, it is more likely that the structure of the mussel bed (including the proximity of individual mussels and the presence of retained sand) would explain the lack of visible damage. The apparent lack of damage to mussel beds meant it was unlikely that the carnivore *L. vinosa* would be 'attracted' to the 'footstep' quadrats. Therefore, the failure to detect a difference in the abundance of *L. vinosa* in experimental 'control' and 'trampled' areas of mussel beds was not unexpected.

Despite the lack of 'footstep'-driven change to mussel beds it is predicted that ongoing trampling of sufficient frequency, duration and force is likely to adversely affect mussels. This prediction is supported by Brosnan and Crumrine (1994) who reported severe, persistent and long-term degenerative changes in mussel beds in response to prolonged trampling pressure.

The 'Dislodgment' Experiments

Gastropods were observed to be prone to dislodgment (and overturning) when exposed to recreational trampling. The effects of 'overturning' were experimentally investigated and all overturned species were found to be displaced significantly further over one tidal cycle than 'control' animals. However, when the numbers of recovered animals were compared the outcome was dependent on the selected experimental site. At Kingston Park significantly lower recovery rates of all tested species were recorded in 'overturned' treatments, while at Port Stanvac only *B. nanum* matched this trend. This difference was postulated to be due to the substrata composition. I hypothesised that the more complex substrata mix at Port Stanvac would tend to physically prevent 'overturned' animals from being displaced long distances by an incoming tide unlike the flat, architecturally simple bedrock at Kingston Park. This hypothesis was supported by the fact that recovered animals at Kingston Park tended to have travelled further than equivalent animals at Port Stanvac. However, the distances involved were not extreme and may be a sampling artefact or represent slight site-specific variations in gastropod foraging behaviours.

A similar experiment by Povey and Keough (1991) found low gastropod recovery rates but no differences in the percentages of animals recovered in 'overturned' and 'control' treatments. They thought this was due to the rapidity with which overturned animals righted themselves. However, a non-replicated experiment conducted at Port Stanvac found that not all overturned animals rapidly righted themselves. When overturned in shallow water, 40% of *N. atramentosa* and 70% of *A. constricta* were found to have righted themselves less than 20 minutes after being overturned, while these species rarely righted themselves when overturned on dry rock. The same unreplicated experiment revealed that *B. nanum* animals did not right themselves after 30 minutes regardless of whether they were overturned in shallow water or on dry rock. If animals remain overturned until the incoming tide wets them they are more likely to be displaced further than animals which are adherent to the rocks or rapidly right themselves, and they will consequently be more difficult to recover. It should be pointed out that the findings from the 'unreplicated overturning experiment' were not conclusive and may be little more than a sampling artefact.

As reported by Povey and Keough (1991) it was apparent that trampling did not readily dislodge limpets. Therefore, it would have been unrealistic to overturn these animals. Instead, it was decided to directly step on them and again assess any changes over one tidal cycle. Following application of a 'step' and completion of one tidal cycle all *C. tramoserica* animals were found in their 'home' positions. This outcome was consistent with the work of Povey and Keough (1991) and implied that the selected *C. tramoserica* individuals were not affected by being stepped on and that they were probably homing. The animals were not observed for the duration of this experiment and it is possible that the 'footstep' induced them to tightly clamp to the rock and not to forage. However, foraging in another species of limpet (*Patella vulgata*) has been reported to occur most frequently during nocturnal low tides (Santina *et al.* 1994) and the experiment incorporated such a tide. The animals used in this experiment were also relatively large (greater than 2.5cm in diameter) and smaller animals may be more susceptible to 'footstep' damage.

7.6.3 The Trampling Experiments

The results of the trampling experiments performed on 'bare' habitat in the mid-eulittoral zone revealed that, in general, the gastropods that dominated this area were not very sensitive to trampling. Similar results were reported by Povey and Keough (1991) who found that 'bare rock' habitat was less affected by trampling than *Coralline* or *Homosira* algal mats (see also Keough and Quinn 1998). However, the outcomes of trampling depend on the intensity and duration of the perturbation (Underwood 1989), the topography and character of the site and substrata (Povey and

Keough 1991) and the physical character of the species and assemblage which is exposed to the disturbance. It is also possible that the past history of disturbance experienced by a site may influence the effect of a new disturbance (Keough and Quinn 1998).

The 'Weekend' Tramping Experiment

A 'weekend' of high intensity trampling (20 passages per day) resulted in a different direction of change in the intertidal assemblage (on average) than was seen in the 'control' and 'lightly' trampled treatments (Fig. 7.10). A PCC and MCAO multiple regression illustrated that the changes in the 'control' and 'lightly' trampled treatments were significantly linked to the abundance of *B. nanum*, *A. constricta* and *Notoacmea* spp. (Fig. 7.10).

A statistical analysis of the effect of 'weekend' trampling on the abundance of *B. nanum* failed to find any significant treatment effects when size classes were combined but did find a significant result when 'small' animals were considered. 'Small' *B. nanum* were less abundant in the 'heavily' trampled treatment both immediately after trampling and following the recovery period. This effect was suggested by the outcomes of the small-scale experiments, which found low incidences of damage to gastropods that had been exposed to a single 'footstep'. However, as mentioned previously, the 'high' intensity trampling (heavy) used in the 'weekend' trampling experiment was extremely high compared to the observed rate of visitation at all GSV sites (including Kingston Park where this experiment was conducted).

The summary statistics generated from the 'weekend' trampling experiment were interesting, in that all treatments (apart from the 'light' treatment in relation to Pielou's Evenness) showed consistent differences in the number of taxa, species richness, Shannon-Wiener Diversity and Pielou's Evenness between the pre-impact and the immediately post-impact sampling times. This occurred irrespective of treatment and was uninformative in its own right. The failure of summary statistics to detect trends associated with trampling supports the outcomes of a literature review by

Keough and Quinn (1991) who found that population level effects can often more reliably reflect trends occurring under trampling pressure than community measures.

The 'School-Holiday' Trampling Experiment

The 'school-holiday' trampling experiment was carried out at Port Stanvac and the more complex substrata may have provided a refuge for a proportion of the intertidal assemblage. This may also account for the greater variability (resulting in significant 'treatment' effects purely by chance) in 'plots' before treatments were implemented. No clear assemblage patterns were apparent at any of the sampling times and community measures were not helpful in elucidating trampling effects at the intensities (and duration) investigated. Univariate assessment revealed that 'small' *B. nanum* decreased in abundance in response to 'light' and 'medium' level trampling which was maintained for two weeks (on days when tidal access allowed), and that the decrease was comparatively greater in response to a 'medium' trampling pressure. However, when the recovery period had passed no significant effects persisted.

7.6.4 Implications for Ongoing Monitoring

Some of the investigations covered in this chapter have implications to an ongoing monitoring program involving *B. nanum* (the bioindicator of choice for ongoing monitoring (refer to Chapters 4 & 6)). Firstly, the influence of topographic complexity on *B. nanum* abundance has been illustrated or inferred. This means that care should be taken in the ultimate choice of study sites for ongoing monitoring. Perhaps more importantly, the susceptibility of 'small' *B. nanum* to prolonged (two-week), 'medium' intensity trampling, and 'weekend' 'heavy' intensity trampling has been established. This can be accommodated in an ongoing monitoring program focusing on population level changes by monitoring the size distribution as well as the abundance of *B. nanum*.

The 'medium' experimental trampling level is likely to overestimate the trampling associated with ongoing monitoring of study sites. Based on preliminary monitoring, (Chapter 4) ongoing monitoring is expected to involve minimal disturbance and equate to no more than two trampling passages to sections of study sites over a single day. Therefore, ongoing monitoring most closely approximates 'light' 'weekend' trampling which did not result in significant population level treatment effects to *B. nanum*.

The low recreational use of study sites in GSV reduces the possibility of recreation confounding an ongoing monitoring program. Therefore, it is not necessary to adjust the monitoring design to accommodate for changes occurring as a consequence of recreational activities in GSV. The low incidence of overturned *B. nanum* in response to a single 'footstep' is also a favourable outcome when ongoing monitoring is being considered. Overturned gastropods are likely to be transported further over a tidal cycle than non-disturbed gastropods but the risk of significant numbers of animals being overturned during monitoring of study sites or recreational shore use is minimal and is again unlikely to confound the outcomes of monitoring.

The dislodgment reported as a response by some gastropods to oil exposure (Denny *et al.* 1985, Suchanek 1993, Trussell *et al.* 1993) and the results of the 'overturning' experiments, where experimentally 'overturned' animals were transported further than undisturbed control animals, has implications to ongoing monitoring. These findings suggest that population level decreases in gastropod abundance (including *B. nanum*) may occur as a consequence of oil exposure. This enables some expectation of the direction of change in *B. nanum* numbers likely to occur at an impacted site in the acute phase of a 'sufficiently' large oil spill.

Chapter 8. Recommended Ongoing Monitoring Design for Mobil, Port Stanvac

8.1 Introduction

The ultimate aim of this study was to develop a monitoring program to quantify the impact of an operational oil spill from Mobil's Port Stanvac Oil Refinery. In order to achieve this aim it was necessary to work through a number of sequential steps.

These involved:

- gaining familiarity with Gulf St Vincent (GSV), refinery operation, past studies in the region and which disturbances, in particular oil, are likely to affect the area (Chapter 1 & Appendix A),
- gaining familiarity with the intertidal region and the properties of oil and how this pollutant is likely to affect intertidal animals and plants (Chapters 1 & 2; Appendices C & D),
- determining the most appropriate monitoring design within an intertidal context based on the literature (Chapter 2),
- optimising sampling protocols (Chapter 3),
- conducting a 15 month study to investigate spatial and temporal trends in intertidal communities (Chapter 4),
- modelling an oil spill with a view to selection of the most likely 'impact' sites (Chapter 5),
- selection of an appropriate bioindicator organism (Chapter 6) and
- investigating how trampling is likely to affect the study sites and ultimately the monitoring program (Chapter 7).

A breakdown of the project into its 5 broad phases has been given previously (Chapter 1). This chapter attempts to link and summarise the outcomes of the various investigative phases of the project and produce a series of recommendations to Mobil concerning the 'best' monitoring program for their requirements.

In addition to tailoring a monitoring design to suit Mobil's needs, the company required completion of the first sampling run of the recommended monitoring program. Data generated from this initial sampling were used to further refine the monitoring design, with modifications being discussed in this chapter. A final report was presented to Mobil detailed the optimal monitoring design, sampling recommendations and methodology (Appendix V) and a two page summary of the project was also compiled for Mobil (Appendix W).

8.2 Aims

The specific aims of this project were to:

1. Establish the baseline (existing) condition of the intertidal area at Port Stanvac and determine spatial and temporal trends.
2. Select an appropriate bioindicator from the suite of organisms at GSV sites.
3. Design an ongoing monitoring program capable of detecting an oil spill impact and differentiating this from effects associated with confounding factors.

8.3 The Best Monitoring Design for Port Stanvac

A literature review of monitoring designs capable of detecting an environmental impact (Chapter 2) advocated the use of a Beyond-BACI design for preliminary monitoring (Chapter 4) as well as for ongoing monitoring (Underwood 1991a, 1992 & 1993a). This design utilises at least a single 'impact' site and multiple 'control' sites which are sampled many times before and after an impact occurs. The purpose of this design is to detect whether there are changes at the 'impact' site that are greater than would be expected <u>on average</u> at the 'control' sites. Data collected during sampling is then analysed using an Analysis of Variance (ANOVA) to statistically partition variance due to such factors as sampling times, locations, and the 'before *versus* after impact' categories (Chapter 4). The basic Beyond-BACI design and the stages involved in using such a design will be explained in section 8.4.4.

8.4 Preliminary Monitoring of GSV Sites

8.4.1 GSV Background Information

Investigation of literature pertaining to the GSV region revealed the lack of long-term ongoing data for the area (Chapter 1 & Appendix A). The health of the Port Stanvac shoreline and adjacent shores in GSV has not been well documented and very few ecological studies have been conducted in the region (but see Paxinos and Clarke 1996 for an overview).

Womersley (1988) conducted intertidal surveys directly around the Port Stanvac Refinery in 1979, 1980 and part of 1981 and this work is of direct relevance to the project. The Womersley study aimed to establish the abundance and seasonal variation characteristic of dominant biota at different tidal levels and to determine a biological baseline against which future environmental changes could be assessed. The majority of this work occurred at two sites, the boat ramp at Port Stanvac and a rock situated slightly offshore at Curlew Point. The main conclusion was that the Port Stanvac biota was 'richer' than adjacent biota, especially that to the north of the refinery. This was attributed to the deeper water close to the Port Stanvac shore and the private ownership of the refinery but was based on assessment of a limited number of sites. An important finding arising from the Womersley study was the high seasonal fluctuation in animal abundance coupled with extreme variation between years. This resulted in a recommendation for detailed long term surveys (up to 5 years duration) to establish seasonal trends against the high background variability.

The lack of detailed ecological studies in the vicinity of Port Stanvac is surprising as a number of factors (besides an oil spill) potentially impact the region in and around Port Stanvac (Chapter 1 & Appendix A). These include dredging (currently being investigated by the University of Adelaide), the Mitsubishi storm water outfall which gives an intermittent, seasonal discharge of water runoff close to the northern boundary of the refinery, and the E&WS secondary treated sewage discharge from Christies Beach (currently being investigated by M. Loo at the University of Adelaide). Mobil also discharges treated refinery effluent towards its northern boundary and this could potentially affect local biota. In addition, Christies Creek and the Onkaparinga River flow into the coastal waters to the south of Port Stanvac (contributing sediment, freshwater and pollutants), while northward sand drift in winter and spring can impact on the coastline (see Chapter 4). The final factor which may influence the health of the Port Stanvac coastline arises from the private ownership of the area, which partially protects intertidal biota from the trampling and collection pressure in similar, but publicly accessed, areas.

8.4.2 Mobil's Port Stanvac Oil Refinery

The Port Stanvac Oil Refinery receives crude oil for refinement and exports refined oil and other products. One of the potential problems associated with refinery operation is accidental release of oil into the marine environment. Accidental oil spillage can occur from the two mooring points, referred to as the "Deep Ocean Point" and the "Wharf Point", or via the pipeline that feeds into the refinery (Appendix A, Fig. A.3). Two cargoes of 100,000 tonnes and one cargo of 150,000 tonnes of crude oil are imported monthly via the "Deep Ocean Point", while 25,000 tonnes of refined fuel oil is exported from this point twice a week. Wharf operation sees exports of 50,000 tonnes of refined fuel oil and 15,000 tonnes of lube oil per month, while twice a year 35,000 tonnes of light oils and other substances are sent from the refinery. In the event of oil entering the ocean as a result of routine loading and unloading it is likely that it will impact on the rocky intertidal region as it is swept ashore by the action of wave, wind, tides and water currents (both tidal and non-tidal).

Mobil is aware that a potential risk of their operation is release of oil into the marine environment. To this end they want a monitoring program in place which will enable an objective assessment of injury (if any) to the coast following an oil spill and its recovery following such an event. In addition, a suitable monitoring program will allow Mobil to have discussions with the Environmental Protection Authority (EPA) concerning the consequences of an oil spill, mount a defence in response to any charges that may arise, and minimise the cost impact of such charges. On a broader level Mobil want to be environmentally aware of the effects of their activities. An ongoing Beyond-BACI intertidal monitoring program should satisfactorily meet all these objectives.

8.4.3 Phase 1: The Pilot Study

The rocky intertidal region was most likely to be impacted by an operational oil spill (Chapter 1) and presented some sampling advantages over other regions (such as subtidal) (Chapter 2 & Appendix C). Therefore, the pilot study focused on the intertidal region (see Chapter 3). A Beyond-BACI design was advocated *a priori* for preliminary and ongoing monitoring which made it necessary to select a number of spatially separate sites which could serve as 'control' and 'impact' sites. These were chosen from a suite of suitable sites; suitability being based on criteria such as ease of access and similarity in substrata character and species assemblages (Underwood 1989 & 1991b).

The primary aims of phase 1 were to select suitable study sites, become familiar with organisms inhabiting different intertidal zones and to determine the optimal sampling strategies for use in the intertidal region. It must be noted that any study site could serve as an 'impact' site if a perturbation (of any type) intervened during preliminary sampling.

Site Selection

A number of 'rocky' sites extending to the north and south of the Port Stanvac Oil Refinery and equivalent areas within the confines of the refinery were visited during the pilot study phase. Nine sites extending from Kingston Park (to the north of Port Stanvac) to Robinson Point (to the south) were chosen for ongoing monitoring during 1995 and 1996 (Chapter 3, Fig. 3.1). The history of small (past) oil spills and patterns of circulation within GSV allowed prediction of three potential impact sites within the boundaries of Port Stanvac (designated PS1, PS2 & PS3).

Two 'zones' were recognisable within the mid-eulittoral section at study sites and these were designated 'upper' (landward) and 'lower' (seaward). During this phase of the monitoring program all sites and 'zones' of interest were described (Chapter 3) so that they could be relocated when preliminary monitoring commenced (Chapter 4).

Optimal Sampling Protocols

During the pilot study all dominant animals visible to the naked eye (e.g. greater than 2mm in diameter) were identified to species (apart from *Notoacmea* spp.). Plants were classified to genus, apart from some small brown and red algal species and encrusting algae that were given artificial groupings on the basis of their gross morphology. Two field master sheets were compiled on which to enter dominant animals and plants and related physical parameters (Appendices K & J), and a photographic record of animals was also amassed (Appendix L). Plant life was sparse at selected study sites and it was evident that these would make poor bioindicators. Therefore, the search for suitable biological variables centred on intertidal animals.

Since it was not possible to choose a suitable bioindicator *a priori* it was decided during the pilot study phase that all animals and plants visible within quadrats would be censused, with animals being assigned to three broad size categories; 'small', 'medium' and 'large' (see Chapter 3). Intertidal topography was deemed to be amenable to deployment of quadrats rather than requiring transects, so the sampling strategy adopted was random assignment of quadrats at sites. It was decided during this phase of the project that some physical parameters needed to be recorded in conjunction with biota abundance for the duration of the project. These included the presence of oil (subjectively scored on a scale of 0 to 4), substrata composition, substrata elevation, topographic complexity and the percentage of retained water (Chapters 3 & 4). General details for each site including air temperature, water parameters (temperature, pH, conductivity, dissolved oxygen), wave conditions and recreational use of the sites were also assessed. The latter was quantified by the number and activity of people seen on a site over a one-hour period of observation (see Chapter 7).

Sampling strategies requiring investigation were the number and size of quadrats to be used and the method of animal census. Trials were carried out at a limited number of sites. These established that deployment of the smaller quadrat ($0.25m^2$) seven times within each 'zone' gave a satisfactory sampling precision and species capture, and that *in situ* census was more accurate than either video or photographic assessment of animals (Chapter 3).

8.4.4 Phase 2: The Preliminary Study

In an attempt to investigate spatial and temporal trends at selected study sites it was necessary for ongoing intertidal assessment. This preliminary assessment involved monitoring nine sites (selected during the pilot study) for a period of about 15 months. The monitoring methods used for preliminary monitoring were judged (during phase 1 of this project) to be time effective and achieve a satisfactory level of sampling precision (see Chapter 3).

A Beyond-BACI design was used to ensure that if an oil spill or some other perturbation occurred during preliminary monitoring its effects could be statistically investigated. This design uses a univariate approach but as a suitable bioindicator was not identified *a priori* and since community patterns within and between sites were of interest, assemblage census was the focus of preliminary monitoring. *Bembicium nanum* was chosen as the biological variable of interest for those perturbations that were investigated with Beyond-BACI analyses during the preliminary study.

Preliminary monitoring involved using two specific time scales; ‘Periods’ which were two to three months apart, within which ‘Times’, two to three weeks apart, were nested. ‘Periods’ and ‘Times’ were ultimately nested in ‘Before/After’ (Table 8.1). Examining change over these temporal scales is useful as it allows a determination of short-term as well as more persistent longer-term change at an impact site following a perturbation. Within each of the temporal scales sampling times were randomly chosen from the days when tidal conditions allowed site access. All sites at each time were sampled as close as possible to the same day (actually ranging from 1-3 days) during low tide. Sampling continued according to this regime for 15 months but when a disturbance occurred the post-impact sampling commenced immediately and continued at the same intervals as the pre-impact sampling.

Table 8.1 The sampling schedule used for preliminary monitoring of selected study sites. In this instance two sampling periods were completed before the 'sand perturbation' intervened. 'Periods' are 2 to 3 months apart and 'Times' are 2 to 3 weeks apart.

Before Impact				**After Impact**			
Period 1		Period 2		Period 3		Period 4	
Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2

Three main perturbations intervened during preliminary sampling; northward sand drift, a ruptured effluent pipe at Port Stanvac (which discharged its contents intertidally), and an oil spill. In addition, storm mobilisation of substrata differentially and intermittently affected study sites (Chapter 4). A broad overview of the effects of these disturbances and comments on spatial and temporal trends across study sites will be given in this section. In addition, a description of a Beyond-BACI design and a worked example of its use will be presented using data pertaining to the northward sand drift.

8.4.4.1 A Beyond-BACI Design

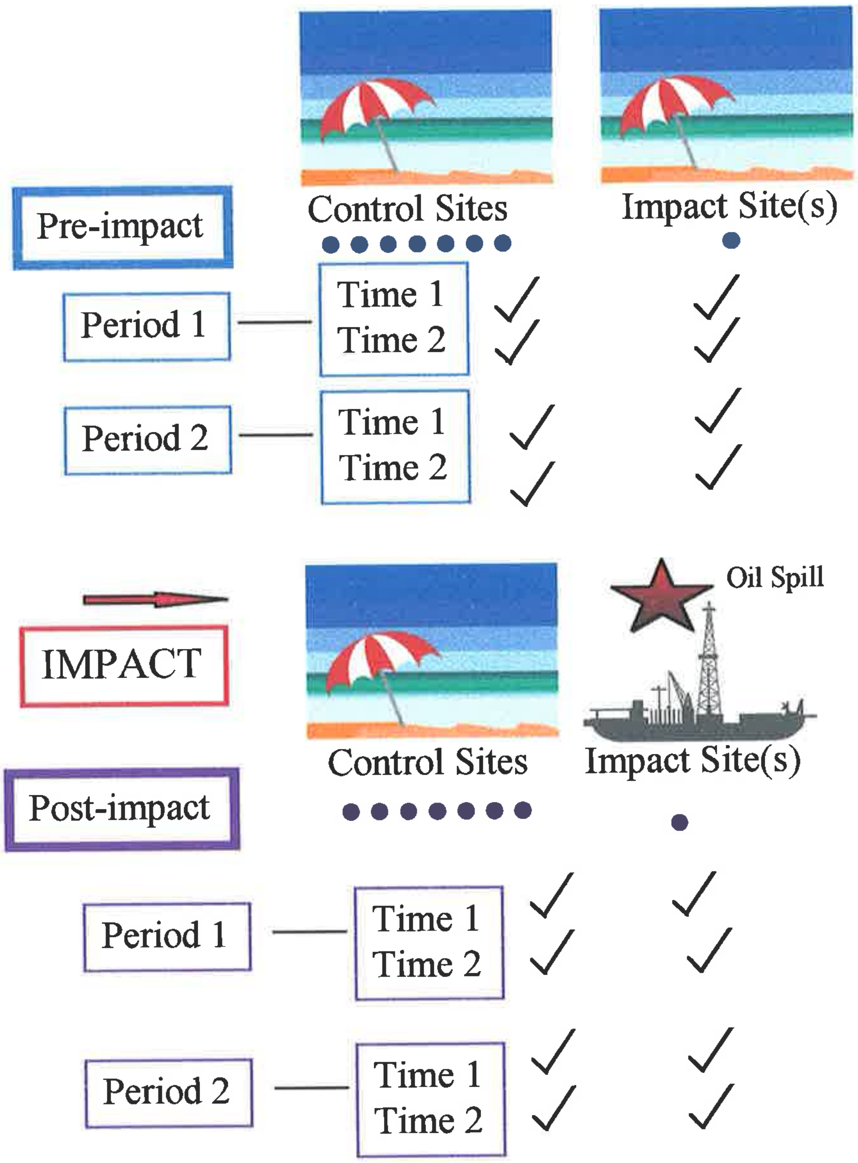
A Beyond-BACI monitoring design involves the use of multiple control sites that can be compared to one or more impact sites over time (as a temporal sampling series). All sites are monitored for some time before and after an impact occurs. Although biological variables are expected to fluctuate at all sites over time, an impact is expected to cause a temporal change in the disturbed location that will be different from the average change occurring in the unimpacted control locations. The analysis used in such a design involves a series of statistical tests to determine whether an unusual pattern of temporal change is specific to the impact site(s) and coincident with the onset of the disturbance (Underwood 1993a). The stages involved in using a Beyond-BACI design and analysis are shown in Fig. 8.1.

(next two pages)

Fig. 8.1 The stages involved in using a Beyond-BACI design to monitor for an oil spill perturbation using the abundance of *B. nanum* as the univariate measure of interest. The sampling schedule (1) involves comparing an 'impact' site with a number of 'control' sites and the processing and handling of data (2) is fully described in Chapter 4 and the following section.

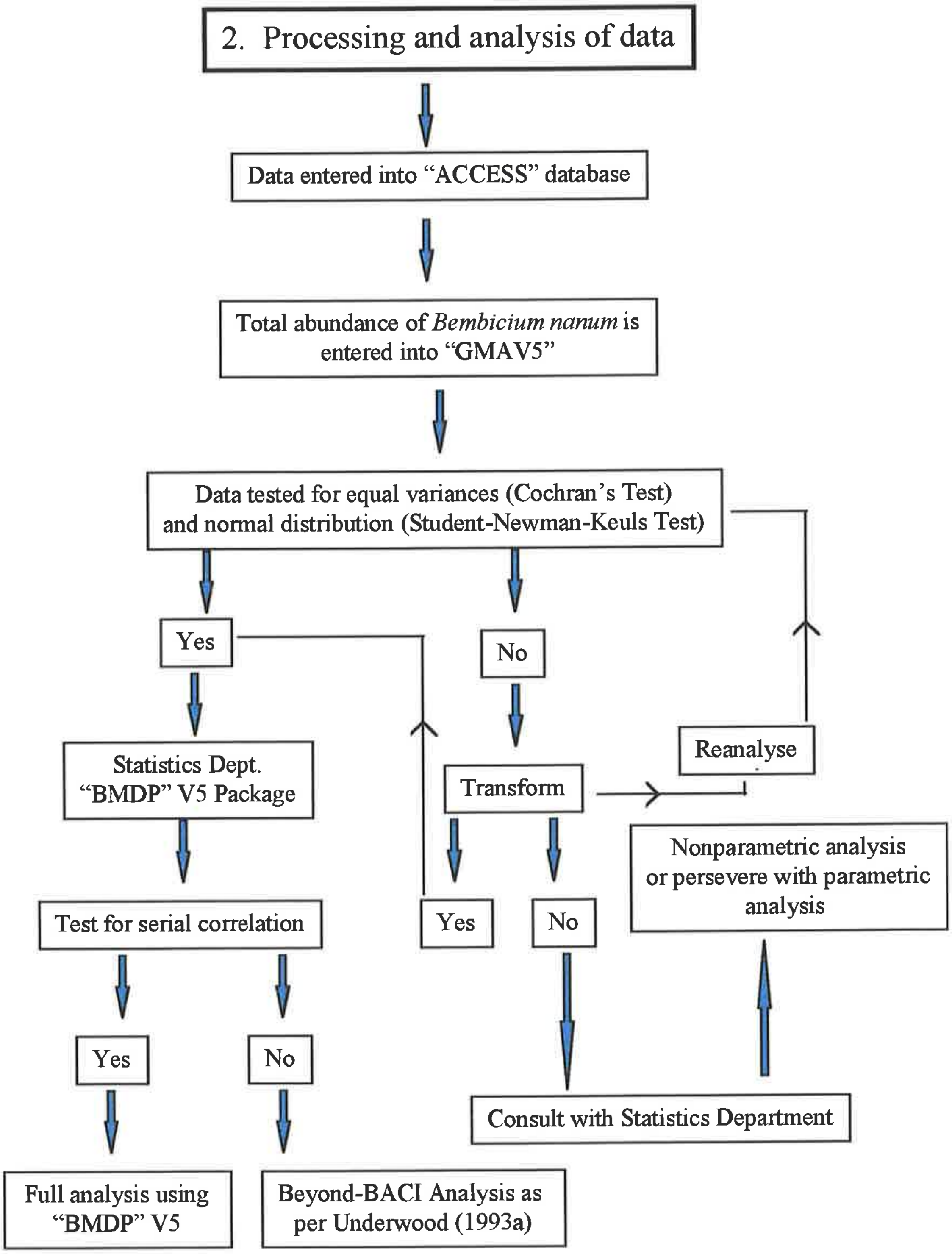
The stages involved in monitoring for an oil-spill impact

1. Sampling Schedule



✓ = abundance counts of *Bembicium nanum* using 7 x $0.25m^2$ quadrats.

The stages involved in monitoring for an oil-spill impact



8.4.4.2 Beyond-BACI Analysis of the 'Sand' Perturbation: A Worked Example

In June 1995 northward sand drift heavily cloaked the Hallett Cove site (HCA) but did not appear to noticeably perturb the other study sites. The main change coincident with the sand drift was a population crash of *B. nanum* at the 'affected' site while numbers continued to fluctuate over a wide range in the remaining sites. A comparison of the substrata composition at control sites and the Hallett Cove site during this time clearly revealed an increase in sand at the impacted site of more than 95% immediately post-impact (P3T1) and only slightly increased sand loads (on average) in the set of control sites (Fig. 8.2).

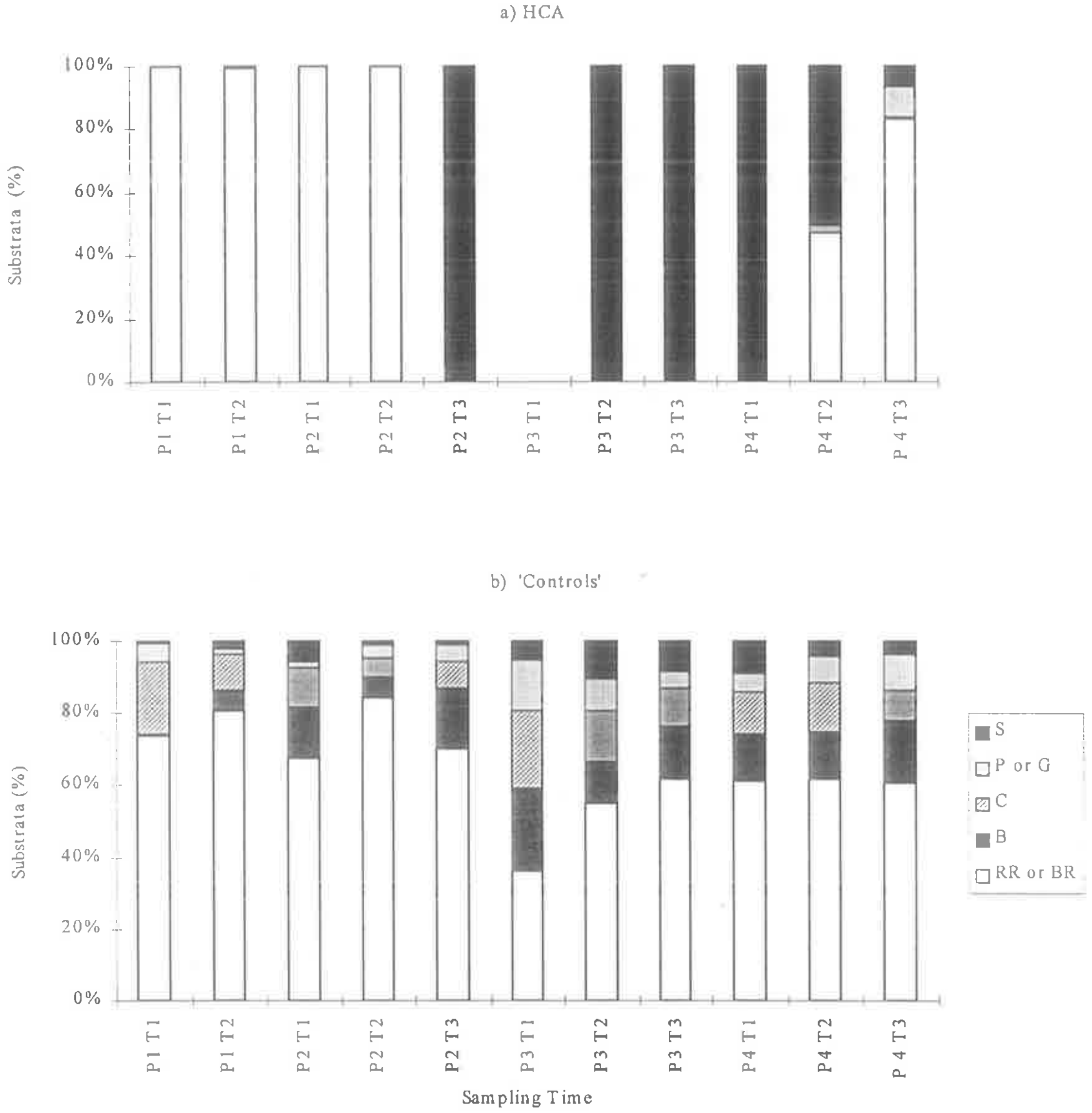


Fig. 8.2 Comparison of substrata composition between the sand affected HCA site (a) and the set of Beyond-BACI control sites (b) during 1995. The graphed substrata composition shown in (b) represents average changes in substrata occurring in the set of controls but the resultant standard error has been omitted. Sampling times are shown on the *x*-axis and have been categorised according to the sampling 'Period' (P) and 'Time' (T) e.g. P3T1 is the first post-impact sampling time. Substrata types are shown in the legend; RR or BR= bedrock or reef-rock, B= boulder, C= cobble, P or G= pebble or gravel, S= sand. The percentage contribution of the recognised substrata grades at sites are plotted on the *y*-axis.

Despite the early intervention of the 'sand perturbation' it was possible to test the significance of alterations in *B. nanum* abundance using a Beyond-BACI analysis and two pre-impact and two post-impact 'Periods'. To conduct this analysis Hallett Cove (HCA) served as an 'impact' site and five other sites, which were consistently able to be accessed, (namely Marino Rocks, Kingston Park, PS1, PS2 and PS3) were used as the Beyond-BACI 'controls'. The general design used for the Beyond-BACI 'sand perturbation' and the main factors involved are shown in Table 8.2.

Table 8.2 The general design and main factors and levels used in the Beyond-BACI Design for the 'sand perturbation' analysis. Refer also to Table 8.1 for the time intervals associated with the temporal scales of 'Periods' and 'Times'. 'Before' refers to pre-impact data and 'After' refers to post-impact data.

Factor	General Design	'Sand-Impact' Number of levels
1	**Before vs After (B)** orthogonal and fixed	2
2	**Periods (P)** nested in B, random	2
3	**Times (T)** nested in B and P, random	2
4	**Locations (L)** orthogonal and fixed	6

Data generated from the two pre-impact and two post-impact sampling periods were entered into the "GMAV5" Program produced by Underwood (see Appendix N). "GMAV5" is a five factor analysis of variance program capable of dealing with complex models comprised of orthogonal or nested, fixed or random factors. It also tests heterogeneity of variances using Cochran's test and compares means using Student-Newman-Keuls tests.

The Beyond-BACI analysis proceeded as described by Underwood (1993a). To calculate the appropriate ANOVA terms four separate analyses are performed (see Table 8.3). The data are first analysed with all the locations considered as a set with no division of control and impact sites (Analysis a). Data are then reanalysed without the 'impact' site (Analysis b). Next, in order to manage the nested factor of 'Times' within 'Before/After', only the data from 'Before' are analysed (Analysis c). The final analysis uses the 'Before' data, but this time the 'impact' site is omitted (Analysis d). From these four analyses the final variances can be obtained using subtractions and additions of the variance components generated (Table 8.3) as described in Underwood (1993a) and shown in Table 8.4.

The final variances obtained are then subjected to statistical tests (Table 8.5) to see if there are significant differences between the impact and control sites at the temporal scales of interest and if these differences are coincident with the impact in question (as described fully in Underwood 1993a).

Table 8.3 The method involved in calculation of variance values in an asymmetrical Beyond-BACI design to tease out the relative contributions of the factors of interest following an impact. Four separate analyses are performed; a) incorporating all data, b) control data only, c) before data only and d) the control, before data. 'Periods' and 'Times' of sampling are as shown in Table 8.1, 'Locations' refer to study sites and 'Before' and 'After' categories refer to pre-impact and post-impact data respectively. Bracketed letters in the 'Source of Variation' column indicate a nested factor. SS=sum of squares, df=degrees of freedom (After Underwood 1993a).

Analysis **Source of Variation**	**a** **(all data)** SS & df	**b** **(controls)** SS & df	**c** **(before)** SS & df	**d** **(before controls)** SS & df
Before *vs* After = B			-	-
Periods = P(B)				
Times = T(P*B)				
Locations = L	a1	b1		
B x L	a2	b2	-	-
P(B) x L	a3	b3	c1	d1
T(P*B) x L	a4	b4	c2	d2
Residual				
Residual	a			
Total				

Table 8.4 The method by which final variances are calculated for a Beyond-BACI design following an impact. Final values are calculated using preliminary analyses shown in Table 8.3 (After Underwood 1993a). SS=sum of squares, df=degrees of freedom. See Table 8.3 and text for further details.

Source of variation	SS	df	MS	Calculated from
Before *vs* After = B				a
Periods (P) = P(B)				a
Times (B) = T(B)				a
Locations = L				a1
Impact *vs* Controls = I				a1-b1
Among Controls = C				b1
B x L				a2
B x I				a2-b2
B x C				b2
P(B) x L				a3
P(Bef) x L				c1
P(Bef) x I				c1-d1
P(Bef) x C				d1
P(Aft) x L				a3-c1
P(aft) x I				a3-c1-b3+d1
P(Aft) x C				b3-d1
T(B*P) x L				a4
T(Bef) x L				c2
T(Bef) x I				c2-d2
T(Bef) x C				d2
T(Aft) x L				a4-c2
T(Aft) x I				a4-c2-b4+d2
T(Aft) x C				b4-d2
Residual				a
Total				a

Table 8.5 The sequence of statistical tests used in a Beyond-BACI analysis to test for significant environmental impacts at a range of temporal scales. Final variance values (Table 8.4) are used as the basis of these tests (After Underwood 1993a).

1. Test for interaction among times (T) of sampling that differ between Impacted vs Control locations.

1a	No short term interaction among controls; T(aft)xC/Res is not significant, T(aft)xC is eliminated, go to 1b1. Short-term temporal interaction among controls; T(aft)xC/Res is significant, go to 1b2.
1b	**1**. T(aft)xI/Res not significant: no short-term interaction, go to 2. T(aft)xI/Res significant: go to 1c. **2**. T(aft)xI/T(aft)xC not significant: no short-term interaction: NO IMPACT DETECTED; END. T(aft)xI/T(aft)xC significant: go to 1c.
1c.	Two-tailed tests: T(Aft)xI/T(Bef)xC is significant and T(Aft)xC/T(Bef)xC is not. Therefore effect is specific to impact site and coincident with start of perturbation. IMPACT DETECTED. Two-tailed tests: either T(Aft)xI/T(Bef)xC is not significant or T(Aft)xC/T(Bef)xC is significant. Effect non-specific. NO IMPACT DETECTED; END.

2. Test for interaction among periods (P) of sampling that differ between Impacted vs Control locations.

2a	No medium-term temporal interaction among controls: P(aft)xC/Res is not significant, P(aft)xC is eliminated go to 2b1. Medium-term temporal interaction among controls; P(aft)xC/Res is significant, go to 2b2.
2b	**1**. P(aft)xI/Res not significant: no medium-term interaction, go to 3. P(aft)xI/Res significant: go to 2c.
2b	**2**. P(aft)xI/P(aft)xC not significant: no medium-term interaction: NO IMPACT DETECTED; END. P(aft)xI/P(aft)xC significant: go to 2c.
2c	Two-tailed tests: P(Aft)xI/P(Bef)xC is significant and P(Aft)xC/ P(Bef)xC is not. Therefore effect is specific to impact site and coincident with start of perturbation. IMPACT DETECTED. Two-tailed tests: either P(Aft)xI/P(Bef)xC is not significant or P(Aft)xC/P(Bef)xC is significant. Effect non-specific. NO IMPACT DETECTED; END.

3. Test for longer-term interactions that differ between Impacted vs Control locations.

3a	No Before/After interaction that differs between I and C locations; BxC/Res not significant and is eliminated, go to 3a1. Before/After interaction among controls; BxC/Res is significant, go to 3a2.
3a	**1**. BxI/Res is significant: IMPACT DETECTED. BxI/Res is not significant: NO IMPACT DETECTED.
3a	**2**. BxI/BxC is significant: IMPACT DETECTED. BxI/BxC is not significant: NO IMPACT DETECTED.

The 'Sand' Impact Analysis

The Beyond-BACI analysis of the 'sand' perturbation used a subset of the data obtained during preliminary monitoring (shown in Appendix V). Two sampling 'Periods' were completed before the perturbation intervened and the next two 'Periods' after this event were used as post-impact data. Two sampling 'Times' were nested in each of the 'Periods' (see Tables 8.1 & 8.2 for the sampling design and the temporal scales involved in the analysis). A preliminary data analysis was performed using "GMAV5" (Appendix N). This revealed that variances were heterogeneous even after a number of transformations were tried (Cochran's C= 0.0991 $P<0.05$). In general the data were normally distributed (tested using the Anderson-Darling statistic and the Student-Newman-Keuls test). However, all groupings were not normally distributed even after transformation. Despite the fact that two assumptions of ANOVA were violated the analysis was undertaken using $\log_{10}(x+1)$ transformed data as sample sizes were equal, and extreme heterogeneity of variances were not displayed. Data were initially entered into "Microsoft, Excel" and then saved as a *.csv (comma-separated-value) file for input into "GMAV5". The analyses were conducted as described by Underwood (1993a) using Tables 8.3 and 8.4 and "GMAV5". The raw results of the initial set of four analyses (Table 8.6) were then used to generate the final ANOVA table (Table 8.7).

Table 8.6 Calculation of analyses of impact in an asymmetrical Beyond-BACI design using the 'sand' perturbation data set (After Underwood 1993a). SS=sum of squares, df=degrees of freedom.

Analysis	**a**		**b**		**c**		**d**	
	(all data)		**(controls)**		**(before)**		**(before controls)**	
Source of Variation	SS	df	SS	df	SS	df	SS	df
Before *vs* After = B	40.53	1	0.73	1	-	-	-	-
Periods = P(B)	7.41	2	7.10	2	6.91	1	7.09	1
Times = T(P*B)	4.01	4	3.96	4	2.03	2	2.76	2
Locations = L	166.30	5	153.71	4	62.65	3	25.76	4
B x L	178.76	5	31.44	4	-	-	-	-
P(B) x L	16.87	10	14.23	8	11.00	5	10.58	4
T(P*B) x L	36.88	20	20.78	16	14.12	10	10.64	8
Residual	97.14	288	73.24	240	44.41	144	37.45	120
Total	547.89	335	305.18	279	141.11	167	94.28	139

Table 8.7 Calculation of final variances in a Beyond-BACI design following the 'sand perturbation' at Hallett Cove. Final values were calculated using preliminary analyses shown in Table 8.6. The details shown in the final column of the table are clarified by reference to Table 8.4 (After Underwood 1993a). SS= sum of squares, df= degrees of freedom.

Source of variation	**SS**	**df**	**MS**	**Calculated from**
Before *vs* After = B	40.53	1	40.53	a
Periods (P) = P(B)	7.41	2	3.71	a
Times (B) = T(B)	4.01	4	1.00	a
Locations = L	166.30	5	33.26	a1
Impact *vs* Controls = I	12.59	1	12.59	a1-b1
Among Controls = C	153.71	4	38.43	b1
B x L	178.76	5	35.75	a2
B x I	147.32	1	147.32	a2-b2
B x C	31.44	4	7.86	b2
P(B) x L	16.87	10	1.69	a3
P(Bef) x L	11.00	5	2.20	c1
P(Bef) x I	0.42	1	0.42	c1-d1
P(Bef) x C	10.58	4	2.65	d1
P(Aft) x L	5.88	5	1.18	a3-c1
P(aft) x I	2.23	1	2.23	a3-c1-b3+d1
P(Aft) x C	3.65	4	0.91	b3-d1
T(B*P) x L	36.88	20	1.84	a4
T(Bef) x L	14.11	10	1.41	c2
T(Bef) x I	3.47	2	1.74	c2-d2
T(Bef) x C	10.64	8	1.33	d2
T(Aft) x L	22.77	10	2.28	a4-c2
T(Aft) x I	12.63	2	6.32	a4-c2-b4+d2
T(Aft) x C	10.14	8	1.27	b4-d2
Residual	97.14	288	0.34	a
Total	547.89	335		a

The variances in Table 8.7 were then used to calculate the significance of the treatments of interest as described in Underwood (1993a) and shown in Table 8.5. The results are shown below;

1. *Test for an interaction among 'Times' that differs between impact and control locations:*

T(Aft) x C / Res = 3.76, $F_{crit(1)0.05,8,288}$ = 1.97 ($P<0.005$). Significant short term temporal interaction between controls.

T(Aft) x I / T(Aft) x C = 4.98, $F_{crit(1)0.05,2,8}$ = 4.46 ($0.025<P<0.05$). Significant short term interaction.

T(Aft) x I / T(Bef) x I = 3.64, $F_{crit(2)0.05,2,2}$ = 39, ($0.20<P<0.50$). Non-significant effect, not specific to the 'impact' location. No impact detected at the temporal scale of 'Times'.

2. *Test for an interaction among 'Periods' that differs between impact and control locations:*

P(Aft) x C / Res = 2.70, $F_{crit(1)0.05,4,288}$ = 2.40 ($0.025<P<0.05$). Significant medium-term temporal interaction among control sites.

P(Aft) x I / P(Aft) x C = 2.44, $F_{crit(1)0.05,1,4}$ = 7.71 ($0.10<P<0.25$). Non-significant difference. No medium-term impact detected at the temporal scale of 'Periods'.

3. *Test for a longer term interaction that differs in control and impact locations:*

B x C / Res = 23.30, $F_{crit(1)0.05,4,288}$ = 2.40 ($P<<<0.0005$). Significant 'Before/After' interaction among controls.

B x I / B x C = 18.74, $F_{crit(1)0.05,1,4}$ = 7.71 ($0.025<P< 0.01$). Significant effect detected, indicating detection of a 'sand-impact' at the temporal scale of 'Before/After'. Impact detected at the temporal scale of 'Before/After'.

The Beyond-BACI analysis failed to detect an impact at the temporal scale of 'Times' or 'Periods' but did reveal an effect at the longer temporal scale of 'Before/After'. In order to consider the importance of the failure to detect an impact at the shorter temporal scales it was necessary to determine the confidence, or predictive power of the analyses. Therefore, a power analysis was performed as described in Underwood (1993a) using the formula;

$F_{crit} / (1+n\varnothing)$;
where $1+n\varnothing$ = MS T(Aft) x I / MS Res (or MS P(Aft) x I / MS Res) and F_{crit} is the critical value of the F distribution.

An F distribution table (Zar 1984) was then used to convert the value obtained using this formula to 'Power'. For further discussion of the theory behind the calculation of power refer to Underwood (1993a). Calculations are shown below;

The power of the analysis to detect an impact at the temporal scale of 'Times';

$F_{crit(1)0.05,2,288}$ / (T(Aft) x I / Res) = 3.03/18.73 = 0.16, $Fdist_{(0.16,2,288)}$ = P = 0.85.

The power of the analysis to detect an impact at the temporal scale of 'Periods';

$F_{crit(1)0.05,1,288}$ / (P(Aft) x I / Res) = 3.87/6.61 = 0.59, $Fdist_{(0.59,1,288)}$ = P = 0.44.

The power analysis revealed that the probability of the ANOVA detecting an impact at the temporal scale of 'Times' was 0.85 but the equivalent test at the temporal scale of 'Periods' yielded a very low power of 0.44. The low power in the latter case was primarily a result of the early intervention of the 'sand' perturbation but the instability of some of the control sites would also have been a contributing factor. The less stable control sites were differentially subjected to boulder and cobble mobilisation under storm conditions, a situation which was coincident with the sand influx (see Fig. 8.2 & Chapter 4). The lower than desired power to detect an impact at the temporal scale of 'Times' would also be due in part to the instability of some of the 'control' sites as well as the early intervention of the perturbation. To have any confidence in the statistical results at the temporal scales of

'Times' and 'Periods' against the high degree of inherent variability characteristic of the study sites (see Chapter 4) a longer term data set than the one analysed would be needed (especially in the consideration of 'Periods').

Serial correlation

The data used for the Beyond-BACI analysis involving the 'sand' perturbation were potentially serially correlated, meaning that samples were not independent over time. To further explore this problem the data were taken to Phil Leppard at the Statistics Department, University of Adelaide, and independently analysed. The analysis was performed using an unbalanced repeated measures model with structured covariance matrices in the "BMDP Statistical Software V5 Package" (1990). Results were generated as a within subject correlation matrix. This analysis revealed that serial correlation was only present at low levels (1%), suggesting that the results obtained using "GMAV5" and Underwood's Beyond-BACI analysis were informative (see Fig. 8.1).

8.4.4.3 Beyond-BACI and the Ruptured Effluent Pipe

The rupture of the effluent pipe at Port Stanvac occurred on the 29th of August 1995. Although the pipe continued to discharge its contents intertidally after this time (see Chapter 4) it appeared that the new site at Port Stanvac (PS1A) was primarily affected during the first few days of this episode. The discharged water had no chemically detectable hydrocarbons but emitted an odour of hydrocarbons, had an oily sheen, was heated (with temperatures 15^0C above ambient water temperature), less saline (with a conductivity reading 32 to 42mS lower than adjacent water) and showed fluctuating pH levels (initially being more acidic than the 'controls').

The effect of the ruptured effluent pipe was analysed as described in the worked example involving the 'sand' perturbation but the factor 'Times' involved three levels which were two to three weeks apart rather than the two levels involved in the former analysis. It was assumed that the 'effluent-impact' site (PS1A) supported the same densities of *B. nanum* as the adjacent PS1 site pre-impact although PS1A was not monitored prior to the pipe rupturing. On the acceptance of this assumption the pre-impact data collected from PS1 was used as pre-impact data for the PS1A site. Full descriptions of the monitoring design, assumptions made, management of the data and analyses used were given in Chapter 4. Beyond-BACI analyses failed to detect an impact at the temporal scale of 'Times' (*P*=0.063), 'Periods' (*P*=0.256) or 'Before/After' (*P*=0.608), although the power to detect an impact at the temporal scales of 'Times' and 'Periods' was lower than the desired *a priori* power of 0.95.

The low power to detect effluent related changes in the abundance of *B. nanum* can be attributed to the causes discussed in relation to the power of the Beyond-BACI 'sand' perturbation analysis. An additional source of low power was likely to be the assumption that the PS1 and adjacent PS1A sites supported the same densities of *B. nanum* pre-impact despite obvious substrata differences and increased water retention at PS1A. This assumption would have increased the post-impact variance associated with the analysis and decreased the power of the appropriate analysis (e.g. an increase in the MS residual variance will result in a lower power). Therefore, although the analysis itself was a useful test of Beyond-BACI methodology the results were not truly informative due to the lack of real pre-impact data for the PS1A site and the early intervention of the 'effluent' perturbation during preliminary monitoring.

8.4.4.4 The Oil Spill

The release of Arabian light crude oil occurred from the 'Deep Ocean Point' on the 23rd of September 1996 at about 1300 hours. A second discharge was believed to have occurred at approximately 1630 hours (pers. comm. Pfennig). It was initially reported that 100L of oil was spilt but this volume has since been upgraded to 10 000 litres (pers. comm. Pfennig) although the exact details of the spill have not been released by the Environmental Protection Authority. Tidal heights remained high during the day the spill occurred with the majority of the oil believed to have grounded on the night of the spill.

I made two trips to affected and adjacent unaffected sites in GSV on the 24th and the 26th of September 1996. The high tides that coincided with the initial trip meant that study sites were not accessible to determine if any immediate short-term changes were evident. However, this trip was used to assess the spread and extent of grounded oil. Oil was present at the most affected site in the form of a chocolate 'mousse'. Oil present in this form has been reported to smother intertidal animals (see Appendix D) but this was not observed to occur with this oil spill. The lack of obvious acute effects were probably due to the rapid removal of oil by both artificial and natural means and the relatively small amounts of 'mousse' involved.

Spilt oil was found to have beached over quite a wide area extending from slightly north of the beach behind the Witton Bluff Restaurant, into the mouth of the Onkaparinga River, and finishing slightly to the south of the Port Noarlunga South site. Since Port Noarlunga South had been exposed to oiling it was designated an 'impact' site, while all other study sites served as control sites in reference to this perturbation.

The cleanup operation was observed on the initial visit to GSV. At this time oil-contaminated sand and plant material were manually removed from the shore and affected rocks were seen being scraped free of oil by workers. A boom was used in the mouth of the Onkaparinga River to contain oil and prevent it from travelling further into the river system. This oil was then skimmed from the surface of the water. Another factor that would have influenced the degree of oiling observed on the coast of GSV, was the use of dispersants to force the oil into the water column. It had been reported that dispersant was used close to the point of oil spillage (pers. comm. Pfennig) which would have prevented some of the released oil from grounding.

The return visit to GSV sites on the 26th of September revealed that the cleanup operation was progressing well. At this time five 'control' sites and the 'impact' site were able to be assessed and their animals censused (see Chapters 4 & 6). The data obtained at this time (post-impact data) was compared to pre-spill data for the set of 'controls' and the 'impact' site. It was apparent during this visit that high tides had carried the oil across the Port Noarlunga South site without leaving any obvious residue except on the landward edge of the small cliff which marks the site (Chapter 3: Plate 3.13). Most of this oil was then deposited higher on the shore (well above the mid-eulittoral zone) where fewer animals and plants were likely to be affected.

Post-oil spill sampling failed to reveal any obvious changes in animal presence or densities at the 'impact' site which, coupled with the fact that oil had been carried across the mid-eulittoral zone rather than deposited on it, meant that a Beyond-BACI analysis was not likely to be informative. Therefore, a (3D) SSH MDS ordination analysis, which placed the sites (at each sampling time) in species defined space (as defined by the presence and abundance of the animals recorded at a site), was performed (refer to Chapters 4 & 6). This failed to detect any differences between the 'impact' site and the selected 'control' locations, with the average post-impact positions of the set of 'control' sites and the 'impact' site remaining within the pre-impact range of positions (Chapter 6: Fig. 6.7).

The failure to detect any immediate effect of the oil spill on mid-eulittoral biota was probably a combined function of a number of factors. These included the rough weather (which broke up the slick), the rapid cleanup and the high tides, which are common in spring and which ensured that the oil grounded high on the beach (where it could do minimal damage). It is possible that some intertidal animals would have been exposed to low volumes of the water-soluble fraction (WSF) of the crude oil, and the dispersant may also have had some local effect on animals it contacted. This exposure could result in delayed effects (such as reduced reproductive success) which were undetectable immediately after the spill. However, in view of the initial findings and the relatively small volumes of oil involved, delayed (chronic) effects were expected to be minimal.

8.4.4.5 General Spatial and Temporal Trends

All study sites fluctuated in terms of the abundance of their dominant animals and their assemblage structure during the preliminary study. Minor seasonal patterns in variability were seen with the SSH MDS Ordination but the variability in assemblage structure within and between sites (Chapter 4: Figs 4.54 & 4.55) appeared to mask any clear seasonal trends (Chapter 4: Fig. 4.56). To detect definitive seasonal patterns against this high background variability a longer-term data set would be needed.

It was clear that physical parameters acting at study sites were affecting assemblage patterns although these did not regress significantly with the ordination (Chapter 4: Table 4.19). The lack of a significant relationship between the assessed physical parameters and taxa ordination space was postulated to be due to the interaction of a number of these factors (with each other and abiotic factors) and temporal fluctuations in the relative importance of these factors. This means that it is unlikely that a simple linear relationship between the main physical characteristics of a site and taxa ordination space exists.

The more 'stable' 'Southern' sites separated strongly from the ordination positions of the other sites indicating they had a slightly different assemblage structure. Witton Bluff was markedly different to all other study sites and supported a completely different assemblage, closer to that expected in a subtidal environment. The position of this site in ordination space was found to regress strongly with *T. undulatus* and a range of other species (Chapter 4: Table 4.18). In view of its unique assemblage this site is not recommended for retention as a study site for ongoing monitoring.

The need to select 'stable' study sites comprised of embedded reef-rock (such as Robinson Point) or immobile bedrock (such as the 'upper' zone at PS1, Hallett Cove and Port Noarlunga South) was clearly indicated by the confounding effects of storm movement of mobile substrata at sites such as Marino Rocks. Mobilisation of substrata resulted in 'unstable' assemblages and low numbers of species and individuals post-perturbations. Similar effects have been reported in mobile boulder communities subjected to physical disturbance (McGuiness 1987a & b).

The sand influxes to 'Northern' sites during 1995 and 1996 indicated that care needs to be exercised in selecting 'Northern' sites for ongoing monitoring. It is important that the sites selected for inclusion in the ongoing monitoring program have a minimal risk of being exposed to a 'sand' perturbation or being affected by storm mobilisation of substrata, either of which could confound an oil spill monitoring program. Therefore, all selected study sites will need to be reassessed and possibly new 'upper' regions chosen before ongoing monitoring commences.

B. nanum abundance and Implications to the Ongoing Monitoring Program

Fluctuations in the abundance of *B. nanum* and other less common gastropods were observed during preliminary monitoring. *B. nanum* was the most common species found in the 'upper' section of the mid-eulittoral zone at the majority of study sites and was recommended as the *a priori* bioindicator for the monitoring program. Large variations in *B. nanum* abundance were observed during preliminary monitoring, both within and between sites (Chapter 4). At certain times of the year these variations appeared to coincide with major physical changes (e.g. substrata mobilisation at 'unstable' sites) while at other times abundance fluctuations appeared to be linked to new recruitment or other biotic variables such as competition and predation. The dominance of physical factors in structuring a population at certain times of the year was demonstrated by the influx of sand to the HCA site in July 1995 (Fig. 8.3). The sand thickly covered substrata at the site and was followed by a rapid decline in the abundance of *B. nanum*. This change was not seen in the set of control sites used in the Beyond-BACI analysis of the 'sand' perturbation. No animals (including *B. nanum*) were able to exist at the sand affected site from the 10th of September until the beginning of November 1995, and the abundance of *B. nanum* had not recovered to its pre-impact levels before a second sand influx occurred in May 1996. This highlights the importance of assessing the percentage of different substrata grades present at a study site as well as the size distribution and absolute numbers of the species of interest, in this case *B. nanum*. In this way substrata disturbances which may confound an investigated perturbation will be identified and the timing of *B. nanum* settlement waves will be known. This information can then be used to explain changes in the abundance of *B. nanum* which are independent of an oil perturbation and may elucidate the mechanism of post-oil spill recovery (e.g. recruitment versus local immigration).

Perhaps the most significant and overriding result generated from preliminary monitoring was the high degree of inherent variability which is a feature of the intertidal assemblage in general and in GSV in particular. This variability was also found by Womersley (1988) and highlights the need for a long term, well designed and powerful monitoring program.

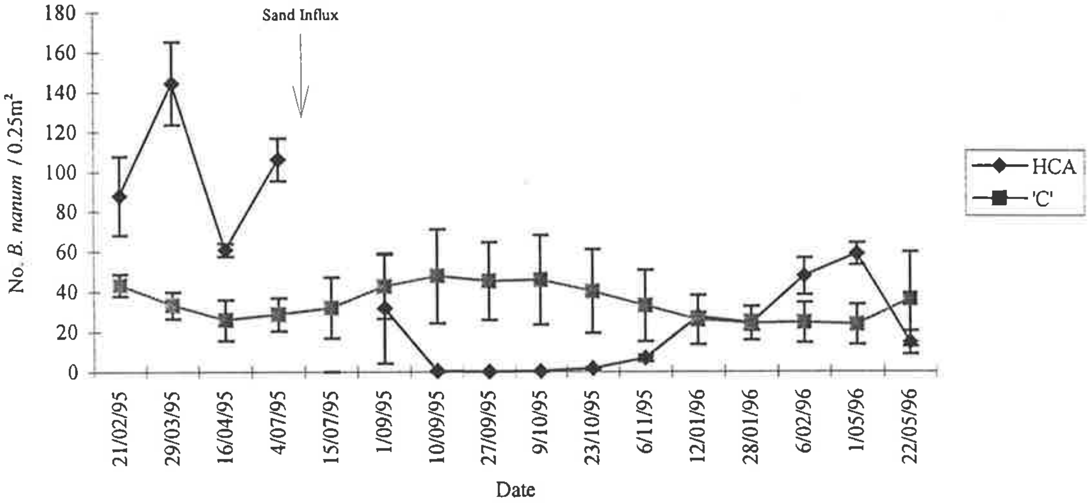


Fig. 8.3 A comparison of the total abundance of *B. nanum* at the 'sand' perturbed Hallett Cove site (HCA) and the set of control sites (designated 'C') used in the Beyond-BACI analysis of this event. A subset of the data used to generate this graph was also used for the Beyond-BACI assessment of the impact of the 'sand' perturbation on *B. nanum* abundance. The 'control' abundance has been calculated as the average abundance of *B. nanum* occurring at the five control sites (Marino Rocks, Kingston Park, PS1, PS2 & PS3) at each sampling time. The timing of the sand influx is arrowed and the abundance of *B. nanum* per 0.25m^2 (shown on the *y*-axis) declines rapidly after this event. The sampling dates shown on the *x*-axis represent the actual day of sampling ± 1 day. HCA was not able to be sampled on the 15th of July 1995 due to high tides which restricted site access.

8.5 Phase 3: Modelling of an Oil Spill

Modelling an oil spill from the refinery under varying tidal and seasonal conditions revealed the extreme variability in predicted grounding sites and volumes of oil arriving at the shore (Chapter 5). This variability depended on the timing of oil release in relation to wind and tidal conditions (the major factors affecting passage of oil), the point of spillage, and the volume and type of oil spilt. Crude oil is expected to be more damaging and to have a greater impact intertidally than petrol which, although more volatile tends to weather more rapidly. Therefore, the modelling results predicting the seasonal grounding sites of crude oil spilt from the refinery were considered of most relevance to an ongoing monitoring program.

Some seasonal patterns in oil spill grounding were evident from the modelling work (see Chapter 5). However, regardless of the type of oil released, the timing of that release within the tidal cycle, and whether the oil was spilt from the 'Deep Ocean Point' or the 'Wharf Point' (Appendix A: Fig. A.3), it would appear that 'Northern' sites (particularly Hallett Cove) and 'Central' study sites are most likely to be perturbed by an operational oil spill from the refinery.

The variability seen in the oil spill simulations over a range of temporal scales (e.g. hourly, daily and seasonally) highlighted the need to retain a wide spatial distribution and a relatively high number of study sites for the ongoing monitoring program. This increases the probability of at least one of the selected study sites being exposed to oil in the event of a spill from the refinery. It also reduces the risk of all sites being significantly contaminated in a large volume oil spill (thus effectively eliminating any 'control' sites from the Beyond-BACI monitoring design). To this end it is recommended that all sites, apart from Witton Bluff, be retained for ongoing monitoring, although further assessment of site suitability is required.

8.6 Phase 4: Selection of a Bioindicator

The small prosobranch gastropod *Bembicium nanum* (Lamarck) was the only species of animal present in sufficient numbers at the majority of study sites to be useful in a statistical assessment of environmental impact. *B. nanum* was one of a number of common herbivorous gastropods found in GSV but it tended to tolerate conditions high in the mid-eulittoral zone where access was not as restricted and most other gastropods were sparsely represented. It was also the only assessed species which did not display a 'preference' for the undersurface of rocks, a behavioural strategy which would have made sampling more difficult (refer to Chapter 6).

B. nanum adults generally only attain a maximum width of about 2cm (Quinn *et al.* 1992) and their longevity has been estimated at between 4-8 years. Reproductive maturity in some populations in New South Wales has been estimated to occur at an average shell width of 11mm, 10-12 months after settlement on the shore (Underwood 1975b). Females spawn yellow egg masses in spring from which larvae hatch and enter the plankton where they are believed to spend a long time, possibly up to a year (Underwood 1975b).

The longevity of this species means that a local population can survive through several consecutive years of sparse larval recruitment. However, due to the long planktonic stage and thus wide dispersal of larvae, local adult population dynamics have no influence on the number of new recruits arriving to an area (Underwood 1975b). If an oil spill decimates a local population it is predicted that recovery should be relatively rapid as new recruits arrive and mature animals migrate from unaffected areas. For successful recolonisation by new recruits to occur they must first be transported to the affected area at an appropriate stage of development and the shore conditions (modified by oil) need to be suitable for settlement and ongoing survival. However, other species may be able to opportunistically settle and claim the space vacated by the oil. These opportunists may then outcompete or preclude *B. nanum* from the area and prevent or slow recovery of oil-impacted *B. nanum* populations.

Two experiments exposing *B. nanum* individuals to crude oil and refined product (petrol) over one tidal cycle, revealed that it was not killed when exposed to low concentrations of either product but did show behavioural changes (Chapter 6). The primary response noted was closure of the operculum and subsequent dislodgment following exposure to small volumes of either Arabian light crude oil or unleaded Mobil petroleum. This suggested a cause-and-effect relationship between *B. nanum* and oil and implied this species would be a useful bioindicator of oil pollution. The lack of acute experimental mortality when exposed for a short time to realistic amounts of oil is favourable as it implies that *B. nanum* is not likely to respond to a 'trivial' oil spill.

Due to the adherent nature of crude oil and the rapid weathering of the more toxic refined product, it is likely that exposure to crude oil would be more damaging to *B. nanum* populations than exposure to petrol. A significant crude oil spill could result in an initial decrease in *B. nanum* abundance due to dislodgment (noted experimentally and reported in gastropods) and in severe cases smothering of the animals (refer to Chapters 2 & 6). Either of these responses would manifest as population level change (the *a priori* focus of the monitoring program).

The experiment involving exposure of small numbers of *B. nanum* to Arabian light crude oil found that 8-36% of animals lost adherence when exposed directly to crude oil or its water soluble fraction (WSF) (Chapter 6: Fig. 6.2b & c). This experiment involved exposure of animals to small volumes of oil and it is predicted that a greater percentage of animals would be affected in a 'real' oil spill than were affected experimentally. Therefore, a realistic 'effect size' in relation to an oil spill would be a 50% greater change in *B. nanum* abundance at the impact site(s) in comparison to the control sites following oil exposure. The 'effect size' of interest in an ongoing monitoring program will be considered in more detail later in this chapter. The results of the 'crude oil' experiment suggest that the immediate short term response seen in a *B. nanum* population exposed to sufficient quantities of oil or its WSF would be an initial decrease in abundance.

B. nanum would be an appropriate indicator of oil induced change for a number of reasons. It is abundant at study sites and the adults do not appear to travel as far as other animals and so are unlikely to be able to avoid oil exposure (Chapter 7). Additionally, it shows some response to oil contamination but is not extremely sensitive, it does not display cryptic behaviour and it is herbivorous like the majority of other (non-sessile) gastropods (Chapter 6). This last point means that it is likely to ingest and contact oil in a similar manner to other less numerous herbivorous gastropods and be in some ways 'representative' of similar gastropod species. Another favourable feature is the lengthy planktonic stage. This suggests that recovery of an oil affected population could be rapid as new recruits are transported to the area, provided that local shore conditions are capable of supporting the new animals and their arrival and/or establishment is not blocked by opportunistic species which outcompete *B. nanum* for space or food.

Taxonomically, *Bembicium nanum* (Lamarck) belongs to;

Phylum- Mollusca,
Class- Gastropoda,
Sub-Class- Prosobranchia,
Order- Mesogastropoda,
Superfamily- Littorinacea,
Genus- *Bembicium* Philippi,
Species- *nanum* (Lamarck).

8.7 Phase 5: Human Visitation and Recreational Trampling

8.7.1 Human Recreational Visitation

An investigation of recreational use of GSV study sites revealed differential human visitation to perform a range of recreational activities, but visitation pressure during 1995 and 1996 was assessed to be generally low (Chapter 7). High weighted impacts were recorded at two of the 'Northern' sites on two occasions when fossickers were observed collecting gastropods for consumption or bait. However, human predation of this type should be minimal now that legislation prohibiting this activity at GSV sites has been passed (Chapter 7). In general, even when visitation was relatively high, impact to intertidal areas was judged to be minimal. However, the most commonly observed recreational activity was expected to cause small levels of dislodgment of some intertidal gastropods (including *B. nanum*).

Dislodgment and subsequent overturning of animals was a possible result of recreational trampling but could also occur in response to oil exposure. An experimental investigation to determine the effects of overturning common gastropods (*B. nanum*, *A. constricta* and *N. atramentosa*) found that in general less animals were recovered in 'overturned' treatments than in the equivalent controls (Chapter 7). However, substrata type was postulated to have an influence on the number of 'overturned' animals that were recovered. For example, more animals were recovered at sites where the dominant substrata type was considered more complex (e.g. Port Stanvac). A similar relationship appeared to exist between substrata complexity and the distance travelled by recovered 'overturned' animals. At the less topographically complex Hallett Cove site 'overturned' animals which were recovered were found to have travelled further than the equivalent animals at Port Stanvac. Another interesting finding was that (on average) adult *B. nanum* animals (in both control and 'overturned' treatments) were displaced shorter distances than recovered animals of the other species at either study site. Assuming that *B. nanum*, *A. constricta* and *N. atramentosa* were equally likely to be dislodged by an oil spill, *B. nanum* abundance should be a conservative estimate of the effects of oil on the abundance of the other gastropods. However, such an assumption overlooks the cryptic behaviour of *A. constricta* and *N. atramentosa* (Chapter 6) which may balance the increased risk of dislodgment occurring as a physical or a behavioural response to oil exposure. The cryptic behaviour in question is the 'preference' these animals show for the undersurfaces (or sides) of mobile rocks and their tendency to aggregate in crevices or rock pools (Underwood 1976a & b) which may afford a refuge from direct oil contact. The above assumption also overlooks effects related to size differences between the three species.

An unreplicated experiment in which *B. nanum*, *A. constricta* and *N. atramentosa* were overturned found that these species were slow to right themselves. *B. nanum* animals were particularly slow and remained overturned and clamped shut over a thirty minute observation period (Chapter 7). If this is a 'true' result and not a sampling artefact this behaviour suggests that animals dislodged by oil exposure or recreational trampling are more likely to be transported greater distances from a home site than undisturbed animals.

8.7.2 The Effects of Trampling

Two different trampling disturbances were investigated, one designed to simulate a 'weekend' trampling disturbance (representing the type of traffic experienced on a rocky shore during a busy weekend) and the other designed to simulate a 'school-holiday' trampling disturbance (representing the type of traffic experienced during a two-week school holiday period). Full details of the experimental design and analyses were given in Chapter 7.

A 'Weekend' Trampling Disturbance

The 'weekend' trampling experiment used two trampling intensities; 'light' (two passages per day) and 'heavy' (twenty passages per day); and an untrampled 'control'. An MDS Ordination of animal taxa generated from the assemblage data collected found that the 'heavy' plots showed an average direction of change which was directed into a different quadrat than the vectors of change for the 'control' and 'light' plots (Chapter 7: Fig. 7.10). A randomised block analysis of the difference in 'small' *B. nanum* abundance indicated significant treatment effects, with the differences existing between the 'heavy' trampled treatment and the 'control' treatment (with the former having less 'small' animals). The same trends were apparent after a one week recovery period. An analysis of the total abundance of *B. nanum* in the three treatments revealed significant differences immediately following trampling and after the recovery period. However, a *post hoc* analysis could not detect any differences between the treatments. Despite this, it was apparent that trampling at the higher intensity resulted in a lower average abundance of *B. nanum* compared to the other treatments and that 'small' animals were most affected.

A 'School-Holiday' Trampling Disturbance

The 'School-Holiday' trampling disturbance again investigated two trampling intensities; 'light' (two passages a day) and 'medium' (5 passages a day); and an untrampled 'control'. The 'medium' intensity treatment was believed to be more realistic of the intensity of trampling experienced by any small area of the shore during a school holiday period or a weekend (based on the observed recreational use of GSV sites during 1995 and 1996).

The MDS Ordination did not reveal any clear patterns between treatments at any of the sampling times (pre-impact, immediately post-impact and after a two week recovery period). The treatment 'plots' showed a high degree of separation in terms of their community composition which, coupled with considerable within plot variability, made identification of community based trends according to treatment effects very difficult (Chapter 7: 7.15a & b). No significant treatment effects could be found when either the total abundance of *B. nanum* or the abundance of only 'small' *B. nanum* animals was examined statistically.

It was apparent that the low levels of trampling investigated in the 'school-holiday' trampling experiment were not sufficient to cause significant treatment effects in terms of the abundance of *B. nanum*. The outcomes of this experiment are relevant to the monitoring program as they support the likelihood of the low trampling intensities associated with sampling intertidal biota having no significant impact on the abundance of *B. nanum* or on community patterns in general.

8.8 Phase 6: The Ongoing Monitoring Design Recommended for Port Stanvac

Based on the outcomes of the literature reviews of relevant material (rocky intertidal characteristics, monitoring designs and oil characteristics and biota effects) and the results of phases 1-5, it was possible to make final recommendations for the optimal design of an ongoing monitoring program suited to the requirements of Mobil. The recommended monitoring program needs to be ongoing and long-term due to the high degree of spatial and temporal variability characterising GSV sites (see Chapter 4 and Womersley (1988)). In order to optimise the recommended monitoring design it was necessary to reassess the sites chosen for preliminary monitoring. This reassessment focused on the assemblages present at study sites (in particular whether *B. nanum* was present and how abundant it was), the composition and stability of the substrata and the ease of access and location of sites. The latter is important to consider as it determines the potential usefulness of sites as potential 'control' or 'impact' locations in a Beyond-BACI monitoring program.

8.8.1 Site Redefinition

At the end of the preliminary monitoring phase of this project it was apparent that some of the study sites were more suited to long term monitoring. Therefore, all sites were reassessed and if needed redefined, for example if the original site appeared to be especially susceptible to natural substrata perturbations, new, more stable sites, was selected.

Of the nine preliminary study sites, Witton Bluff did not have a suitable suite of animals and was not included as a final site for inclusion in the ongoing monitoring program. PS2, PS3, Marino Rocks and Hallett Cove were all redefined due to the potential for repeated sand influx at the latter site, and mobilisation of adjacent boulder and cobble substrata at the other sites. The new sites were believed to be more stable than the sites they replaced while still being dominated by *B. nanum*. It is recommended that one 'zone' (e.g. one level within the mid-eulittoral region) is to be sampled within each of the designated study sites and, except where otherwise specified, the substrata of interest is predominantly flat bedrock. The sampled region at each of the redefined study sites is equivalent to the 'upper' zone previously described (see Chapter 3) and will be discussed in more detail below. Where it is stated that a site is sampled in two directions, random numbers are used to assign the quadrat position by moving the specified distance in the first direction followed by the required distance in the second direction. A description of the selected study sites are given below and their approximate location is shown in Chapter 3 (Fig. 3.1).

Kingston Park (Plates 8.1 & 8.2)

This site is as described in Chapter 3. It is situated at the end of a Service Road which is turned into from Esplanade Road (Appendix E: Map 152, Ref. E14.5). At the end of the Service Road is a seawall with a cemented lower section. The site to be sampled commences 24m from the start of this seawall and extends a further 11m. The area is worked towards the south and the west.

The sampled section of the site is located to the south of a small boat ramp. The substrata is predominantly flat bedrock with very little elevation, interspersed by areas of rounded cobble, boulder and pebble that overlie some of the bedrock, and which dominate close to the low tide mark.

Marino (Plates 8.3, 8.4 & 8.5)

This site replaces the previously described Marino Rocks site. The Marino site is located to the south of Kingston Park and is further north than the original Marino Rocks study site. It is accessed from a car park at the end of Jervois Road (Appendix F: Map 164, Ref. D0.5). A large square rock formation in the cliff landward of the sampled area is located 41.9m from the start of the concrete section of the boat ramp on the beach. From this rock a distance of 21.8m is measured to locate the start of the sampled area which extends a further 4.8m west. The area is worked to the west and the south and sampling is in the lower, flatter bedrock interspersing the more upthrust grey and slightly eroded rocks.

Hallett Cove (Plates 8.6 & 8.7)

This site was redefined following the preliminary study. The new site is situated beyond the Surf Life Saving Club at Herron Way, adjacent to the car park that is entered from Grand Central Ave. (Appendix G: Map 175, Ref. Q1). Sampling can commence 33m from the base of the ramp allowing entry to the beach and can continue for a further 16m from this point. The sampled area is situated directly to the south of the original Hallett Cove site and is predominantly a cobble and boulder field with entrapped sand. It was formally referred to as HCB. The area is worked to the west and south of the starting position.

Port Stanvac Study Sites

The refinery is entered via Refinery Road (Appendix G: Map 175, Ref. N15). All Port Stanvac sites are accessed by car via the coastal track within the refinery. A compulsory Safety Test needs to be done prior to working at the refinery and a permit must be obtained to allow vehicle entry into the plant.

The beach within the confines of the Port Stanvac Oil Refinery is predominantly rocky, with flat bedrock interspersed by heavily upthrust bedrock and is overlaid in some areas by large amounts of mobile substrata. Topographically this stretch of coast is the most complex and varied of all the designated sections of coast.

PS1 (Plates 8.8, 8.9 & 8.10)

This site is as described in Chapter 3. It is reached at the end of the coastal refinery road and is the most northern site within the refinery. The actual area to be sampled begins at a point 30m to the south of the join on the effluent discharge pipe, and 7m to the west. The sampled area extends a further 15m west of this point and is worked in a west and south direction. The substratum is predominantly flat bedrock with occasional upthrust sections, and is overlaid in parts by areas of cobble and boulder.

PS2 (Plates 8.11, 8.12 & 8.13)

This site is close to the previously described PS2 site but has been redefined. The new PS2 site is accessed from the coastal refinery road and is reached before PS1. It is located by measuring a distance of 48m to the west of survey peg no. 302 (the second blue surveyor's peg to the north of a large rock column) to an area of obvious upthrust rock. From this point a distance of 7m west is traveled (approximately 55m west of the survey peg in total) to reach a flatter bedrock strata which extends for approximately 30m. Sampling continues in a southerly direction and is restricted to this stratum.

PS3 (Plates 8.14 & 8.15)

This site has been redefined and is situated to the north of the previously described PS3 site. The new site commences 71m south of the rocks at the base of the southern side of the wharf and is directly in line with the third light pole on the wharf. It is also approximately 56m west of a large, grey, man-made boulder situated at the edge of the sand. The sampled region consists of a flat bedrock stratum that runs from north to south and is wider in its southern dimension. The area is worked to the west and south along the strata.

Port Noarlunga South (Plates 8.16, 8.17 & 8.18)

This site is some distance from the Port Stanvac sites and is entered from Esplanade Road beyond the Onkaparinga River. It is on the southern side of Onkaparinga Head, to the north of a Trig Point that is located in a car park (Appendix I: Map 195, Ref. E12). The site is reached via a path from the car park, and the reef to be sampled is the last one north of the path immediately adjacent to deep water. Sampling begins 24m to the west of an eroded hole in the centre of a small cliff landward of the intertidal reef and extends a further 18m from this point. The centre of the reef is worked in a west and south direction. This site consists of a stable substratum characterised by large eroded holes that tend to retain water and form small rock pools.

Robinson Point (Plates 8.19 & 8.20)

This site is further south than the previous one and is again reached from Esplanade Road. The car park adjacent to bus stop 84 is entered, and the site accessed via stairs to the beach (Appendix I: Map 195, Ref. F15). The reef being sampled is the first to the south of the stairs. Sampling begins 68.5m from the base of the cliff and extends for a further 26m. Robinson Point consists of homogeneous substrata of embedded boulder and cobble with entrapped sand that stabilises and semi-cements the rocks in their positions. As such it is a relatively stable site, made even more so by the sheltered aspect of the reef. For these reasons it is considered to be equivalent to sites with immobile bedrock substrata in terms of its stability. Robinson Point is low-lying and difficult to access at times.

Plate 8.1. The Kingston Park study site is reached from a Service Road. At the base of the ramp is a man-made seawall used to locate the 'zone' to be sampled.

Plate 8.2. The area sampled at the Kingston Park study site. The study region extends from just beyond the darker bedrock in the foreground and stops before the cobble is reached.

Plate 8.3. The Marino study site is located to the north of the boat ramp from which this photo was taken.

Plate 8.4. At Marino the substrata sampled is the flatter regions of bedrock occurring amongst more elevated bedrock. The sampled substrata lies to the seaward side of the paler strata.

Plate 8.5. The sampled zone at the Marino site begins where the person is standing.

Plate 8.6. The Hallett Cove site is located in the cobble and boulder field directly in front of the base of the ramp seen in the background.

Plate 8.7. The tape marks the beginning of the sampled region in the cobble and boulder field at Hallett Cove. The original study site used in preliminary sampling (HCA) is shown to the right of the new site and was prone to sand influx. HCA served as the 'impact' site in the Beyond-BACI analysis of the 'sand' perturbation which intervened during preliminary sampling.

Plate 8.8. Location of the PS1 site is via the coastal track at the refinery. The car is parked at the southern end of the track, adjacent to PS1.

Plate 8.9. The refinery effluent pipe runs across the intertidal region south of PS1. The pipe join from which measurements are made to locate the site is situated seaward of the cement box. The large pipe on the cliff in the background discharges runoff from the Mitsubishi Manufacturing Plant.

Plate 8.10. The wooden 0.25m^2 quadrat in position at the PS1 site. The substratum is predominantly stable bedrock with fissures and small eroded holes. The small molluscs present as brown specks on the rock are mainly *B. nanum.*

Plate 8.11. This photo was taken facing east from PS2, the central study site within the refinery. The area to be sampled is located using the surveyor's peg which is to the right of the boulder positioned at almost road level to the left of the car.

Plate 8.12. The sampled strata at PS2 is shown in the foreground of this plate where the quadrat is positioned. Note the large amount of mobile boulder and cobble substrata close to the sampled area.

Plate 8.13. This photo was taken facing south along the bedrock strata that is sampled at PS2. Sampling at this site proceeds within the confines of the strata and is not carried out on adjacent mobile rock.

Plate 8.14. The PS3 site lies to the south of the refinery wharf and ship-to-shore pipeline. The quadrat in the foreground of this plate is positioned on the bedrock strata which is sampled at this site.

Plate 8.15. This plate again shows the PS3 study site. This time the area is viewed from the shore facing the sea (west).

Plate 8.16. The landward natural seawall (or cliff) used to locate the area to be sampled at the Port Noarlunga South site.

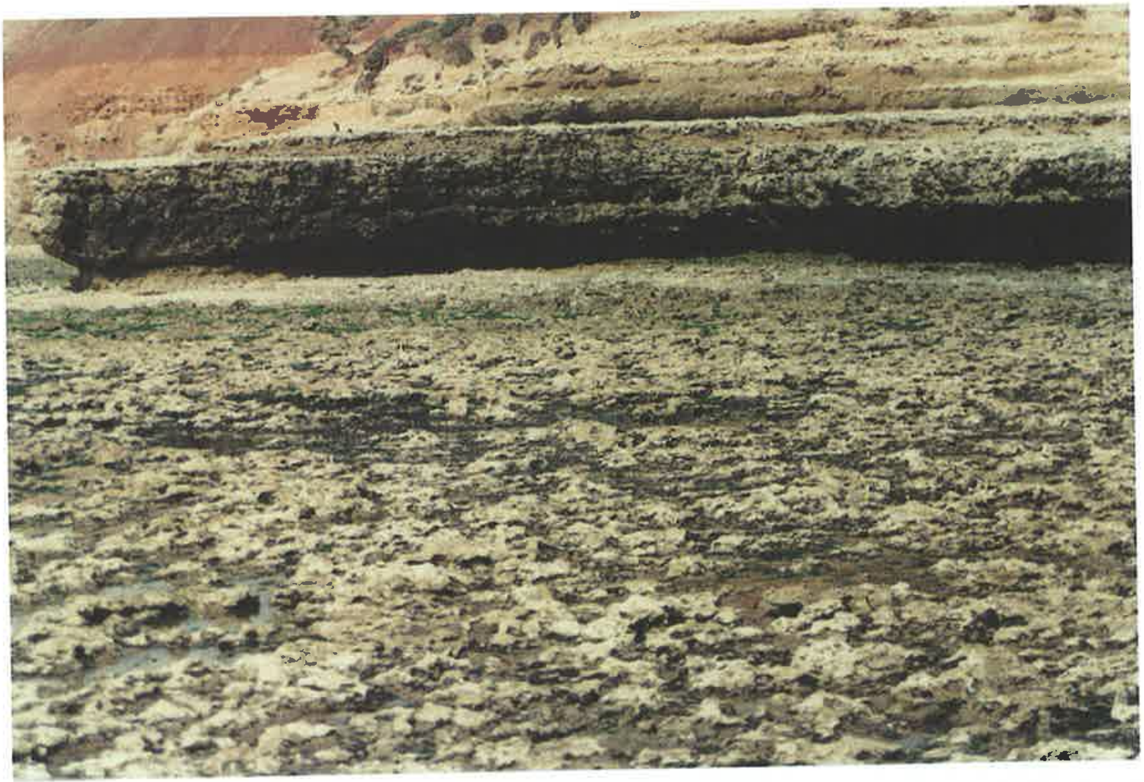


Plate 8.17. A distant view of the seawall that lies to the east of the Port Noarlunga South site. The sampled area is shown in the foreground.

Plate 8.18. The Port Noarlunga South site is a low-lying reef which has formed from bedrock eroded by constant wave action to form some quite deep holes.

Plate 8.19. The access path to the Robinson Point site is shown. The area to be sampled is a reef that lies to the south of the stairs. A stormwater outfall discharges runoff to the north of this site under high rainfall conditions.

Plate 8.20. Sampling at the Robinson Point site begins where the person is shown. This site consists of predominantly embedded cobble which is secured by sand and mussels and is therefore relatively stable.

8.8.2 Design Considerations

The spatial scale of interest in relation to an oil spill and the ongoing monitoring program is at the level of the reef (or equivalent expanse of the rocky shore). Minor localised changes (at the spatial scale of the quadrat) would be tolerated within a perturbed reef but significant changes at the larger scale would not be considered acceptable. The recommended temporal scales of interest remain those chosen for the preliminary phase of this project; namely 'Periods' and 'Times' (refer to Chapter 4).

The 'sand' perturbation occurred early in the preliminary monitoring program and this reduced the power of the Beyond-BACI analysis to detect a 'true' sand driven impact even if one did exist (refer to section 8.4.4.2). A long term monitoring program was recommended *a priori* to detect an oil impact in GSV. However, the variability in *B. nanum* populations during preliminary monitoring and the low power of the 'sand' analysis to detect an impact (at the two temporal scales of interest) made it necessary to determine how long the sampling should have been conducted in order to achieve the desired power (see Chapter 4). This was tested as described by Underwood (1993a) using the 'sand' impact data and analysis (Tables 8.6 & 8.7) and hypothetically increasing the number of intervening 'Periods' and 'Times' before the perturbation occurred. To achieve the desired power of 0.95 at the 0.05 probability level for the temporal scale of 'Times', pre-impact sampling needed to continue for 7 'Periods', while 16 'Periods' of sampling were needed at the longer temporal scale of 'Periods (Table 8.8).

Table 8.8 A power analysis using the results shown in Table 8.7 which were generated from the 'sand' impact data. The analysis involves an assessment of the power to detect an impact at the temporal scales of 'Times' (T) and 'Periods' (P), as the number of 'Periods' before the perturbation intervenes are manipulated. The original analysis is as described in Underwood (1993a) and variance components are as shown in Table 8.7. Fcrit. = the critical F value associated with each variance component at the 0.05 level of probability (see Zar 1984). 1+nø =the MS variance of the listed variance component/MS residual. Calculations were made using values with 3 s.f. but table entries are only shown to 2 s.f.

'Periods' = 7

Components	SS	df	MS	1+nø	Fcrit.	Fcrit./(1+nø)	Power
P(aft)xI	2.23	6	0.37	3.70	2.12	0.57	0.75
T(aft)xI	12.63	7	1.80	18.00	2.01	0.11	1.00
residual	97.14	1008	0.10				

'Periods' = 8

Components	SS	df	MS	1+nø	Fcrit.	Fcrit./(1+nø)	Power
P(aft)xI	2.23	7	0.32	3.85	2.01	0.52	0.82
residual	97.14	1152	0.08				

'Periods' = 9

Components	SS	df	MS	1+nø	Fcrit.	Fcrit./(1+nø)	Power
P(aft)xI	2.23	8	0.28	3.72	1.94	0.52	0.84
residual	97.14	1296	0.08				

'Periods' = 10

Components	SS	df	MS	1+nø	Fcrit.	Fcrit./(1+nø)	Power
P(aft)xI	2.23	9	0.25	3.67	1.88	0.51	0.87
residual	97.14	1440	0.07				

'Periods' = 15

Components	SS	df	MS	1+nø	Fcrit.	Fcrit./(1+nø)	Power
P(aft)xI	2.23	14	0.16	3.54	1.71	0.48	0.94
residual	97.14	2160	0.05				

'Periods' = 16

Components	SS	df	MS	1+nø	Fcrit.	Fcrit./(1+nø)	Power
P(aft)xI	2.23	15	0.15	3.52	1.69	0.48	0.95
residual	97.14	2304	0.04				

The above power calculations were based on an immediate post-perturbation decrease in *B. nanum* abundance at the sand 'impacted' site (HCA) of 68%, if the average pre-impact abundance of this animal at this site was used as a baseline (refer to Fig. 8.3). In contrast, minimal change in *B. nanum* abundance occurred over the same time interval in the set of 'control' sites. Therefore, the power analysis was redone using the original 'sand' data set which had been manipulated so that an average decrease in *B. nanum* abundance of 50% was simulated at the 'impact' site immediately after the perturbation. It was postulated that a local decrease of 50% in a *B. nanum* population exposed to a moderate oil spill was realistic of a 'real' spill and would not represent a 'trivial' response. Therefore, the effect size (ES) of interest in relation to the monitoring program was a 50% change in *B. nanum* abundance and although the change could be in either direction it was predicted to be a decrease.

To analyse the power of the 'sand' analysis using the new 50% ES the pre-impact average abundance of *B. nanum* at HCA was calculated and the original post-impact abundance at this site was then replaced with a value which was 50% less than the calculated pre-impact abundance. The immediate post-impact variance was not altered and no other data were changed. An ANOVA using the manipulated $\log_{10}(x+1)$ transformed means and variances was then conducted with "GMAV5". This analysis was equivalent to the 'a' analysis shown in Table 8.6 and gave the output shown in Table 8.9. Using the 'new' values and the results of analyses 'b', 'c' & 'd' (which were not affected by the new ES) the 'Mean Square' values associated with the temporal scales of interest could be calculated (Table 8.10). The relevant sources of variance associated with these temporal scales and detection of an impact are; "P (aft) x I" and "T (aft) x I" (refer to Tables 8.3 & 8.4 for further details). The analysis based on an ES of 50% achieved the desired *a priori* power within the sampling time discussed in relation to the unmanipulated 'sand' data (see Table 8.8). This result shows the importance of a long term monitoring program to achieve the desired power and detect any oil-related trends in a highly variable environment.

Table 8.9 Calculation of analyses of impact in an asymmetrical Beyond-BACI design using the 'sand' perturbation data set after the data had been manipulated as shown in Table 8.9. All results are unchanged from those shown in Table 8.7 apart from analysis 'a' (After Underwood 1993a). SS=sum of squares, df=degrees of freedom.

Analysis	**a**		**b**		**c**		**d**	
	(all data)		**(controls)**		**(before)**		**(before controls)**	
Source of Variation	SS	df	SS	df	SS	df	SS	df
Before *vs* After = B	39.64	1	0.73	1	-	-	-	-
Periods = P(B)	7.56	2	7.10	2	6.91	1	7.09	1
Times = T(P*B)	4.39	4	3.96	4	2.03	2	2.76	2
Locations = L	165.21	5	153.71	4	62.65	3	25.76	4
B x L	174.99	5	31.44	4	-	-	-	-
P(B) x L	17.59	10	14.23	8	11.00	5	10.58	4
T(P*B) x L	39.00	20	20.78	16	14.12	10	10.64	8
Residual	97.14	288	73.24	240	44.41	144	37.45	120
Total	545.5	335	305.18	279	141.11	167	94.28	139

Table 8.10 The 'new' "P (aft) x I" and "T(aft) x I" values were calculated using the 'sand' data shown in Table 8.9 as described in section 8.4.4.2 and Underwood (1993a). The values shown in the table were calculated after the original 'sand' data had been adjusted to simulate a 50% post-perturbation decrease in *B. nanum* abundance at the putatively impacted site. P (aft) x I refers to the post-impact variance which is associated with the 'impact' site at the temporal scale of 'Periods', and T (aft) x I refers to the equivalent variance which can be partitioned to the temporal scale of 'Times'. SS and MS values are shown to 2 s.f.

Source of variation	SS	df	MS
P (aft) x I	2.93	1	2.93
T (aft) x I	14.75	2	7.38
Residual	97.14	288	0.34
Total	545.5	335	

8.8.3 Recommendations for the Ongoing Monitoring Program

An ongoing, long-term monitoring program constantly assessing the condition of GSV sites using the abundance of *B. nanum* as an indicator is recommended due to the persistent risk of an operational oil spill in the region. It must be pointed out that having such a program in place can not guarantee that any of the selected sites will be perturbed in the event of an oil spill (due to the variability discussed in Chapter 5 in reference to oil transport). However, without an ongoing monitoring program no statistical conclusions as to the consequences of an oil spill can be made. Based on the outcomes of phases 1-5 and a literature review of relevant material, the following recommendations for the ongoing monitoring program at Port Stanvac (presented in point form as an executive summary) have been made.

Executive Summary of the Planned Ongoing Monitoring Program

- The monitoring program should be ongoing and long-term (e.g. continuing for a number of years). A Beyond-BACI design (Underwood 1993) is advocated for the program, this uses many 'control' sites (and one or more 'impact' sites) sampled many times before and after an oil spill occurs.
- 8 rocky sites situated within GSV from Kingston Park (north of Port Stanvac) to Robinson Point (south of Port Stanvac), including three sites within the boundaries of the Port Stanvac Oil Refinery (refer to section 8.8.1 for full site descriptions), are suitable for ongoing monitoring. The spatial positioning of these sites is such that it is predicted that at least one will be exposed to some oil in the event of an operational oil spill at the refinery.
- The designated areas at each study site should be sampled using a randomly located $0.25m^2$ quadrat, which is deployed 7 times.
- In the event of an oil spill the affected site(s) should serve as impact site(s) while the remaining sites would act as controls.
- All sites should be sampled on the same day at low tide for each sampling time.
- The animal to be sampled is *Bembicium nanum* and the number in each of four size classes should be recorded. The smallest of these size classes will represent newly settled animals which will not be used in the final analysis, but their numbers through time may give an indication of the healthy dynamics of the system. The suggested size classes are; newly recruited: 2mm or smaller in width, small: greater than 2mm and up to 0.67cm wide, medium: greater than 0.67cm and up to 1.33cm wide, and large: greater than 1.33cm in width.
- The presence of oil should be subjectively assessed (on a scale of 0-4). The suggested oil categories are; 0: no oil, 1: old weathered oil present as 'tar', 2: fresh oil present as a taint or sheen, 3: fresh oil present as an obvious thin film or small globules, 4: fresh oil present in large amounts as a thick oil film. This scoring system is mainly geared to assessing the presence of crude oil, but could still be used if a petrol spill occurred.

- General changes in substrata composition (in particular increased amounts of sand) for each site at each sampling time should also be scored.
- All data should be recorded on field data sheets (Appendix X) and then entered into the "MICROSOFT: ACCESS", Version 2.0 database entitled "PSdat.mdb" (set up for Mobil's use and held by L. Piller).
- Sampling should be stratified to cover two temporal scales;
    1. 'Times'- suggested to be two-three weeks apart (randomly assigned) and nested in sampling periods, and
    2. 'Periods'- two-three months apart, and again randomly assigned (see Chapter 4 and the worked example for details).
- The recommended effect size to be detected is a 50% greater change in *B. nanum* numbers at the impact site than is seen on average at the control sites. "Effect size" refers to a 'true' difference between the impact site(s) and the control sites. The term "recommended effect size" refers to the magnitude of such a true difference that the monitoring program is designed to have a statistically acceptable chance of detecting. The "acceptable chance" is the designed statistical power of the monitoring program.
- Two errors that can occur in a monitoring program are the false detection of an impact (a type I error) or the failure to detect an impact that does exist (a type II error). Both errors are considered equally undesirable and so it is proposed that the study be designed so that their probabilities are set equally to 0.05. In other words, the recommended statistical power for the monitoring program is 0.95.
- Thus, the recommended aim of the monitoring program is that if there were 'truly' a 50% greater change in *B. nanum* abundance occurring at the 'impact' site(s) in comparison to the 'control' sites then the chance of the study detecting it as a significant impact at the 5% level would be 95%.
- Once an impact has occurred and the appropriate sampling been completed, a preliminary analysis using "BMDP" Statistical Software V5 (or a similar package) (see Appendix O) needs to be run to test for serial correlation in the data set. It is recommended that this be done through the Statistics Department, University of Adelaide. If serial correlation is present, a more extensive analysis needs to be performed, but if this problem is insignificant, then a Beyond-BACI analysis can be

performed using "GMAV5" (Appendix N). The stages to be worked through in using a Beyond-BACI design are shown in Fig. 8.1.

A costing of various management options for the maintenance of this project have been presented to Mobil but have not been included in this thesis to maintain client confidentiality.

8.9 Initial Sampling for the Ongoing Monitoring Program

The initial sampling of the study sites selected for ongoing monitoring was done on the 17th of October 1996 and again on the 11th of November 1996. The next sampling 'Period' should commence in February 1997 if the recommended schedule of sampling is to be maintained. However, sampling can commence (leaving the first sampling run data as pilot information) at any time. All study sites were censused on a single day and the data are attached as Appendix Y: a)-d).

Support materials available to Mobil and held in the Zoology Department, University of Adelaide include:

- a database file set up in "MICROSOFT: ACCESS" to store and handle the data,
- a macro to calculate average abundances entered as raw values in the database. This can be altered to enable a calculation of standard error,
- a $0.25m^2$ sampling quadrat, a metre rule, a calliper (to determine animal size) and a 50m tape measure.

The "GMAV5" package used to perform the Beyond-BACI ANOVA's is owned by the University of Adelaide and is available for use if the monitoring program is run through the University of Adelaide.

8.9.1 Initial Ongoing Sampling

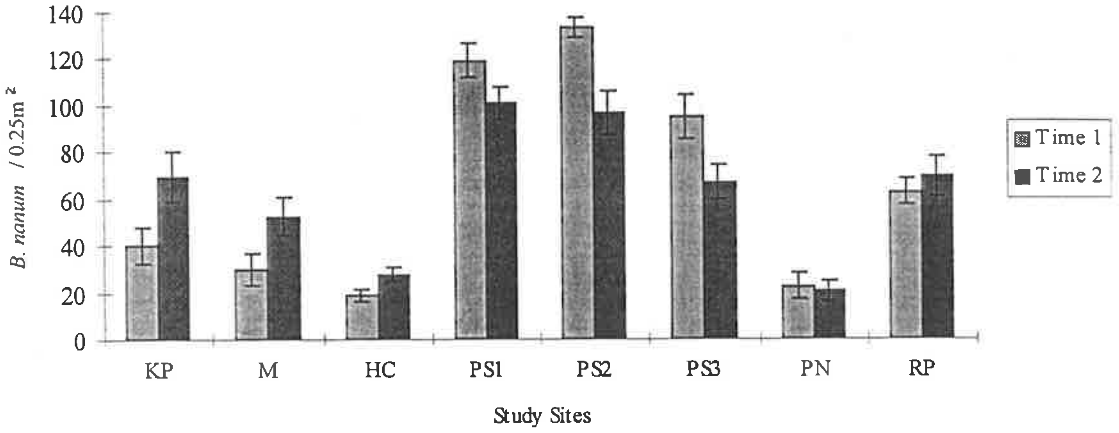
B. nanum Abundance and Sampling Precision

The first sampling 'Period' was completed according to the recommendations given in section 8.8.3. Substrata at study sites were not mobilised by storm action during this time and no sand influx was observed at any of the sites. The most unstable site selected for ongoing monitoring was Hallett Cove, which is susceptible to mobilisation of its boulder and cobble substrata under certain weather conditions and is also prone to sand inundation.

Data collected during the first sampling 'Period' have been presented graphically (Figs 8.4 & 8.5) and the raw abundance data is included as Appendix Y. There were clear differences in the total abundances of *B. nanum* at the monitored sites. Port Stanvac study sites supported the highest number of this species. In contrast, Hallett Cove (the most likely site to be influenced by substrata mobilisation) and Port Noarlunga South (a very stable site) had low densities of *B. nanum*, with less than 30 animals (on average) per $0.25m^2$ being recorded at both sites (Fig. 8.4a). Temporal differences in *B. nanum* abundance occurred within sites, but in general abundances were more similar within than between sites. Trends apparent at the second sampling 'Time' (compared to the first sampling 'Time') were an increase in abundance at 'Northern' sites, the reverse trend at 'Central' sites and little change at 'Southern' study sites.

An examination of the sampling precision (refer to Chapter 3) associated with deployment of seven quadrats revealed that all sites other than Port Noarlunga South and Marino Rocks had a precision score below 0.19 at both sampling times, and that no site recorded a precision higher than 0.24 (Fig. 8.4b). This was consistent with the precision values associated with sampling the 'upper' zones of study sites during the pilot study phase of this project (see Chapter 3). If Mobil adopts the recommended monitoring program and a temporally large data set is obtained prior to an operational oil spill occurring, it may be possible to reduce the number of study sites included in the analysis. This could be achieved by eliminating those sites which exhibit the greatest background variability (e.g. unrelated to the perturbation), namely Marino and/or Port Noarlunga South. However, the advantages of this manipulation would need to be weighed against power considerations. It is recommended that all study sites identified for inclusion in the ongoing monitoring program are monitored for as long as the program continues and are included in a Beyond-BACI analysis of oil perturbation effects (unless severely perturbed by an unrelated event).

a) Total abundance of *B. nanum*



b) Sampling Precision

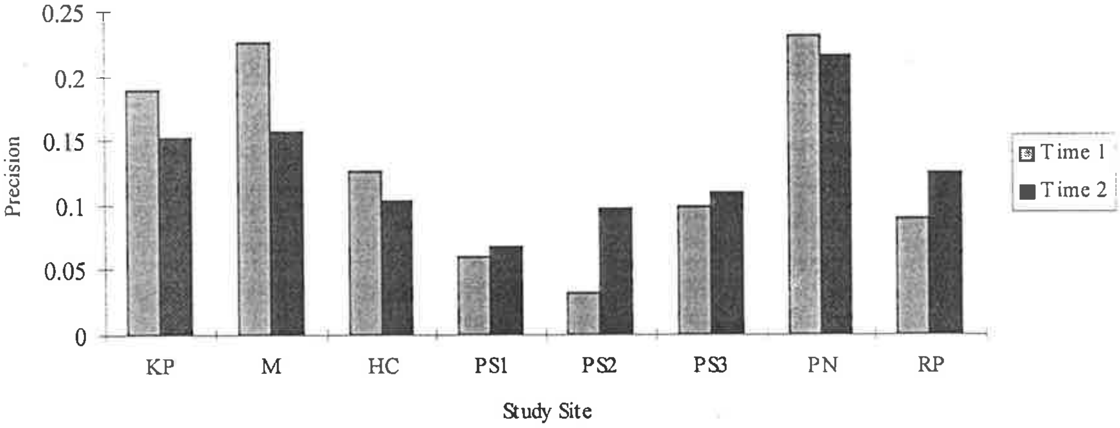


Fig. 8.4 **a)** The total abundance of *B. nanum* is shown for each of the study sites selected for ongoing monitoring. Total abundance has been calculated as the average number of *B. nanum* (combining size classes) per 0.25m^2 of substrata (*B. nanum* / 0.25m^2) for each of the sampling times (Time 1 & Time 2). Error bars represent the standard error associated with sampling. **b)** The precision associated with each sampling time has also been shown for each of the study sites following deployment of seven 0.25m^2 quadrats (see text for further details). The monitored study sites are shown on the *x*-axis for each of the graphs and are; Kingston Park (KP), Marino (M), Hallett Cove (HC), the Port Stanvac sites (PS1, PS2 & PS3), Port Noarlunga South (PN) and Robinson Point (RP).

Size Considerations

No recruitment was noted at the study sites during initial 'ongoing' sampling. If new recruits had been found these would have been recorded but it is recommended that they are not included in a future Beyond-BACI analysis. This is because animals less than 2mm in diameter are difficult to accurately quantify and their numbers can fluctuate markedly over a short time as they attempt to become established as part of the existing population against such pressures as predation, competition and desiccation. Their presence and abundance provides information about the health of an area but their high inherent variability and variable recruitment patterns between sites could confound a statistical analysis (but see Chapter 4). It is therefore recommended that only *B. nanum* animals greater than 2mm in diameter are used in a Beyond-BACI analysis of oil related change.

It was apparent during sampling that the study sites selected for analysis differed not only in the abundance of *B. nanum* they supported but also in the size distribution of the animals which were found (Fig. 8.5a & b). However, the population structure was consistent within sites at both sampling 'Times'. In general, 'medium' sized animals dominated all study sites apart from the 'Southern' study sites where the contribution of 'large' animals was high; greater than 60% at Port Noarlunga South and almost 95% at Robinson Point (Fig. 8.5a & b). The greater proportion of 'large' animals is probably due to the protected aspect and greater water retention rates characteristic of these sites. This, in association with a high degree of substrata stability (see Chapter 4) may encourage enhanced epilithon growth and allow herbivores such as *B. nanum* to achieve higher growth rates and attain their full size.

Herbivores at some of the more densely populated sites (e.g. PS1 & PS2) not only face greater competition for available food but also may have lower amounts of epilithon to graze due to shorter inundation times experienced by these sites and less favourable conditions for epilithon growth (see Chapter 4). Either of these factors could result in slower herbivore animal growth rates and generally smaller animals. Due to the clear size differences between the selected study sites I recommend continuing to monitor *B. nanum* abundance within size classes. Retention of this information during the ongoing monitoring program will enable oil-induced differences in animal density and recovery of an area affected by oil to be attributed to new recruitment or a migratory influx of mature animals.

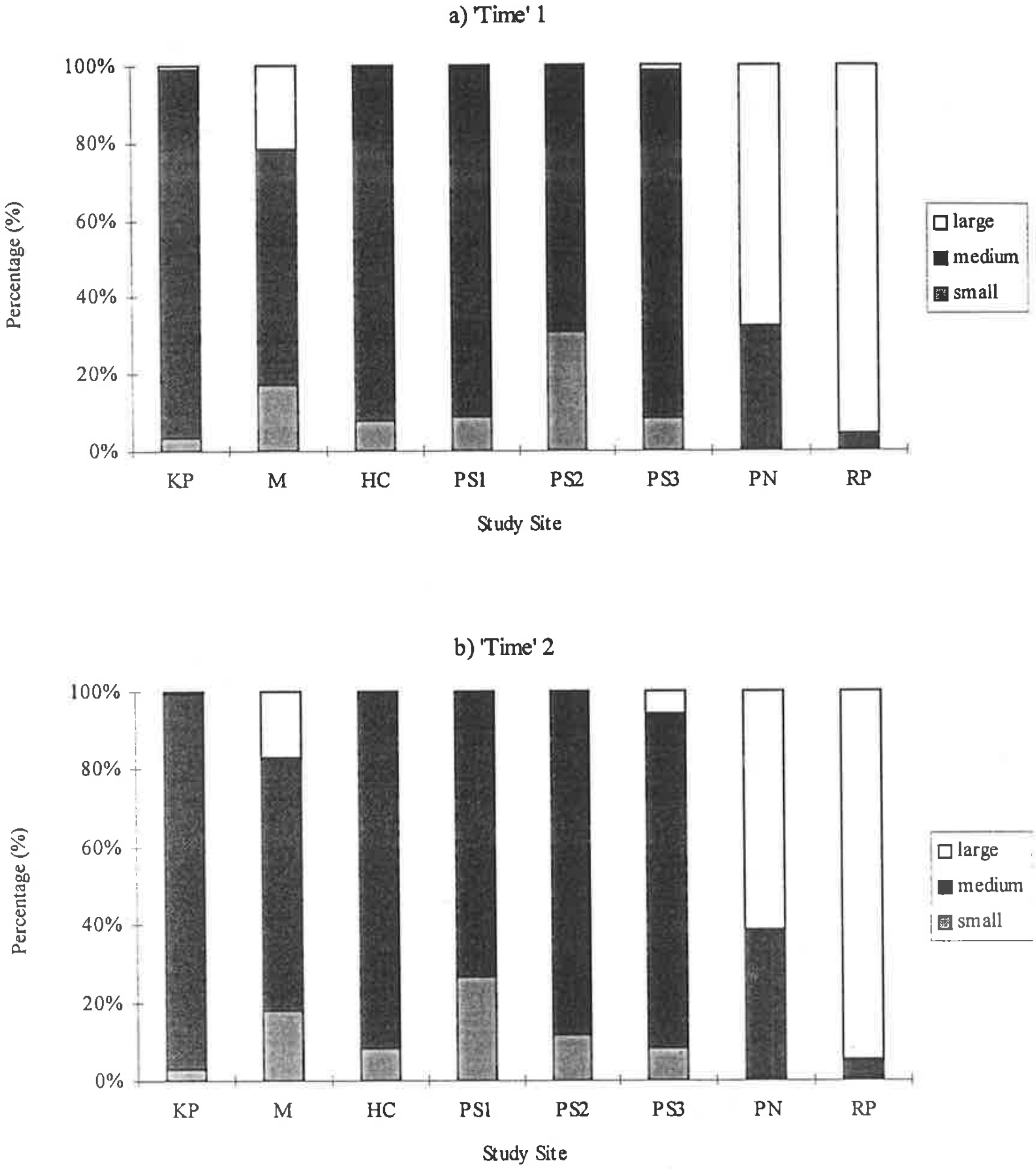


Fig. 8.5 The population structure of *B. nanum* is shown for each of the study sites selected for ongoing monitoring. The recognised size classes are shown in the legend and are described in the text for the two sampling times: 'Time' 1 (a) and 'Time 2' (b). Population structure has been described as the percentage of the total *B. nanum* animals censused which can be categorised into each of the size classes (*y*-axis). The monitored study sites are shown on the *x*-axis for each of the graphs and are; Kingston Park (KP), Marino (M), Hallett Cove (HC), the Port Stanvac sites (PS1, PS2 & PS3), Port Noarlunga South (PN) and Robinson Point (RP).

8.10 Conclusions

Based on the results of this project the best chance of detecting an oil spill in the vicinity of Port Stanvac is to have an ongoing monitoring program in place. A Beyond-BACI design (as detailed in section 8.8) is recommended with statistical analyses proceeding as described by Underwood (1993a).

The results of the Beyond-BACI analysis of the 'sand' perturbation revealed the need for long-term monitoring to detect an 'oil' impact against the high degree of background variability characteristic of the rocky intertidal area generally (Appendix C) and GSV specifically (Chapter 4). The length of monitoring required to detect the 'sand' perturbation at the longer temporal scale of 'Periods' (if it resulted in a 50-68% decrease in *B. nanum* abundance at the 'impact' site) was calculated to be equivalent to 16 'Periods' (see section 8.8). This is equivalent to at least 37.5 months of pre-impact sampling and corresponds to the recommendations made by Womersley (1988) who advocated at least 5 years of sampling to be able to detect seasonal intertidal trends at Port Stanvac. However, this calculation was based on monitoring of the original study sites, some of which were subjected to the confounding influences of substrata mobilisation during the course of preliminary monitoring. The redefinition of study sites (section 8.8.1) is expected to decrease the variability arising from this quarter and thus increase the power of a Beyond-BACI analysis, which may reduce the length of monitoring required if an oil spill occurs. It must be pointed out that only 7 'Periods' were required to achieve the desired power and detect the specified 'sand' impact at the temporal scale of 'Times', which is equivalent to at least 15.5 months of pre-impact sampling.

The seriousness of an oil spill event can be examined using a Beyond-BACI approach. For example, a transient decrease in *B. nanum* abundance at the temporal scale of 'Times' followed by a rapid recovery is likely to be 'acceptable' to environmental monitoring bodies, but a persistent impact detectable at the temporal scale of 'Periods' is much more serious and is indicative of longer-term change. If the monitoring program is adopted by Mobil, further discussion with their management board in conjunction with the EPA is desirable. The aim of this meeting would be to clearly define *a priori* what degree of change is acceptable in the event of an oil spill to both the EPA and Mobil.

9. References

Abel, P.D. (1976) Effect of some pollutants on the filtration rate of *Mytilus*. *Marine Pollution Bulletin* **7**, 228-231.

Addessi, L. (1994) Human disturbance and long-term changes on a rocky intertidal community. *Ecological Applications* **4**, 786-797.

Akberali, H.B. and Trueman, E.R. (1985) Effects of environmental stress on marine bivalve molluscs. *Advances in Marine Biology* **22**, 101-198.

Anderson, D.T. (1962) The reproduction and early life histories of the gastropods *Bembicium auratum* (Quoy & Gaimard) (Fam. Littorinidae), *Cellana tramoserica* (Sower) (Fam. Patellidae) and *Melanerita melanotragus* (Smith) (Fam. Neritidae). *Proceedings of the Linnean Society of N.S.W.* **87**, 62-68.

Anderson, G.R.V., Ehrlich, A.H., Roughgarden, P.R., Russel, J.D. and Talbot, F.H. (1981) The community structure of coral reef fishes. *American Naturalist* **117**, 476-495.

Anderson, M.J. (1995) Variations in biofilms colonising artificial surfaces: seasonal effects and effects of grazers. *Journal of the Marine Biological Association of the U.K.* **75**, 705-714.

Anderson, M.J. (1996) A chemical cue induces settlement of Sydney rock oysters, *Saccostrea commercialis*, in the Laboratory and in the field. *Biology Bulletin* **190**, 350-358.

Andrew, N.L. and Mapstone, B.D. (1987) Sampling and the description of spatial pattern in marine ecology. *Oceanography and Marine Biology Annual Review* **25**, 39-90.

Antia, E.E. (1993) A morphodynamic model of sandy beach susceptibility to tar pollution and self-cleansing on the Nigerian coast. *Journal of Coastal Research* **9**, 1065-1074.

Antrim, L.D., Thom, R.M., Gardiner, W.W., Cullinan, V.I., Shreffler, D.K. and Bienert, R.W. (1995) Effects of petroleum products on bull kelp (*Nereocystis luetkeana*). *Marine Biology* **122**, 23-31.

Aronson, R.B., Edmunds, P.J., Precht, W.F., Swanson, D.W. and Levitan, D.R. (1994) Large-scale, long-term monitoring of Caribbean coral reefs: simple, quick, inexpensive techniques. *Atoll Research Bulletin* **421**, 1-19.

Astles, K.L. (1993) Patterns of abundance and distribution of species in intertidal rock pools. *Journal of the Marine Biological Association of the U.K.* **73**, 555-569.

Avolizi, R.J. and Nuwayhid, M. (1974) Effects of crude oil and dispersants on bivalves. *Marine Pollution Bulletin* **5**, 149-153.

Axiak, V., George, J.J. and Moore, M.N. (1988) Petroleum hydrocarbons in the marine bivalve *Venus verrucosa*: accumulation and cellular responses. *Marine Biology* **97**, 225-230.

Baker, J.M. (1983) Impact of oil pollution on living resources. *The Environmental Supplement* **3**, 5-48.

Baker, J.M. (1991) Guidelines on biological impacts of oil pollution. *International Petroleum Industry Environmental Conservation Association (IPIECA) Report Series.* Volume **1**, 1-15.

Battershill, C.N. and Bergquist, P.R. (1982) Responses of an intertidal gastropod to field exposure of an oil and a dispersant. *Marine Pollution Bulletin* **13**, 159-162.

Beauchamp, K.A. and Gowing, M.M. (1982) A quantitative assessment of human trampling effects on a rocky intertidal community. *Marine Environmental Research* **7**, 279-293.

Beer, T., Humphries, R.B. and Bouwhuis, R. (1983) Modelling nearshore oil slick trajectories. *Marine Pollution Bulletin* **14**, 141-144.

Begon, M., Harper, J.L. and Townsend, C.R. (1986) *Individuals, Populations and Communities.* Blackwell Scientific Publications, Victoria, Australia.

Belbin, L. (1991) *PATN: Pattern analysis package.* [Computer program manual]. Division of Wildlife Ecology, Government Printer, CSIRO, Canberra.

Belbin, L. (1992) *PATN-Pattern analysis package (version 3.3).* [Computer program]. Division of Wildlife Ecology, CSIRO, Canberra.

Bence, J.R. and Nisbet, R.M. (1989) Space-limited recruitment in open systems: the importance of time delays. *Ecology* **70**, 1434-1441.

Bender, E.A., Case, T.J. and Gilpin, M.E. (1984) Perturbation experiments in community ecology: theory and practice. *Ecology* **65**, 1-13.

Berlow, E.L. (1997) From canalization to contingency: historical effects in a successional rocky intertidal community. *Ecological Monographs* **67**, 435-460.

Bernhardson, C.S. (1975) Type I error rates when multiple comparison procedures follow a significant *F* test of ANOVA. *Biometrics* **31**, 229-232.

Bernstein, B.B. and Zalinski, J. (1983) An optimal sampling design and power tests for environmental biologists. *Journal of Environmental Management* **16**, 35-43.

Beyers, D.W. (1998) Causal inference in environmental impact studies. *Journal of the North American Benthological Society* **17**, 367-373.

Black, R. (1979) Competition between intertidal limpets: an intrusive niche on a steep resource gradient. *Journal of Animal Ecology* **48**, 401-411.

Blackman, R.A.A. and Law, R.J. (1981) The *Eleni V* oil spill; return to normal conditions. *Marine Pollution Bulletin* **12**, 126-130.

Blackman, R.A.A., Baker, J.M., Kelly, J. and Reynard, S. (1973) The *Dona Marika* oil spill. *Marine Pollution Bulletin* **4**, 181-182.

Blake, R.W. (1979) Exploitation of a natural population of *Arenicola marina* (L.) from the north-east coast of England. *Journal of applied Ecology* **16**, 663-670.

Blumer, M. (1971) Scientific aspects of the oil spill problem. *Environmental Affairs* **1**, 54-73.

BMDP Version 5 (1990) BMDP Statistical Software Inc. Los Angeles, USA. [Software Manuals Vol. 1 & Vol. 2].

Borgmann, U. and Munawar, M. (1989) A new standardized sediment bioassay protocol using the amphipod *Hyalella azteca* (Saussure). *Hydrobiologia* **188/189** 425-531.

Branch, G.M. and Branch, M.L. (1981) Experimental analysis of intra-specific competition in an intertidal gastropod *Littorina unifasciata*. *Australian Journal of Marine and Freshwater Research* **32**, 573-589.

Brawley, S.H. and Johnson, L.E. (1991) Survival of fucoid embryos in the intertidal depends upon development stage and microhabitat. *Journal of Phycology* **27**, 179-186.

Brodersen, C. (1987) Rapid narcosis and delayed mortality in larvae of King Crabs and Kelp Shrimp exposed to the water-soluble fraction of crude oil. *Marine Environmental Research* **22**, 233-239.

Bros, W.E. and Cowell, B.C. (1987) A technique for optimizing sample size (replication). *Journal of Experimental Marine Biology and Ecology* **114**, 63-71.

Brosnan, D.M. and Crumrine, L.L. (1994) Effects of trampling on marine rocky shore communities. *Journal of Experimental Marine Biology and Ecology* **177**, 79-97.

Browder, J.A. (1988) Introduction: aquatic organisms as indicators of environmental pollution. *Water Resources Bulletin* **24**, 927-929.

Brown, A.C. (1996) Intertidal rock inundation by sand as an evolutionary corridor for benthic marine invertebrates. *South African Journal of Science* **92**, 162.

Buhler, D.R. and Williams, D.E. (1988) The role of biotransformation in the toxicity of chemicals. *Aquatic Toxicology* (Amsterdam) **11**, 19-28.

Buikema, A.L.Jr., Niederlehner, B.R. and Cairns, J.Jr. (1982) Biological monitoring part IV- toxicity testing. *Water Research* **16**, 239-262.

Burd, B.J., Nemec, A. and Brinkhurst, R.O. (1990) The development and analytical methods in benthic marine infaunal studies. *Advances in Marine Ecology* **26**, 169-247.

Burns, K.A. (1993) Analytical methods used in oil spill studies. *Marine Pollution Bulletin* **26**, 68-72.

Burns, K.A. and Smith, J.L. (1980) Hydrocarbons in Victorian coastal waters. *Australian Journal of Marine and Freshwater Research* **31**, 251-256.

Burton, G.A. Jr. and Scott, K.J. (1992) Sediment toxicity evaluations. Their niche in ecological assessments. *Environmental Science and Technology* **26**, 2068-2075.

Butler, A.J. (1987) Ecology of *Pinna bicolor* gmelin (Mollusca:Bivalvia) in Gulf St Vincent, South Australia: density, reproductive cycle, recruitment, growth and mortality at three sites. *Australian Journal of Marine and Freshwater Research* **38**, 743-769.

Butler, A.J. and Chesson, P.L. (1990) Ecology of sessile animals on hard substrata: the need to measure variation. *Australian Journal of Ecology* **15**, 521-531.

Bye, J.A.T. (1976) Physical oceanography of Gulf St Vincent and Investigator Strait Chapter 11, pp. 143-160. **In**: C.R. Twidale, M.J. Tyler and B.P. Webb (eds) *Natural History of the Adelaide Region.* Royal Society of South Australia (Inc.), Adelaide.

Bye, J.A.T. and Harbison, P. (1991) Transfer of inland salts to the marine environment at the head of Spencer Gulf, South Australia. *Palaeoecology* **84**, 357-368.

Bye, J.A.T. and Ng, S.C. (1994) The FLOWC Model. *Selected Topics in Atmospheric and Marine Sciences* **11**, 1-25. School of Earth Sciences, Flinders University, South Australia.

Cairns, J. (1994) Ecosystem health through ecological restoration: barriers and opportunities. *Journal of Aquatic Ecosystems* **3**, 5-14.

Cairns, J. Jr. (1983) Are single species toxicity tests alone adequate fro estimating environmental hazard? *Hydrobiologia* **100**, 47-57.

Cairns, J. Jr. and Niederlehner, B.R. (1987) Problems associated with selecting the most sensitive species for toxicity testing. *Hydrobiologia* **153**, 87-94.

Cairns, J.Jr. and Mount, D.I. (1990) Aquatic toxicology. Part 2. *Environmental Science and Technology* **24**, 154-160.

Cairns, J.Jr. and Van der Schalie, W.H. (1982) Biological monitoring. Part 1- Early warning systems. pp. 1179-1196. **In**: J. Cairns, Jr., A.L. Buikema, Jr., D.S. Cherry, E.E. Herricks and W.H. Van der Schalie (eds). *Biological Monitoring in Water Pollution.* Pergagon Press, New York.

Cairns, J.Jr., McCormick, P.V. and Niederlehner, B.R. (1993) A proposed framework for developing indicators of ecosystem health. *Hydrobiologia* **263**, 1-44.

Calow, P. (1989) The choice and implementation of environmental bioassays. *Hydrobiologia* **188/189**, 61-64.

Carballo, J.L., Naranjo, S.A. and Garcia-Gomez, J.C. (1996) Use of marine sponges as stress indicators in marine ecosystems at Algeciras Bay (southern Iberian Peninsula). *Marine Ecology-Progress Series* **135**, 109-122.

Carefoot, T. H. and Simpson R. D. (1977) *Seashore Ecology.* University of Queensland Press, Quennsland.

Carleton, J.H. and Done, T.J. (1995) Quantitative video sampling of coral reef benthos: large-scale application. *Coral Reefs* **14**, 35-46.

Carls, M.G. (1987) Effects of dietary and water-borne oil exposure on larval Pacific herring (*Clupea harengus pallasi*). *Marine Environmental Research* **22**, 253-270.

Castilla, J.C. and Bustmante, R.H. (1989) Human exclusion from rocky intertidal of Las Cruces, central Chile: effects on *Durvillaea antarctica* (Phaeophyta, Durvilleales). *Marine Ecology Progress Series* **50**, 203-214.

Castilla, J.C. and Durán, L.R. (1985) Human exclusion from the rocky intertidal zone of central Chile: the effects on *Concholepas concholepas* (Gastropoda). *Oikos* **45**, 391-399.

Caterall, C.P. and Poiner, I.R. (1987) The potential impact of human gathering on shellfish populations, with reference to some NE Australian intertidal flats. *Oikos* **50**, 114-122.

Celander, M., Broman, D., Förlin, L. and Näf, C. (1995) Effects of petroleum hydrocarbons on the hepatic cytochrome P450 1A1 system in rainbow trout. *Marine Environmental Research* **39**, 61-65.

Chang, R. (1991) *Chemistry.* Fourth Edition. McGraw-Hill Inc., Sydney.

Chapman, M.G. and Underwood, A.J. (1994) Disperal of the intertidal snail, *Nodolittorina pyramidalis*, in response to the topographic complexity of the substratum. *Journal of Experimental Marine Biology and Ecology* **179**, 145-169.

Chapman, M.G. and Underwood, A.J. (1996) Experiments on effects of sampling biota under intertidal and shallow subtidal boulders. *Journal of Experimental Marine Biology and Ecology* **207**, 103-126.

Chapman, M.G., Underwood, A.J. and Skilleter, G.A. (1995) Variability at different spatial scales between a subtidal assemblage exposed to the discharge of sewage and two control assemblages. *Journal of Experimental Marine Biology and Ecology* **189**, 103-122.

Chapman, M.G., Underwood, A.J. and Skilleter, G.A. (1995) Variability at different spatial scales between a subtidal assemblage exposed to the discharge of sewage and two control assemblages. *Journal of Experimental Marine Biology and Ecology* **189**, 103-122.

Chasse, C. (1978) The ecological impact on and near shores by the *Amoco Cadiz* oil spill. *Marine Pollution Bulletin* **9**, 298-301.

Chilton, N.B. and Bull, C.M. (1984) Influence of predation by a crab on the distribution of the size-groups of three intertidal gastropods in South Australia. *Marine Biology* **83**, 163-170.

Chilton, N.B. and Bull, C.M. (1986) Size related selection of two intertidal gastropods by the reef crab *Ozius truncatus. Marine Biology* **93**, 475-480.

Christie, H. and Berge, J.A. (1995) In situ experiments on recolonization of intertidal mudflat fauna to sediment contaminated with different concentrations of oil. *Sarsia* **80**, 175-185.

Clark, P.J. and Ward, T.J. (1994) The response of southern hemisphere saltmarsh plants and gastropods to experimental contamination by petroleum hydrocarbons. *Journal of Experimental Marine Biology and Ecology* **175**, 43-57.

Clark, R.B. (1989) *Marine Pollution.* 2nd Edition. pp. 33-64. Oxford Scientific Publications, Clarendon Press, Oxford.

Clark, R.B. (ed) (1982) The impact of oil pollution on marine populations, communities and ecosystems. *Philosophical Transactions of the Royal Society of London B* **297**, 183-443.

Clarke, K.R. (1990) Comparisons of dominance curves. *Journal of Experimental Marine Biology and Ecology* **138**, 143-157.

Clarke, K.R. (1993) Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* **18**, 117-143.

Clarke, K.R. and Green, R.H. (1988) Statistical design and analysis for a 'biological effect' study. *Marine Ecology-Progress Series* **46**, 213-226.

Clarke, K.R. and Warwick, R.M. (1994a) *Change in marine communities: an approach to statistical analysis and interpretation.* Natural Environment Research Council, United Kingdom.

Clarke, K.R. and Warwick, R.M. (1994b) *User Guide to PRIMER v3.1b* (Plymouth Routines in Multivariate Ecological Research). [Computer Manual]. Plymouth, United Kingdom.

Coast Protection Board (1984) *Adelaide Coast Protection Strategy Review.* Coastal Management Branch Conservation Programmes Division; South Australian Department of Environment and Planning.

Cobelas, M.A., Verdugo, M. and Rojo, C. (1995) Time series of multivariate data in aquatic ecology. *Aquatic Sciences* **57**, 185-198.

Cohen, J. (1988) *Statistical Power Analysis for the Behavioural sciences..* 2nd Edition. Lawrence Erlbaum Associates, New Jersey, U.S.A.

Cole, R.C., Ayling, A.M. and Creese, R.G. (1990) Effects of marine reserve protection at Goat Island, northern New Zealand. *New Zealand Journal of Marine and Freshwater Research* **24**, 197-210.

Coles, J.A., Farley, S.R. and Pipe, R.K. (1994) Effects of fluoranthene on the immunocompetence of the common marine mussel, *Mytilus edulis. Aquatic Toxicology* **30**, 367-379.

Connell J.H. (1961b). The influence of interspecific competition and other factors on the distribution of the barnacle *Chthamalus stellatus*. *Ecology* **42**, 710-723.

Connell, J.H. (1961a). Effects of competition, predation by *Thais lapillus* and other factors on natural populations of the barnacle *Balanus ballanoides*. *Ecological Monographs* **31**, 61-104.

Connell, J.H. (1974) Field experiments in marine ecology. pp. 21-54. **In**: R. Mariscal (ed). *Experimental Marine Biology.* Academic Press, New York.

Connell, J.H. (1978) Diversity in tropical rain-forests and tropical reefs. *Science* **199**, 1302-1310.

Connell, J.H. and Keough, M.J. (1985) Disturbance and patch dynamics of subtidal marine animals on hard substrata. pp. 125-151. **In**: S.T.A. Pickett and P.S. White (eds). *The Ecology of Natural Disturbance and Patch Dynamics.* Academic Press, New York, USA.

Connell, J.H. and Slayter, R.O. (1977) Mechanisms of succession in natural communities and their role in community stability and organization. *American Naturalist* **111**, 1119-1143.

Connell, S.D. and Jones, G.P. (1991) The influence of habitat complexity on postrecruitment processes in a temperate reef fish population. *Journal of Experimental Marine Biology and Ecology* **151**, 271-294.

Connell, S.D. and Jones, G.P. (1991) The influence of habitat complexity on post-recruitment processes in a temperate reef fish population. *Journal of Experimental Marine Biology and Ecology* **151**, 271-294.

Constable, A.J. (1991) The role of science in environmental protection. *Australian Journal of Marine and Freshwater Research* **42**, 527-538.

Cove, M.N. (1994) Effluent Water Quality Monitoring Program. *Adelaide Refinery Environment Management Handbook.* Unpublished Internal Adelaide Refinery Document. 13pp.

Cowell, E.B. (1969) The effects of oil pollution on salt-marsh communities in Pembrokeshire and Cornwall. *Journal of Applied Ecology* **6**, 133-142.

Cripps, G.C. and Priddle, J. (1995) Hydrocarbon content of an Antarctic infaunal bivalve- historical record or life cycle changes? *Antarctic Science* **7**, 127-136.

Dakin, W.J. (1950). *Australian Seashores.* Angus and Robertson, Sydney, 372pp.

Davies, J.M., Davies, I.M., Hawkins, A.D., Johnstone, R., McVicar, A., McLay, A., Topping, G. and Whittle, K. (1993) Interim report of the marine monitoring programme on the Braer oil-spill. *Marine Policy* **17**, 441-448.

Day, R.W. and Quinn, G.P. (1989) Comparisons of treatments after an analysis of variance in ecology. *Ecological Monographs* **59**, 433-463.

Dayton, P.K. (1971) Competition, disturbance and community organization: the provision and subsequent utilization of space in a rocky intertidal community. *Ecological Monographs* **41**, 351-389.

De Vogelaere, A.P. and Foster, M.S. (1994) Damage and recovery in intertidal *Fucus gardneri* assemblages following the 'Exxon Valdez' oil spill. *Marine Ecology-Progress Series* **106**, 263-271.

Dean, R.L. and Connell, J.H. (1987) Marine invertebrates in an algal succession. I. Variations in abundance and diversity with succession. *Journal of Experimental Marine Biology and Ecology* **109**, 195-215.

den Hartog, C. and Jacobs, R.P.W.M. (1980) Effects of the "Amoco Cadiz" oil spill on an eelgrass community at Roscoff (France) with special reference to the mobile benthic fauna. *Helgoländer Meeresuntersuchungen* **33**, 182-191.

Denley, E.J. and Underwood, A.J. (1979) Experiments on factors influencing settlement, survivaal and growth of two species of barnacle in NSW. *Journal of Experimental Marine Biology and Ecology* **36**, 269-293.

Denny, M.W., Daniel, T.L. and Koehl, M.A.R. (1985) Mechanical limits to size in wave swept organisms. *Ecological Monographs* **55**, 69-102.

Dethier, M.N (1982) Pattern and process in tidepool algae: factors influencing seasonality and distribution. *Botanica Marina* **25**, 55-66.

Dethier, M.N (1984) Disturbance and recovery in intertidal pools: maintenance of mosaic patterns. *Ecological Monographs* **54**, 99-118.

Digby, P.G.M. and Kempton, R.A. (1987) *Multivariate Analysis of Ecological Communities.* Chapman and Hall, New York.

Dostine, P.L., Humphrey, C.L. and Faith, D.P. (1993) Requirements for effective biological monitoring of freshwater ecosystems. *Technical Memorandum* **43**. Northern Territory University Printing, Northern Territory.

Dufrêne, M. and Legendre, P. (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs* **67**, 345-366.

Duke, N.C., Pinzon, Z.S. and Prada, M.C. (1997) Large-scale damage to mangrove forests following two large oil spills in Panama. *Biotropica* **29**, 2-14.

Durán, L.R. and Castilla, J.C. (1989) Variation and persistence of the middle rocky intertidal community of central Chile, with and without human harvesting. *Marine Biology* **103**, 555-562.

Durán, L.R., Castilla, J.C. and Oliva, D. (1987) Intensity of human predation on rocky shores at Les Cruces in central Chile. *Environmental Conservation* **14**, 143-149.

Eberhardt, L.L (1978) Appraising variability in population studies. *Journal of Wildlife Management* **42**, 207-238.

Eberhardt, L.L and Thomas, J.M. (1991) Designing environmental field studies. *Ecological Monographs* **61**, 53-73.

Ehrhardt, M. and Blumer, M. (1972) *Environmental Pollution* **3**, 179-194.

Ehrhardt, M.G. and Burns, K.A. (1993) Hydrocarbons and related photo-oxidation products in Saudi Arabian Gulf coastal waters and hydrocarbons in underlying sediments and bioindicator bivalves. *Marine Pollution Bulletin* **27**, 187-197.

Ellis, J.I. and Schneider, D.C. (1997) Evaluation of sampling design for environmental impact assessment. *Environmental Monitoring and Assessment* **48**, 157-172.

Elmgren, R., Hansson, S., Larsson, U., Sundelin, B. and Boehm, P.D. (1983) The 'Tsesis' oil spill: Acute and long-term impact on the benthos. *Marine Biology* **73**, 51-65.

Emlen, J.M. (1989) Terrestrial population models for ecological risk assessment : a state of the art review. *Environmental Toxicology and Chemistry* **8**, 831-842.

Emson, R.H. and Faller-Fritsch, R.J. (1976) An experimental investigation into the effect of crevice availability on abundance and size-structure in a population of *Littorina rubis* (Maton): Gastropoda: Prosobranchia. *Journal of Experimental Marine Biology and Ecology* **23**, 285-297.

Essaid, H.I., Herkelrath, W.N. and Hess, K.M. (1993) Simulation of fluid distributions observed at a crude oil spill incorporating hysteresis, oil entrapment, and spatial variability of hydraulic properties. *Water Resources Research* **29**, 1753-1770.

Ewa-Oboho, I.O. and Abby-Kalio, N.J. (1994) Effects of simulated oil exposure on two intertidal macrozoo benthos: *Tympanotonus* (L) and *Uca tangeri* (Eydoux, 1935) in a tropical estuarine ecosystem. *Ecotoxicology and Environmental Safety* **28**, 232-243.

Fadeiro, M.E. and Veronis, G. (1977) On weighted-mean schemes for the finite-difference approximation to the advection-diffusion equation. *Tellus* **29**, 512-522.

Fairweather, P.G. (1990) Ecological changes due to our use of the coast: research needs versus effort. *Proceedings of the Ecological Society of Australia* **16**, 71-77.

Fairweather, P.G. (1991a) Statistical power and design requirements for environmental monitoring. *Australian Journal of Marine and Freshwater Research* **42**, 555-567.

Fairweather, P.G. (1991b) A conceptual framework for ecological studies of coastal resources: an example of a tunicate collected for bait on Australian seashores. *Ocean and Shoreline Management* **15**, 125-142.

Fairweather, P.G. (1993) Links between ecology and ecophilosophy, ethics and the requirements of environmental management. *Australian Journal of Ecology* **18**, 3-19.

Fairweather, P.G. and Underwood, A.J. (1991) Experimental removals of a rocky intertidal predator: variations within two habitats in the effects on prey. *Journal of Experimental Marine Biology and Ecology* **154**, 29-75.

Faith, D.P., Humphrey, C.L. and Dostine, P.L. (1991) Statistical power and BACI designs in biological monitoring: Comparative evaluation of measures of community dissimilarity based on benthic macroinvertebrate communities in Rockhole Mine Creek, Northern Territory, Australia. *Australian Journal of Marine and Freshwater Research* **42**, 589-602.

Faith, D.P., Minchin, P.R. and Belbin, L. (1987) Compositional dissimilarity as a robust measure of ecological distance. *Vegetatio* **69**, 57-68.

Farke, H., Wonneberger, K., Gunkel, W. and Dahlmann, G. (1985) Effects of oil and a dispersant on intertidal organisms in field experiments with a mesocosm, the Bremerhaven Caisson. *Marine Environmental Research* **15**, 97-114.

Farmer, D. and Li, M. (1994) Oil dispersion by turbulence and coherent circulations. *Oceanographic Engineering* **21**, 575-586.

Farrell, T.M. (1989) Succession in a rocky intertidal community: the importance of disturbance size and position within a disturbed patch. *Journal of Experimental Marin biology and Ecology* **128**, 57-73.

Farrell, T.M. (1991) Models and mechanisms of succession: an example from a rocky intertidal community. *Ecological Monographs* **61**, 95-113.

Farrington, J.W. and Tripp, B.W. (1993) International Mussel Watch. *Oceanus* **36**, 62-64.

Farrington, J.W., Goldberg, E.D., Risebrough, R.W., Martin, J.H. and Bowen, V.T. (1983) U.S. "Mussel Watch" 1976-1978: an overview of the trace-metal, DDE, PCB,hydrocarbon, and artificial radionuclide data. *Environmental Science and Technology* **17**, 490-496.

Fiadeiro, M.E. and Veronis, G. (1977) On weighted-mean schemes for the finite difference approximation to the advection-diffusion equation. *Tellus* **29**, 512-522.

Floc'h, J. and Diouris, M. (1980) Initial effects of Amoco Cadiz oil on intertidal algae. *Ambio* **9**, 284-286.

Foster, M.S., Harrold, C. and Hardin, D.D. (1991) Point vs. photo quadrat estimates of the cover of sessile marine organisms. *Journal of Experimental Marine Biology and Ecology* **146**, 193-203.

Friedman, M. (1937) The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the American Statistical Association* **32**, 675-701.

Gaines, S.D. and Bertress, M.D. (1992) Dispersal of juveniles and variable recruitment in sessile marine species. *Nature* **360**, 579-580.

Gaines, S.D. and Roughgarden, J. (1985) Larval settlement rate: a leading determinate of structure in an ecological community of the marine intertidal zone. *Proceedings of the National Academy of Science U.S.A.* **82**, 3707-3711.

Garrity, S.D. (1984). Some adaptations of gastropods to physical stress on a tropical rocky shore. *Ecology* **65**, 559-574.

Garrity, S.D. and Levings, S.C. (1990) Effects of an oil spill on the gastropods of a tropical intertidal reef flat. *Marine Environmental Research* **30**,119-153.

Garrity, S.D. and Levings, S.C. (1993) Effects of an oil spill on some organisms living on mangrove (*Rhizophora mangle* L.) roots in low wave-energy habitats in Caribbean Panama. *Marine Environmental Research* **35**, 251-271.

Gary, J.H. and Handwerk, G.E. (1994) *Petroleum Refining. Technology and Economics.* Third Edition. pp. 23-32. Marcel Dekker Inc., New York.

Gauch, H.G. and Whittaker, R.H. (1981) Hierarchical classification of community data. *Journal of Ecology* **69**, 537-557.

Gauch, H.G. Jn (1982) *Multivariate Analysis in Community Ecology.* Cambridge University Press, Cambridge U.K.

George, J.D. (1980) Photography as a marine biological research tool. pp. 45-115. **In**: *The Shore Environment Vol 1: Methods.* J.H. Price, D.E.G. Irvine and W.F. Farnham (eds). Academic Press, London.

Gerrodette, T. (1987) A power analysis for detecting trends. *Ecology* **68**, 1364-1372.

GESAMP (1977) The impact of oil on the marine environment. Joint Group of Experts on the Scientific Aspects of Marine Pollution. *Reports and Studies* **6** (FAO, Rome).

Ghazanshahi, J., Huchel, T.D. and Devinny, J.S. (1983) Alteration of southern California rocky shore ecosystems by public recreational use. *Journal of Environmental Management* **16**, 379-394.

Giesy, J.P. and Graney, R.L. (1989) Recent developments in and intercomparisons of acute and chronic bioassays and bioindicators. *Hydrobiologica* **188/189**, 21-60.

Giesy, J.P., Rosiu, C.J., Graney, R.L., Newsted, J.L., Benda, A., Kreis, R.G.Jr, and Norvath, F.J. (1988) Toxicity of Detroit River (Michigan, USA) sediment interstitial water to the bacterium *Photobacterium phosphoreum. Journal of Great Lakes Research* **14**, 502-513.

Glasby, T.M. (1997) Analysing data from post-impact studies using assymetrical analyses of variance - a case study of epibiota on marinas. *Australian Journal of Ecology* **22**, 448-459.

Glasby, T.M. and Underwood, A.J. (1996) Sampling to differentiate between pulse and press perturbations. *Environmental Monitoring and Assessment* **42**, 241-252.

Glegg, G.A. and Rowland, S.J. (1996) The Braer oil spill - hydrocarbon concentrations in intertidal organisms. *Marine Pollution Bulletin* **32**, 486-492.

Godfrey, P.J. (1978) Diversity as a measure of benthic macroinvertebrate community response in water pollution. *Hydrobiologia* **57**, 111-122.

Goldberg, E.D. (1986) The mussel watch concept. *Environmental Monitoring and Assessment* **7**, 91-103.

Gosselin, L.A. and Qian, P. (1996) Early post-settlement mortality of an intertidal barnacle: a critical period for survival. *Marine Ecology-Progress Series* **135**, 69-75.

Graney, R.L. and Giesy, J.P. Jr. (1986) Effects of long-term exposure to pentachlorophenol on the free amino acid pool and energy reserves of the freshwater amphipod *Gammarus pseudolimnaeus* Bousfield (Crustacea, Amphipoda). *Ecotoxicology and Environmental Safety* **12**, 233-251.

Grant, D.L., Clarke, P.J. and Allaway, W.G. (1993) The response of grey mangrove (*Avicennia marina* (Forsk.) Vierh) seedlings to spills of oil. *Journal of Experimental Marine Biology and Ecology* **171**, 273-295.

Grasmuck, N., Haury, J., Leglize, L. and Muller, S. (1995) Assessment of the bio-indicator capacity of aquatic macrophytes using multivariate analysis. *Hydrobiologia* **300/301**, 115-122.

Gray, J.S. (1989) Effects of environmental stress on species rich assemblages. *Biological Journal of the Linnean Society* **37**, 19-32.

Gray, J.S. and Pearson, T.H. (1982) Objective selection of sensitive species indicative of pollution-induced change in benthic communities. 1. Comparative methodology. *Marine Ecology Progress Series* **9**, 111-119.

Gray, J.S., Aschan, M., Carr, M.R., Clarke, K.R., Green, R.H., Pearson, T.H., rosenberg, R. and Warwick, R.M. (1988) Analysis of community attributes of the benthic macrofauna of Frierfjord/Langesundfjord and in a mesocosm experiment. *Marine Ecology Progress Series* **46**, 151-165.

Gray, J.S., Clarke, K.R., Warwick, R.M. and Hobbs, G. (1990) Detection of initial effects of pollution on marine benthos: an example from the Ekofisk and Eldfisk oilfields, North Sea. *Marine Ecology Progress Series* **66**, 285-299.

Green, R.H. (1979) *Sampling Design and Statistical Methods for Environmental Biologists.* Wiley-Interscience, New York.

Green, R.H. (1989) Power analysis and practical strategies for environmental monitoring. *Environmental Research* **50**, 195-205.

Green, R.H. (1993) Application of repeated measures designs in environmental impact and monitoring studies. *Australian Journal of Ecology* **18**, 81-98.

Grigg, R.W. (1994) Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. *Marine Ecology Progress Series* **103**, 25-34.

Grzechnik, M. (1995) A tidal model of Gulf St. Vincent, South Australia, with particular attention to Outer Harbor and Port Stanvac. Revised Honours Thesis. Department of Applied Maths, University of Adelaide, South Australia.

Gundlach, E.R., Ruby, C.H., Hayes, M.O. and Blount, A.E. (1978) The *Urquiola* oil spill, La Coruna, Spain: impact and reaction on beaches and rocky coasts. *Environmental Geology* **2**, 131-143.

Guzman, H.M., Jackson, J.B.C. and Weil, E. (1991) Short term ecological consequences of a major oil spill on Panamanian subtidal reef corals. *Coral Reefs* **10**, 1-12.

Hawkins, S.J. and Hartnoll, R.G. (1983a) Grazing of intertidal algae by marine invertebrates. *Oceanography and Marine Biology: Annual Review* **21**, 195-282.

Hawkins, S.J. and Hartnoll, R.G. (1983b) Changes in a rocky shore community: an evaluation of monitoring. *Marine Environmental Research* **9**, 131-181.

Hayes, M.O., Michel, J., Montello, T.M., Aurand, D.V., Al-Mansi, A.M., Al-Moamen, A.H., Sauer, T.C. and Thayer, G.W. (1993) Distribution and weathering of shoreline oil one year after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 135-142.

Hellaway, J.M. (1986) *Biological Indicators of Freshwater Pollution and Environmental Management.* Elsevier, New York, New York.

Help, C., Warwick, R.M., Carr, M.R., Herman, P.M.J., Huys, R., Smol, N. and Van Holsbeke, K. (1988) Analysis of community attributes of the benthic meiofauna of Frierfjord/Langesundfjord. *Marine Ecology-Progress Series* **46**, 171-180.

Herricks, E.E. and Cairns, J. Jr. (1982) Biological monitoring. Part III- Receiving system methodology based on community structure. *Water Reseach or Resources* **16**, 141-153.

Hewitt, J.E., McBride, G.B., Pridmore, R.D. and Thrush, S.F. (1993) Patchy distributions: optimising sample size. *Environmental Monitoring and Assessment* **27**, 95-105.

Hilborn, R. and Stearns, S.C. (1982) On inference in ecology and evolutionary biology: the problem of multiple causes. *Acta Biotheoretica* **31**, 145-164.

Hill, A.S. and Hawkins, S.J. (1990) An investigation of methods for sampling microbial films on rocky shores. *Journal of the Marine Biological Association of the U.K.* **70**, 77-88.

Hill, M.O. (1973) Reciprocal averaging: an eigenvector method of ordination. *Journal of Ecology* **61**, 237-249.

Hockey, P.A.R. and Bosman, A.L. (1986) Man as an intertidal predator in Transkei: Disturbance, community convergence and management of a natural food resource. *Oikos* **46**, 3-14.

Hockey, P.A.R., Bosman, A.L. and Siegfried, W.R. (1988) Patterns and correlates of shellfish exploitation by coastal people in Transkei: An enigma of protein production. *Journal of Applied Ecology* **25**, 353-363.

Holme, N.A. and Barrett, R.L. (1977) A sledge with television and photographic cameras for quantitative investigation of epifauna on the Continental Shelf. *Journal of the Marine Biological Association of the U.K.* **57**, 391-403.

Hose, J.E., Puffer, H.W., Oshida, P.S. and Bay, S.M. (1983) Developmental and cytogenic abnormalities induced in the purple seaurchin by environmental levels of benzo(a)pyrene. *Archives of Environmental Contamination and Toxicology* **12**, 319-325.

Hoult, D.P. (1972) Oil spreading on the sea. *Annual Review of Fluid Mechanics* **4**, 341-368.

Hughes, R.N. and Roberts, D.J. (1980) Growth and reproductive rates of *Littorina neritoides* (L.) in North Wales. *Journal of the Marine Biological Association of the U.K.* **60**, 591-599.

Humphrey, C.L., Bishop, K.A. and Brown, V.M. (1989) Use of biological monitoring in the assessment of effects of mining wastes on aquatic ecosystems of the Alligator Rivers region, tropical northern Australia. *Environmental Monitoring and Assessment* **14**, 139-181.

Humphrey, C.L., Faith, D.P. and Dostine, P.L. (1995) Baseline requirements for assessment of mining impacts using biological monitoring. *Australian Journal of Ecology* **20**, 150-166.

Hurlbert, S.H. (1984) Pseudoreplication and the design of ecological field experiments. *Ecological Monographs* **54**, 187-211.

Huston, M.A. (1985) Patterns of species diversity in coral reefs. *Annual Review of Ecology and Systematics* **16**, 149-177.

Hyland, J.L. and Schneider, E.D. (1976) Petroleum hydrocarbons and their effects on marine organisms, populations, communities, and ecosystems. p. 463 **In**: *Sources, Effects and Sinks of Hydrocarbons in the Aquatic Environment.* American Institute of Biological Science, Washington, D.C.

Jackson, J.B.C., Cubit, J.D., Keller, B.D., Batista, V., Burns, K., Caffey, H.M., Caldwell, R.L., Garrity, S.D., Getter, C.D., Gonzalez, C., Guzman, H.M., Kaufmann, K.W., Knap, A.H., Levings, S.C., Marshall, M.J., Steger, R., Thompson, R.C. and Well, E. (1989) Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* **243**, 37-44.

Jackson, L., Biddleman, T. and Vernberg, W. (1981) Influence of reproductive activity on toxicity of petroleum hydrocarbons to ghost crabs. *Marine Pollution Bulletin* **12**, 63-65.

James, F.C. and McCulloch, C.E. (1990) Multivariate analysis in ecology and systematics: panacea or Pandora's Box? *Annual Review of Ecology and Systematics* **21**, 129-166.

James, M.O. and Kleinow, K.M. (1994) Chapter 1. Trophic transfer of chemicals in the aquatic environment. pp. 1-54. **In**: D.C. Maslins and G.K. Ostrander (eds). *Aquatic Toxicology Molecular, Biochemical, and Cellular Perspectives.* CRC Press, Inc., London.

Jan, R.Q., Dai, C.F. and Chang, K.H. (1994). Monitoring of hard substrate communities. pp. 285-310. **In:** K.J..M. Kramer (ed) *Biomonitoring of Coastal Waters and Estuaries.* CRC Press, Boca Raton, F.L.

Janson, S. and Vegelius, J. (1981) Measures of ecological association. *Oecologia* (Berl.) **49**, 371-376.

Jara, H.F. and Moreno, C.A. (1984) Herbivory and structure in a midlittoral rocky community: a case in southern Chile. *Ecology* **65**, 28-38.

Johnson, R.K., Wiederholm, T. and Rosenberg, D.M. (1993) Freshwater biomonitoring using individual organisms, populations, and species assemblages of benthic macroinvertebrates. pp. 40-125. **In**: D.M.Rosenberg and V.H. Resh (eds). *Freshwater Biomonitoring and Benthic Macroinvertebrates.* Chapman and Hall, London.

Jones, G.P. and Kaly, U.L. (1996) Criteria for selecting marine organisms in biomonitoring studies. pp. 29-48. **In**: R.J. Schmitt and C.W. Osenberg (eds). *Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats.* Academic Press, Inc., London.

Kaly, U.L. and Jones, G.P. (1994) Long-term effects of blasted boat passages on intertidal organisms in Tuvalu: a meso-scale human disturbance. *Bulletin of Marine Science* **54**, 164-179.

Karlson, R.H. and Hurd, L.E. (1993) Disturbance, coral reef communities, and changing coral reef paradigms. *Coral Reefs* **12**, 117-125.

Karr, J.R. (1987) Biological monitoring and environmental assessment: a conceptual framework. *Environmental Management* **11**, 249-256.

Kay, A.M. and Liddle, M.J. (1989) Impact of human trampling in different zones of a coral reef flat. *Environmental Management* **13**, 509-520.

Kenkel, N.C. and Orloci, L. (1986) Applying metric and non-metric multidimensional scaling to some ecological studies: some new results. *Ecology* **67**, 919-928.

Kennelly, S.J. (1987) Physical disturbances in an Australian kelp community. I. Temporal effects. *Marine Ecology-Progress Series* **40**, 145-153.

Kennish, R., Williams, G.A., and Lee, S.Y. (1996) Algal seasonality on an exposed rocky shore in Hong Kong and the dietary implications for the herbivorous crab *Grapsus albolineatus. Marine Biology.***125**, 55-64.

Keough, M.J. and Mapstone, B.D. (1995) Protocols for designing marine ecological monitoring programs associated with BEK mills. National Pulp Mills Research Program *Technical Report* No. **11**. Canberra: CSIRO, 185 pp.

Keough, M.J. and Mapstone, B.D. (1997) Designing environmental monitoring for pulp mills in Australia. *Water Science and Technology* **35**, 397-404.

Keough, M.J. and Quinn, G.P. (1991) Causality and the choice of measurements for detecting human impacts in marine environments. *Australian journal of Marine and Freshwater Research* **42**, 539-554.

Keough, M.J., Quinn, G.P. and King, A. (1993) Correlations between human collecting and intertidal mollusc populations on rocky shores. *Conservation Biology* **7**, 378-390.

Keough, M.J.and Quinn, G.P. (1998) Effects of periodic disturbances from trampling on rocky intertidal algal beds. *Ecological Applications* **8**, 141-161.

Kim, J.H. and Dewreede, R.E. (1996) Effects of patch size and season of disturbance on algal patch recovery in a rocky intertidal community. *Marine Ecology-Progress Series* **133**, 217-228.

Kingsford, M.J., Underwood, A.J. and Kennelly, S.J. (1991) Humans as predators on rocky reefs in New South Wales, Australia. *Marine Ecology-Progress Series* **72**, 1-14.

Klungsøyr, J., Wilhelmsen, S., Westrheim, K., Saetvedt, E. and Palmork, K.H. (1988) The GEEP Workshop: organic chemical analyses. *Marine Ecology-Progress Series* **46**, 19-26.

Kramer, K.J.M., Jenner, H.A. and de Zwart, D. (1989) The valve movement response of mussels: a tool in biological monitoring. *Hydrobiologia* **188/189**, 433-443.

Krebs, C.T. and Burns, K.A. (1977) Long-term effects of an oil spill on populations of the salt-marsh crab *Uca pugnax*. *Science* **197**, 484-487.

Krivolutzky, D.A. (1986) Animals as bioindicators. pp. 27-34. **In**: J. Salanki (ed). *IUBS Monograph Series No. 1. Biological Monitoring of the State of the Environment: Bioindicators. An Overview of the IUBS Program on Bioindicators 1985.* IRL Press for the ICSU Press, U.K.

Krupp, F. and Jones, D.A. (1993) The creation of a marine sanctuary after the 1991 Gulf War oil spill. *Marine Pollution Bulletin* **27**, 315-323.

Kruskal, W.H. and Wallis, W.A. (1952) Use of ranks in one-criterion analysis of variance. *Journal of the American Statistics Association* **47**, 583-621.

Lang, C. and Reymond, O. (1995) An improved index of environmental quality for Swiss rivers based on benthic invertebrates. *Aquatic Sciences* **57**, 172-180.

Laubier, L. (1980) The Amoco Cadiz oil spill: an ecological impact study. *Ambio* **9**, 268-276.

Lemire, M. and Bourget, E. (1996) Substratum heterogeneity and complexity influence micro-habitat selection of *Balanus* sp. and *Tubularia crocea* larvae. *Marine Ecology-Progress Series* **135**, 77-87.

Lenat, D. (1993) A biotic index for the southeastern United States: derivation and list of tolerance values, with criteria for assigning water quality ratings. *Journal of the North American Benthological Society* **12**, 279-290.

Levell, D. (1976) The effect of Kuwait crude oil and the dispersant BP1100X on the lugworm *Arenicola marina L.* pp. 131-188. **In**: J.M. Baker (ed). *Marine Ecology and Oil Pollution.* Applied Science Publishers, Barking.

Levings, C.D., Foreman, R.E. and Tunnicliffe, V.J. (1983) Review of the benthos of the Strait of Georgia and continuous fjords. *Canadian Journal of Fisheries and Aquatic Sciences* **40**, 1120-1141.

Levings, S.C. and Garrity, S.D. (1983) Diel and tidal movements in two co-occurring neretid snails: differences in grazing patterns on a tropical reef shore. *Journal of Experimental Marine Biology and Ecology* **67**, 261-278.

Lewis, J.R. (1961) The littoral zone on rocky shores- a biological or physical entity? *Oikos* **12**, 280-301.

Lewis, J.R. (1964) *The Ecology of Rocky Shores.* London, English Universities Press. 323 pp.

Lewis, J.R. (1978) The implications of community structure for benthic monitoring studies. *Marine Pollution Bulletin* **9**, 64-67.

Liddle, M.J. (1975) A selective review of the ecological effects of human trampling on natural ecosystems. *Biological Conservation* **7**, 17-36.

Liddle, M.J. (1991) Recreational ecology: effects of trampling on plants and corals. *Trends in Ecology and Evolution* **6**, 13-17.

Liddle, M.J. and Kay, A.M. (1987) Resistance, survival and recovery of trampled corals on the Great Barrier Reef. *Biological Conservation* **42**, 1-18.

Lieberman, M., John, D.M. and Lieberman, D. (1984) Factors affecting algal species assemblages on reef and coral substrata of Ghana. *Journal of Experimental Marine Biology and Ecology* **75**, 129-143.

Likens, G.E. (1992) *Ecosystem Approach: Its Use and Abuse. Excellence in Ecology. Series I.* O. Kinne(ed). Ecology Institute, New York.

Littler, M.M., Martz, D.R. and Littler, D.S. (1983) Effects of recurrent sand deposition on rocky intertidal organisms: importance of substrate heterogeneity in a fluctuating environment. *Marine Ecology Progress Series* **11**, 129-139.

Lohse, D.P. (1993) The effects of substratum type on the population dynamics of three common intertidal animals. *Journal of Experimental Marine Biology and Ecology* **173**, 133-154.

Loya, Y. and Rinkevich, B. (1980) Effects of oil pollution on coral reef communities. *Marine Ecology-Progress Series* **3**, 167-180.

Mackay, D.A. and Underwood, A.J. (1977) Experimental studies on homing in the intertidal patellid limpet *Cellana tramoserica* (Sowerby). *Oecologia* (Berl.) **30**, 215-237.

Mackay, D.W., Holmes, P.J. and Redshaw, C.J. (1989) The application of bioassay techniques to water pollution problems- the United Kingdom experience. *Hydrobiologia* **188/189**, 77-86.

MacLulich, J.H. (1986) Experimental evaluation of methods for sampling and assaying intertidal epilithic microalgae. *Marine Ecology-Progress Series* **34**, 275-280.

MacLulich, J.H. (1987) Variations in the density and variety of intertidal epilithic microflora. *Marine Ecology-Progress Series* **40**, 285-293.

Maher, W.A. and Aislabie, J. (1992) Polycyclic aromatic hydrocarbons in nearshore marine sediments of Australia. *The Science of the Total Environment* **112**, 143-164.

Maher, W.A. and Norris, R.H. (1990) Water quality assessment programs in Australia deciding what to measure, and how and where to use bioindicators. *Environmental Monitoring and Assessment* **14**, 115-130.

Maltby, L. and Calow, P. (1989) The application of bioassays in the resolution of environmental problems; past, present and future.

Mapstone, B.D. (1995) Scalable decision rules for environmental impact studies: effect size, type I, and type II errors. *Ecological Applications* **5**, 401-410.

Mapstone, G.M. (1978) Egg capsules and early development in *Siphonaria diemenensis* (Quoy & Gaimard, 1833) and *Siphonaria baconi* (Reeve, 1856). *Journal of the Malacological Society of Australia* **4**, 85-92.

Maslins, D.C., Myers, M.S. and Roubal, W.T. (1983) Organic free radicals associated with idiopathic liver lesions of English Sole (*Parophrys vetulus*) from polluted marine environments. *Environmental Science and Technology* **17**, 679-685.

May, V., Bennett, I., and Thompson, T.E. (1970) Herbivore-algal relationships on a coastal rock platform (Cape Banks, N.S.W.). *Oecologia* (Berlin) **6**, 1-14.

McCormick, M.I. (1994) Comparison of field methods for measuring surface topography and their associations with a tropical reef fish assemblage. *Marine Ecology Progress Series* **112**, 87-96.

McCormick, P.V. and Cairns, J., Jr. (1994) Algae as indicators of environmental change. *Journal of Applied Phycology* **6**, 509-526.

McGuiness, K.A. (1987a) Disturbance and organisms on boulders I. Patterns in the environment and the community. *Oecologia* (Berlin) **71**, 409-419.

McGuiness, K.A. (1987b) Disturbance and organisms on boulders II. Causes of patterns in diversity and abundance. *Oecologia* (Berlin) **71**, 409-419.

McGuiness, K.A. (1990) Effects of oil spills on macro-invertebrates of saltmarsh and mangrove forests in Botany Bay, New South Wales, Australia. *Journal of Experimental Marine Biology and Ecology* **142**, 121-135.

McKee, M.J. and Knowles, C.O. (1986) Effects of fenvalerate on biochemical parameters, survival, and reproduction of *Daphnia magna. Ecotoxicology and Environmental Safety* **12**, 70-84.

McLauren, P. (1985) Behaviour of diesel fuel on a high energy beach. *Marine Pollution Bulletin* **16**, 191-196.

McLulich, J.H. (1987) Variations in the density and variety of intertidal epilithic microflora. *Marine Ecology-Progress Series* **40**, 285-293.

Menge, B.A. and Farrell, T.M. (1989) Community structure and interaction webs in shallow marine hard-bottom communities: test of an environmental stress model. *Advances in Ecological Research* **19**, 189-262.

Metaxas, A. and Scheibling, R.E. (1993) Community structure and organization of tidepools. *Marine Ecology-Progress Series* **98**, 187-198.

Metaxas, A. and Scheibling, R.E. (1994) Spatial and temporal variability of tidepool hyperbenthos on a rocky shore in Nova Scotia, Canada. *Marine Ecology-Progress Series* **108**, 175-184.

Metaxas, A., Hunt, H.L. and Scheibling, R.E. (1994) Spatial and temporal variability of macrobenthic communities in tidepools on a rocky shore in Nova Scotia, Canada. *Marine Ecology Progress Series* **105**, 89-103.

Michener, W.K. (1997) Quantitatively evaluating restoration experiments - research design, statistical analysis, and data management considerations. *Restoration Ecology* **5**, 324-337.

Millard, S.P., Yearsley, J.R. and Lettenmaier, D.P. (1985) Space-time correlation and its effects on methods for detecting aquatic ecological change. *Canadian Journal of Fisheries and Aquatic Science* **42**, 1391-1400.

Miller, S.S. (1990) In a faraway state. *Environmental Science and Technology* **24**, 1286-1289.

Minchin, P.R. (1987) An evaluation of the relative robustness of techniques for ecological ordination. *Vegetatio* **69**, 89-107.

Minchinton, T.E. and Scheibling, R.S. (1993) Free space availability and larval substratum selection as determinants of barnacle population structure in a developing rocky intertidal community. *Marine Ecology-Progress Series* **95**, 233-244.

Mobil Career Pamphlet. Published Employee Relations Department, Mobil Oil Australia, Victoria, Australia.

Moore, M.N. (1985) Cellular responses to pollutants. *Marine Pollution Bulletin* **16**, 134-139.

Moreno, C.A., Lunecke, K.M. and Lépez, M.I. (1986) The response of an intertidal *Concholepas concholepas* (Gastropoda: Muricidae) to protection from man in southern Chile and its effects on benthic-sessile assemblages. *Oikos* **46**, 359-364.

Moreno, C.A., Reyes, A. and Asencio, G. (1993) Habitat and movements of the recruits of *Concholepas concholepas* (Mollusca; Muricidae) in the rocky intertidal of southern Chile. *Journal of Experimental Marine Biology and Ecology* **171**, 51-61.

Moreno, C.A., Sutherland, J.P. and Jara, H.F. (1984) Man as a predator in the intertidal zone of southern Chile. *Oikos* **42**, 155-160.

Moriarty, F. (1983) *Ecotoxicology: The Study of Pollutants in Ecosystems.* Academic Press, London.

Morton, J.E. and Miller, M.C. (1973). *The New Zealand Seashore.* 2nd Edition. Collins, Glasgow, 653 pp.

Nagarkar, S. and Williams, G.A. (1997) Comparative techniques to quantify cyanobacteria dominated epilithic biofilms on tropical rocky shores. *Marine Ecology-Progress Series* **154**, 281-291.

Naverrete, S.A. and Castilla, J.C. (1990) Barnacle walls as mediators of intertidal mussel recruitment- effects of patch size on the utilization of space. *Marine Ecology-Progress Series* **68**, 113-119.

Navigational Map No. AUS 125, Pub. Hydrographic Service, RAN Wollongong, N.S.W.

Neff, J.M., Anderson, J.W., Cox, B.A., Laughlin, R.B., Jr., Rossi, S.S. and Tatem, H.E. (1976) Effects of petroleum on survival, respiration and growth of marine animals. pp. 516-539. **In**: *Sources, Effects and Sinks of Hydrocarbons in the Aquatic Environment.* American Institute of Biological Science, Washington, D.C.

Nelson-Smith, A. (1973a) Effects of oil on marine organisms. pp. 71-98. **In**: *Oil Pollution and Marine Ecology.* Plenum Press, New York.

Nelson-Smith, A. (1973b) Benthic invertebrates. pp. 116-132. **In**: *Oil Pollution and Marine Ecology*. Plenum Press, New York.

Nickerson, N.H. and Thibodeau, F.R. (1983) Destruction of *Ammophila breviligulata* by pedestrian traffic: quantification and control. *Biological Conservation* **27**, 277-287.

Nicotri, M.E. (1977) Grazing effects of four marine intertidal herbivores on the microflora. *Ecology* **58**, 1020-1032.

Noarlunga 6627-4 & PT 6527-1. Third Edition. [Topographical Map].

Nounou, P. (1980) The oil spill age. Fate and effects of oil in the marine environment. *Ambio* **9**, 297-302.

Oliva, D. and Castilla, J.C. (1986) The effect of human exclusion on the population structure of Key-hole Limpets *Fisurella crassa* and *F. limbata* on the coast of central Chile. *Marine Ecology* **7**, 201-217.

Olla, B.L., Bejda, A.J. and Pearson, W.H. (1983) Effects of oiled sediment on the burrowing behaviour of the hard clam, *Mercenaria mercenaria. Marine Environmental Research* **9**, 183-193.

Osenberg, C.W. and Schmitt, R.J. (1996) Detecting ecological impacts caused by human activities. Chapter 1, pp. 3-16. **In**: R.J. Schmitt and O.W. Osenberg (eds). *Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats.* Academic Press Inc., Sydney.

Osenberg, C.W., Schmitt, R.J., Holbrook, S.J., Abu-Saba, K.E. and Flegal, A.R. (1994) Detection of environmental impacts: natural variability, effect size, and power analysis. *Ecological Applications* **4**, 16-30.

Overton, E.B., Sharp, W.D. and Roberts, P. (1994) Toxicity of Petroleum. pp. 133-156. **In**: L.G. Cockerham and B.S. Shane (eds). *Basic Environmental Toxicology*. CRC Press Inc., London.

Owens, E.H. and Rashid, M.A. (1976) Coastal environments and oil spill residues in Chedabucto Bay, Nova Scotia. *Canadian Journal of Earth Sciences* **13**, 908-928.

Owens, E.H. and Robilliard, G.A. (1981) Shoreline sensitivity and oil spills- a re-evaluation for the 1980's. *Marine Pollution Bulletin* **12**, 75-78.

Paine R.T. (1971) A short term experimental investigation of resource partitioning in New Zealand rocky intertidal habitat. *Ecology* **52**, 1096-1106.

Paine R.T. (1974) Intertidal community structure: experimental studies on the relationship between a dominant competitor and its principle predator. *Oecologia (Berlin)* **15**, 93-120.

Paine, R.T. (1966) Food web complexity and species diversity. *American Naturalist* **100**, 65-75.

Paine, R.T. (1984) Ecological determinism in the competition for space. *Ecology* **65**, 1339-1348.

Palmer, M.W. (1993) Putting things in even better order: the advantages of canonical correspondence analysis. *Ecology* **74**, 2215-2230.

Pellerin-Massicotte, J., Pelletier, E. and Paquet, M. (1989) Cellular and biochemical indicators assessing the quality of a marine environment. *Hydrobiologia* **188/189**, 587-594.

Pereira, W.E., Hostettler, F.D. and Rapp, J.B. (1992) Bioaccumulation of hydrocarbons derived from terrestrial and anthropogenic sources in the Asian Clam, *Potamocorbula amurensis*, in San Francisco Bay Estuary. *Marine Pollution Bulletin* **24**, 103-109.

Peterman, R.M. (1990a) Statistical power analysis can improve fisheries research and management. *Canadian Journal of Fisheries and Aquatic Science* **47**, 2-15.

Peterman, R.M. (1990b) The importance of reporting statistical power: The forest decline and acidic deposition example. *Ecology* **71**, 2024-2027.

Peterman, R.M. and Routledge, R.D.(1983) Experimental management of Oregon coho salmon (*Oncorhynchus kisutch*): designing for yield of information. *Canadian Journal of Fisheries and Aquatic Sciences* **40**, 1212-1223.

Peters, R.H. (1991) *A Critique of Ecology*. Cambridge University Press, Cambridge.

Peterson, C.H. (1979) The importance of predation and competition in organizing the intertidal epifaunal communities of Barnegat Inlet, New Jersey. *Oecologia (Berlin)* **39**, 1-24.

Peterson, C.H. (1993) Improvement of environmental impact analysis by application of principles derived from manipulative ecology: Lessons from coastal marine case histories. *Australian Journal of Ecology* **18**, 21-52.

Petrusevics, P. (1990) Water circulation studies in Gulf St Vincent, South Australia. *Argos Newsletter*, **41**, 1-3

Phillips, D.J.H. (1980) *Quantitative Aquatic Biological Indicators*. Applied Science Publishers, London.

Phillips, J.C., Kendrick, G.A. and Lavery, P.S. (1997) A test of a functional group approach to detecting shifts in macroalgal communities along a disturbance gradient. *Marine Ecology-Progress Series* **153**, 125-138.

Pineda, J. and Caswell, H. (1977) Dependence of settlement rate on suitable substrate area. *Marine Biology* **129**, 541-548.

Pople, A., Simpson, R.D. and Cairns, S.C. (1990) An incident of Southern Ocean oil pollution: effects of an oil spillage of diesel fuel on the rocky shore of Macquarie Island (sub-Antarctic). *Australian Journal of Marine and Freshwater Research* **41**, 603-20.

Possingham, H.P. and Roughgarden, J. (1990) Spatial population dynamics of a marine organism with a complex life cycle. *Ecology* **71**, 973-985.

Potts, G.W., Wood, J.W. and Edwards, J.M. (1987) Scuba-diver operated low-light-level video system for use in underwater research and survey. *Journal of the Marine Biological Association of the U.K.* **67**, 299-306.

Povey, A. and Keough, M.J. (1991) Effects of trampling on plant and animal populations on rocky shores. *Oikos* **61**, 355-368.

Powell, T.M. (1989) Physical and biological scales of variability in lakes, estuaries, and the coastal ocean. pp. 157-176. **In**: J. Roughgarden, R.M. May and S.A.

Levin (eds). *Perspectives in Ecological Theory.* Princeton University Press, Princeton.

Pugh, P.J.A. and Davenport, J. (1997) Colonisation vs. disturbance: the effects of sustained ice-scour on intertidal communities. *Journal of Experimental Marine Biology and Ecology* **210**, 1-21.

Quinn, G.P., Wescott, G.C., and Synnot, R.N. (1992) *Life on The Rocky Shores of South-Eastern Australia.* Victorian National Parks Association, Melbourne.

Raffaelli, D. G. and Hughes, R.N. (1978) The effects of crevice size on and availability on populations of *Littorina rudis and Littorina neritoides. Journal of Animal Ecology* **47**, 71-84.

Regoli, F. (1992) Lysosomal responses as a sensitive stress index in biomonitoring heavy metal pollution. *Marine Ecology-Progress Series* **84**, 63-69.

Richards, S.A., Possingham, H.P. and Noye, B.J. (1995) Larval dispersal along a straight coast with tidal currents: complex distribution patterns from a simple model. *Marine Ecology Progress Series* **122**, 59-71.

Rippon, G.D. and Chapman, J.C. (1993) Laboratory procedures for assessing effects of chemicals on aquatic animals. *Technical Memorandum* **42.**

Risk, M.J. (1972) Fish diversity on a coral reef in the Virgin Islands. *Atoll Research Bulletin* **193**, 1-6.

Roberts, D.E., Smith, A., Ajani, P. and Davis, A.R. (1998) Rapid changes in encrusting marine assemblages exposed to anthropogenic point-source pollution - a Beyond-BACI approach. *Marine Ecology-Progress Series* **163**, 213-224.

Rotenberry, J.T. and Wiens, J.A. (1985) Statistical power analysis and community-wide patterns. *The American Naturalist* **125**, 164-168.

Rowland, S.J. and Volkman, J.K. (1982) Biogenic pollutant aliphatic hydrocarbons in *Mytilus edulis* from the North Sea. *Marine Environmental Research* **7**, 117-130.

Russell, G. (1991). Vertical Distribution. pp 43-66. **In**: D.W. Goodall, A.C. Mathieson and P.H. Nienhuis (eds). *Ecosystems of the World 24. Intertidal and Littoral Ecosystems.* Elsevier Science Pub., London.

Rutzler, K. and Sterrer, W. (1970) Oil pollution. Damage observed in tropical communities along the Atlantic seaboard of Panama. *BioScience* **20**, 222-224.

Rykiel, E.J. Jr. (1996) Testing ecological models: the meaning of validation. *Ecological Modelling* **90**, 229-244.

Sami, S., Faisal, M. and Huggett, R.J. (1992) Alterations in cytometric characteristics of hemocytes from the American oyster *Crassostrea virginica* exposed to a polycyclic aromatic hydrocarbon (PAH) contaminated environment. *Marine Biology* **113**, 247-252.

Sanders, H.L., Grassle, J.F., Hampson, G.R., Morse, L.S., Garner-Price, S. and Jones, C.C. Anatomy of an oil spill: long-term effects from the grounding of the barge Florida off West Falmouth, Massachusetts. *Journal of Marine Research* **38**, 265-380.

Sanson, G.D., Stolk, R. and Downes, B.J. (1995) A new method for characterizing surface roughness and available space in biological systems. *Functional Ecology* **9**, 127-135.

Sastry, A.N. and Miller, D.C. (1981) Application of biochemical and physiological responses to water quality monitoring. pp. 265-293. **In**: J. Vernberg, A. Calabrese, F.P. Thurberg and W.B. Vernberg (eds). *Biological Monitoring of Marine Pollutants.* Academic Press Inc., New York.

Sauer, T.C., Michel, J., Hayes, M.O. and Aurand, D.V. (1998) Hydrocarbon characterization and weathering of oiled intertidal sediments along the Saudi Arabian coast two years after the Gulf War oil spill. *Environmental International* **24**, 43-60.

Schindler, D.W. (1987) Detecting ecosystem responses to anthropogenic stress. *Canadian Journal of Fisheries and Aquatic Sciences* **44**, 6-25.

Schlosser, I.J. (1982) Fish community organisation in natural and modified headwater streams. *Canadian Journal of Fisheries and Aquatic Science* **39**, 968-978.

Schneider, D.W., and Frost, T.M. (1996) Habitat duration and community structure in temporary ponds. *Journal of the North American Benthological Society* **15**, 64-86.

Schoch, G.C. and Dethier, M.N (1996) Scaling up: the statistical linkage between organismal abundance and geomorphology on rocky intertidal shorelines. *Journal of Experimental Marine Biology and Ecology* **201**, 37-72.

Shaw, D.G. (1992) The *Exxon Valdez* oil-spill: ecological and social consequences. *Environmental Conservation* **19**, 253-258.

Shaw, D.G. and Wiggs, J. (1980) Hydrocarbons in the intertidal environment of Kachemak Bay, Alaska. *Marine Pollution Bulletin* **11**, 297-300.

Shepherd, S. A. and Thomas, I.M. (eds) (1989) *Marine Invertebrates of Southern Australia. Part II.* South Australian Govt Printing Division, Adelaide, South Australia.

Sidall, R., Pike, A.W. and McVicar, A.H. (1993) Parasites of *Buccinum undatum* (Mollusca: Prosobranchia) as biological indicators of sewage-sludge dispersal. *Journal of the Marine Biological Association of the U.K.* **73**, 931-948.

Sindermann, C.J. (1988) Biological indicators and biological effects of estuarine/coastal pollution. *Water Resources Bulletin* **24**, 931-939.

Skiba, Y.N. (1995) Dual oil concentration estimates in ecologically sensitive zones. *Environmental Monitoring and Assessment* **43**, 139-151.

Skilleter (1995) Environmental disturbance. pp. 263-276. **In**: A.J. Underwood and M.G. Chapman (eds). *Coastal Marine Ecology of Temperate Australia.* Pub. University of New South Wales Press Ltd, Sydney.

Sladeck,V. (1965) The future of the Saprobity System. *Hydrobiologia* **25**, 518-537.

Sloterdijk, H., Champoux, L., Jarry, V., Couillard, Y., and Ross. P. (1989) Bioassay responses of micro-organisms to sediment elutriates from the St. Lawrence River (Lake St. Louis). *Hydrobiologia* **188/189**, 317-335.

Smith, C.M. and Hackney, C.T. (1989) The effects of hydrocarbons on the setting of the American Oyster, *Crassostrea virginica*, in intertidal habitats in southeastern North Carolina. *Estuaries* **12**, 42-48.

Smith, J.D., Bagg, J. and Sin. Y.O. (1987) Aromatic hydrocarbons in seawater, sediments and clams from Green Island, Great Barrier Reef, Australia. *Australian Journal of Marine and Freshwater Research* **38**, 501-510.

Snedecor, G.W. and Cochran, W.G. (1989) *Statistical Methods.* 8th Edition. pp. 59-62. Iowa State UP.

Soule, D.F. (1988) Marine organisms as indicators: reality or wishful thinking? Chapter 1. pp. 1-11. **In**: D.F. Soule and G.S. Kleppel (eds). *Marine Organisms as Indicators.* Springer-Verlag, New York.

Sousa, W. (1979a) Disturbance in marine intertidal boulder fields: the non-equilibrium maintenance of species diversity. *Ecology* **60**, 1225-1239.

Sousa, W. (1979b) Experimental investigations of disturbance and ecological succession in a rocky intertidal algal community. *Ecological Monographs* **49**, 227-254.

Sousa, W. (1984b) The role of disturbance in natural communities. *Annual Review of Ecology and Systematics* **15**, 353-392.

Sousa, W.P (1985) Disturbance and patch dynamics on rocky intertidal shores. pp. 101-124. **In**: Pickett, S.T.A. and White, P.S. (eds). *The Ecology of Natural Disturbance and Patch Dynamics.* Academic Press, New York, USA.

Sousa, W.P. (1980) The responses of a community to disturbance: the importance of successional age and species' life histories. *Oecologia* (Berl.) **45**, 72-81.

Sousa, W.P. (1984a) Intertidal mosaics: patch size, propagule availability, and spatially variable patterns of succession. *Ecology* **65**, 1918-1935.

Southward, A.J. (1991) Forty years of changes in species composition and population density of barnacles on a rocky shore near Plymouth. *Journal of the Marine Biological Association of the United Kingdom* **71**, 495-513.

Spooner, M. (1970) Oil spill in Tarut Bay, Saudi Arabia. *Marine Pollution Bulletin* **1**, 166-167.

Sprague, J.B. (1971) Review Paper. Measurement of pollutant toxicity to fish- III. Sublethal effects and safe concentrations. *Water Research* **5**, 245-266.

Stacey, B.M. and Marcotte, B.M. (1987) Chronic effect of No. 2 fuel oil on population dynamics of harpacticoid copepods in experimental marine mesocosms. *Marine Ecology-Progress Series* **40**, 61-68.

Stekoll, M.S. and Deysher, L. (1996) Recolonisation and restoration of upper intertidal *Fucus gardneri* (Fucales, Phaeophyta) following the *Exxon Valdez* oil spill. *Hydrobiologia* **326/327**, 311-316.

Stephenson, T.A. and Stephenson, A. (1949). The universal features of zonation between tide-marks on rocky coasts. *Journal of Ecology* **37**, 289-305.

Stephenson, T.A. and Stephenson, A. (1972). *Life Between Tidemarks on Rocky Shores*. W.H. Freeman and Co., San Francisco.

Stewart-Oaten, A. (1996a) Goals in environmental monitoring. pp. 7-27. **In**: R.J. Schmitt and O.W. Osenberg (eds). *Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats.* Academic Press Inc., Sydney.

Stewart-Oaten, A., Murdoch, W.W. and Parker, K.R. (1986) Environmental impact assessment: 'pseudoreplication' in time? *Ecology* **67**, 929-940.

Stiles, S. (1992) Influence of environmental factors on genotoxicity of petroleum and PCB compounds on American oyster eggs and embryos. *Environmental Management* **16**, 528.

Storey, A.W. and Edward, D.H.D. (1989) The freshwater mussel, *Westralunio carteri* Iredale, as a biological indicator of organochlorine pesticides. *Australian Journal of Marine and Freshwater Research* **40**, 587-593.

Stromgren, T. (1987) Effect of oil and dispersants on the growth of mussels. *Marine Environmental Research* **21**, 239-246.

Strong, D.R. Jr. (1980) Null hypotheses in ecology. *Synthese* **43**, 271-285.

Stronkhorst, J. (1992) Trends in pollutants in blue mussel *Mytilus edulis* and Flounder *Platichthys flesus* from two Dutch estuaries, 1985-1990. *Marine Pollution Bulletin* **24**, 250-258.

Suchanek, T.H. (1978) The ecology of *Mutilus edulis* L. in exposed rocky intertidal communities. *Journal of Experimental Marine Biology and Ecology* **31**, 105-120.

Suchanek, T.H. (1993) Oil impacts on marine invertebrate populations and communities. *American Zoologist* **33**, 510-523.

Sundberg, P. (1983) Multivariate analysis in marine pollution studies. *Marine Pollution Bulletin* **14**, 208-209.

Sutherland, J.P. (1987) Recruitment limitation in a tropical intertidal barnacle: *Tetraclita panamensis* (Pilsbry) on the Pacific coast of Costa Rica. *Journal of Experimental Marine Biology and Ecology* **113**, 267-282.

Swaileh, K.M., Mesmar, M.N. and Ismail, N.S. (1994) Heavy metal concentrations in common freshwater snails of Azraq Oasis, Jordan. *Hydrobiologia* **286**, 167-173.

Tabachnik, B.G. and Fidell, L.S. (1989) *Using Multivariate Statistics.* 2nd Edition. Harper and Row, New York.

Takada, Y. (1995) Variation of growth rate with tidal level in the gastropod *Monodonta labio* on a boulder shore. *Marine Ecology-Progress Series* **117**, 103-110.

Tatem, H.E., Cox, B.A. and Anderson, J.W. (1978) The toxicity of oils and petroleum hydrocarbons to estuarine crustaceans. *Estuarine and Coastal Marine Science* **6**, 365-373.

Taylor, B.A. and Gerrodette, T. (1993) The uses of statistical power in conservation biology: the Vaquita and Northern Spotted Owl. *Conservation Biology* **7**, 489-500.

Teal, J.M., Farrington, J.W., Burns, K.A., Stegeman, J.J., Tripp, B.W., Woodin, B. and Phinney, C. (1992) The West Falmouth oil spill after 20 years: fate of fuel oil compounds and effects on animals. *Marine Pollution Bulletin* **24**, 607-614.

ter Braak, C.J.F (1996) Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. *Ecology* **67**, 1167-1179.

ter Braak, C.J.F. (1989) CANOCO - an extension of DECORANA to analyze species-environment relationships. *Hydrobiologia* **184**, 169-170.

Thomas, P. and Budiantara, L. (1995) Reproductive life history stages sensitive to oil and naphthalene in Atlantic Croaker. *Marine Environmental Research* **39**, 147-150.

Thrush, S.F., Pridmore, R.D. and Hewitt, J.E. (1996) Impacts on soft-sediment macrofauna. pp. 49-66. **In**: R.J. Schmitt and O.W. Osenberg (eds). *Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats.* Academic Press Inc., Sydney.

Toft, C..A. and Shea, P.J. (1983) Detecting community-wide patterns: estimating power strengthens statistical inference. *American Naturalist* **122**, 618-625.

Trussell, G.C., Johnson, A.S., Rudolph, S.G. and Gilfillan, E.S. (1993) Resistance to dislodgement: habitat and size-specific differences in morphology and tenacity of an intertidal snail. *Marine Ecology-Progress Series* **100**, 135-144.

Tsouk, E., Amir, S. and Goldsmith, V. (1985) Natural self-cleaning of oil-polluted beaches by waves. *Marine Pollution Bulletin* **16**, 11-19.

UBD Street Directory. Adelaide 1994. 31st Edition. Universal Press Pty Ltd, Adelaide, Australia.

Underwood, A.J. (1973) Studies of zonation of intertidal prosobranch molluscs in the Plymouth region. *Journal of Animal Ecology* **42**, 353-372.

Underwood, A.J. (1974) The reproductive cycles and geographical distribution of some common eastern Australian prosobranchs (Mollusca: Gastropoda). *Australian Journal of Marine and Freshwater Research* **25**, 63-88.

Underwood, A.J. (1975) Intertidal zonation of prosobranch gastropods: analysis of densities of four coexisting species. *Journal of Experimental Marine Biology and Ecology* **19**, 197-216.

Underwood, A.J. (1975a) Comparative studies of the biology of *Nerita atramentosa* Reeve, *Bembicium nanum* (Lamarck) and *Cellana tramoserica* (Sowerby)

(Gastropoda: Prosobranchia) in SE Australia. *Journal of Experimental Marine Biology and Ecology* **18**, 153-172.

Underwood, A.J. (1976a) Analysis of patterns of dispersion of intertidal prosobranch gastropods in relation to macroalgae and rock-pools. *Oecologia (Berl.)* **25**, 145-154.

Underwood, A.J. (1976b) Nearest neighbour analyses of spatial dispersion of intertidal prosobranch gastropods within two substrata. *Oecologia (Berl.)* **26**, 257-266.

Underwood, A.J. (1977) Movements of intertidal gastropods. *Journal of Experimental Marine Biology and Ecology* **26**, 191-201.

Underwood, A.J. (1978a) The refutation of critical tidal levels as determinants of the structure of intertidal communities on British shores. *Journal of Experimental Marine Biology and Ecology* **33**, 261-276.

Underwood, A.J. (1978b) An experimental evaluation of competition between three species of intertidal prosobranch gastropods. *Oecologia* (Berlin) **33**, 185-202.

Underwood, A.J. (1979) The ecology of intertidal gastropods. *Advances in Marine Biology* **16**, 111-210.

Underwood, A.J. (1980) The effects of grazing by gastropods and physical factors on the upper limits of distribution of intertidal macroalgae. *Oecologia* (Berlin) **46**, 201-213.

Underwood, A.J. (1981a) Techniques of analysis of variance in experimental marine biology and ecology. *Oceanography and Marine Biology: Annual Review* **19**, 513-605.

Underwood, A.J. (1981b) Structure of a rocky intertidal community in New South Wales: patterns of of vertical distribution and seasonal changes. *Journal of Experimental Marine Biology and Ecology* **51**, 57-85.

Underwood, A.J. (1984a) The vertical distribution and seasonal abundance of intertidal microalgae on a rocky shore in New South Wales. *Journal of Experimental Marine Biology and Ecology* **78**, 199-220.

Underwood, A.J. (1984b) Microalgal food and the growth of the intertidal gastropods *Nerita atramentosa* Reeve and *Bembicium nanum* (Lamarck) at four heights on a shore. *Journal of Experimental Marine Biology and Ecology* **79**, 277-291.

Underwood, A.J. (1984c) Vertical and seasonal patterns in competition for microalgae between intertidal gastropods. *Oecologia* (Berlin) **64**, 211-222.

Underwood, A.J. (1985). Physical factors and biological interactions: the necessity and nature of ecological experiments. pp. 372-390. **In**: P.G. Moore and R. Seed (eds) *The Ecology of Rocky Shores.* Hodder and Stoughton, London.

Underwood, A.J. (1989) The analysis of stress in natural populations. *Biological Journal of the Linnean Society* **37**, 51-98.

Underwood, A.J. (1991a) The logic of ecological experiments: a case history from studies of the distribution of macro-algae on rocky intertidal shores. *Journal of the Marine Biological Association of the U.K.* **71**, 841-866.

Underwood, A.J. (1991b) Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* **42**, 569-587.

Underwood, A.J. (1992) Beyond-BACI: the detection of environmental impacts on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* **161**, 145-178.

Underwood, A.J. (1993a) The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. *Australian Journal of Ecology* **18**, 99-116.

Underwood, A.J. (1993b) Exploitation of species on the rocky coast of New South Wales (Australia) and options for its management. *Ocean and Coastal Management* **20**, 41-62.

Underwood, A.J. (1994a) On beyond-BACI: sampling designs that might reliably detect environmental disturbances. *Ecological Applications* **4**, 3-15.

Underwood, A.J. (1994b) Rocky intertidal shores. Chapter 15, pp 272-296. **In**: L.S. Hammond and R.N. Synot (eds). *Marine Biology.* Longman Cheshire Pty. Ltd. Melbourne.

Underwood, A.J. (1995a) Detection and measurement of environmental impacts. Chapter 20, pp. 311-324. **In**: A.J. Underwood and M.G. Chapman (eds). *Coastal Marine Ecology of Temperate Australia.* Pub. University of New South Wales Press Ltd, Sydney.

Underwood, A.J. (1995b) Ecological research and (research into) environmental management. *Ecological Applications* **5**, 232-247.

Underwood, A.J. (1997) Environmental decision-making and the precautionary principle - what does this principle mean in environmental sampling practice? *Landscape and Urban Planning* (Amsterdam) **37**, 137-146.

Underwood, A.J. and Anderson, M.J. (1994) Seasonal and temporal aspects of recruitment and succession in an intertidal estuarine fouling assemblage. *Journal of the Marine Biological Association of the U.K.* **74**, 563-584.

Underwood, A.J. and Chapman, M.G. (1989) Experimental analyses of the influences of topography of the substratum on movements and density of an intertidal snail, *Littorina unifasciata. Journal of Experimental Marine Biology and Ecology* **134**, 175-196.

Underwood, A.J. and Chapman, M.G. (1995) Rocky shores. Chapter 5, pp. 55-82. **In**: A.J. Underwood and M.G. Chapman (eds). *Coastal Marine Ecology of Temperate Australia.* Pub. University of New South Wales Press Ltd, Sydney.

Underwood, A.J. and Denley, E.J. (1984). Paradigm, explanations and generalisations in models for the structure of intertidal communities on rocky shores. pp. 151-180. **In**: D.R. Strong jr, D. Simberloff, L.G. Abele and A.B. Thistle (eds). *Ecological Communities: Conceptual Issues and the Evidence.* Princeton University Press, New Jersey, U.S.A.

Underwood, A.J. and Fairweather, P.G. (1989) Supply-side ecology and benthic marine assemblages. *Trends in Ecology and Evolution* **4**, 16-20.

Underwood, A.J. and Jernakoff, P. (1981) Effects of interactions between algae and grazing gastropods on the structure of a low-shore intertidal algal community. *Oecologia (Berlin)* **48**, 221-233.

Underwood, A.J. and Kennelly, S.J. (1990) Pilot Studies for designs of human disturbance of intertidal habitats in New South Wales. *Australian Journal of Marine and Freshwater Research* **41**, 165-173.

Underwood, A.J. and Peterson, C.H. (1988) Towards an ecological framework for investigating pollution. *Marine Ecology-Progress Series* **46**, 227-234.

van Tamelen, P.G. (1996) Algal zonation in tidepools: experimental evaluation of the roles of physical disturbance, herbivory and competition. *Journal of Experimental Marine Biology and Ecology* **201**, 197-231.

Vantamelen, P.G., Stekoll, M.S. and Deysher, L. (1997) Recovery processes of the brown alga *Fucus gardneri* following the Exxon Valdez oil spill - settlement and recruitment. *Marine Ecology-Progress Series* **160**, 265-277.

Vargo, S.L. (1981) The effects of chronic low concentrations of No. 2 fuel oil on the physiology of a temperate estuarine zooplankton community in the merl microcosms. pp. 295-322. **In**: J. Vernberg, A. Calabrese, F.P. Thurberg and W.B. Vernberg (eds). *Biological Monitoring of Marine Pollutants.* Academic Press, New York.

Vega, M.M., Marigomez, J.A. and Angulo, E. (1989) Quantitative alterations in the structure of the digestive cell of *Littorina littorea* on exposure to cadmium. *Marine Biology* **103**, 547-553.

Walters, C.J. (1993) Dynamic models and large scale field experiments in environmental impact assessment and management. *Australian Journal of Ecology* **18**, 53-61.

Walters, C.J., Collie, J.S. and Webb, T. (1988) Experimental designs for estimating transient responses to management disturbances. *Canadian Journal of Fisheries and Aquatic Science* **45**, 530-538.

Ward, S. and Quinn, G.P. (1988) Preliminary investigations of the ecology of the intertidal predatory gastropod *Lepsiella vinosa* (Lamarck) (Gastropoda Muricidae). *Journal of Molluscan Studies* **54**, 109-117.

Ward, T.J. and Jacoby, C.A. (1992) A strategy for assessment and management of marine ecosystems: Baseline and monitoring studies in Jervois Bay, a temperate Australian embayment. *Marine Pollution Bulletin* **25**, 163-171.

Wardrop, J.A. (1983) *An assessment of the impacts of spilt crude oil and dispersants on an intertidal wetlands community (mangroves).* Unpublished PhD Thesis, Zoology Department, University of Adelaide.

Wardrop, J.A. (1987) The effects of oils and dispersants on mangroves: a review and bibliography. *Centre for Environmental Studies, University of Adelaide. Occasional Paper No. 2.* K.F. Dyer (ed).

Warwick, R.M. (1986) A new method for detecting pollution effects on marine macrobenthic communities. *Marine Biology* **92**, 557-562.

Warwick, R.M. (1988a) Analysis of community attributes of the macrobenthos of Frierfjord/Langesundfjord at taxonomic levels higher than species. *Marine Ecology-Progress Series* **46**, 167-170.

Warwick, R.M. (1988b) The level of taxonomic discrimination required to detect pollution effects on marine benthic communities. *Marine Pollution Bulletin* **19**, 259-268.

Warwick, R.M. (1993) Environmental impact studies on marine communities: Pragmatical considerations. *Australian Journal of Ecology* **18**, 63-80.

Warwick, R.M. and Clarke, K.R. (1991) A comparison of some methods for analysing changes in benthic community structure. *Journal of the Marine Biological Association of the U.K.* **71**, 225-244.

Warwick, R.M. and Clarke, K.R. (1993) Increased variability as a symptom of stress in marine communities. *Journal of Experimental Marine Biology and Ecology* **172**, 215-226.

Warwick, R.M., Clarke, K.R. and Suharsono (1990a) A statistical analysis of coral community responses to the 1982-83 El Nino in the Thousand Islands, Indonesia. *Coral Reefs* **8**, 171-179.

Warwick, R.M., Platt, H.M., Clarke, K.R., Agard, J. and Gobin, J. (1990b) Analysis of macrobenthic and meobenthic community structure in relation to pollution and disturbance in Hamilton Harbour, Bermuda. *Journal of Experimental Marine Biology and Ecology* **138**, 119-142.

Watt, I., Woodhouse, T. and Jones, D.A. (1993) Intertidal clean-up activities and natural regeneration on the Gulf Coast of Saudi Arabia from 1991 to 1992 after the 1991 Gulf Oil Spill. *Marine Pollution Bulletin* **27**, 325-331.

Wetzel, R.G. and Likens, G.E. (1991) *Limnological Analyses*. Second Edition. pp. 55-68. Springer-Verlag, New York.

Whittaker, R.H. (1967) Gradient analysis of vegetation. *Biological Review* **42**, 207-264.

Widbom, B. and Oviatt, C.A. (1994) The 'World Prodigy' oil spill in Narragansett Bay, Rhode Island: acute effects on macrobenthic crustacean populations. *Hydrobiologia* **291**, 115-124.

Widdows, J. (1985) Physiological responses to pollution. *Marine Pollution Bulletin* **16**, 129-134.

Widdows, J., Burns, K.A., Menon, N.R., Page, D.S. and Soria, S. (1990) Measurement of physiological energetics (scope for growth) and chemical contaminants in mussels (*Arca zebra*) transplanted along a contamination gradient in Bermuda. *Journal of Experimental Marine Biology and Ecology* **138**, 99-117.

Wieczorek, S.K., Clare, A.S. and Todd, C.D. (1995) Inhibitory and facilitatory effects of microbial films on settlement of *Balanus amphitrite amphitrite* larvae. *Marine Ecology-Progress Series* **119**, 221-228.

Wilcoxon, F. (1945) Individual comparisons by ranking methods. *Biometrics Bulletin* **1**, 80-83.

Wilkinson, L. (1990) SYSTAT: *The System for Statistics.* Evanston, IL, SYSTAT, Inc. 1990.

Winer, B.J. (1971) *Statistical Principles in Experimental Design*, 2nd Edition. McGraw-Hill, New York, USA.

Wolff, G.A., Preston, M.R., Harriman, G. and Rowland, J.S. (1993) Some preliminary observations after the wreck of the oil tanker *Braer* in Shetland. *Marine Pollution Bulletin* **26**, 567.

Womersley, H.B.S. (1982) *Port Stanvac Marine Biology Survey: Second report, March 1982.* Adelaide, South Australia. Department of Botany, Adelaide University.

Womersley, H.B.S. (1988) *Port Stanvac Marine Biology Survey: Project report, December 1988.* Adelaide, South Australia. Department of Botany, Adelaide University.

Womersley, H.B.S. and Clarke, S.M. (1979) *Port Stanvac Marine Survey I, December 1977-February 1978.* Report to the South Australian Coastal Protection Board and Port Stanvac Oil Refinery.

Womersley, H.B.S. and Edmonds, S.J. (1958). A general account of the intertidal ecology of South Australian coasts. *Australian Journal of Marine and Freshwater Research* **9**, 217-260.

Womersley, H.B.S. and Thomas, I.M. (1976) Intertidal ecology. pp 175-185. **In**: C.R. Twidale, M.J. Tyler and B.P. Webb (eds). *Natural History of the Adelaide Region.* Royal Society of South Australia (Inc.), Adelaide.

Wynberg, R.P. and Branch, G.M. (1994) Disturbance associated with bait-collection for sandprawns (*Callianassa kraussi*) and mudprawns (*Upogebia africana*): long-term effects on the biota of intertidal sandflats. *Journal of Marine Research* **52**, 523-558.

Yasuno, M. and Whitton, B.A. (1986) Biological monitoring for aqatic pollution. pp. 57-66. **In**: J. Salanki (ed). *Biological Monitoring of the State of the Environment: Bioindicators. IUBS Monograph Series No. 1.* IRL Press, United Kingdom.

Young, C.M. (1990) Larval predation by epifauna on temperate reefs: scale, power and the scarcity of measurable effects. *Australian Journal of Ecology* **15**, 413-426.

Zar, J.H. (1984) *Biostatistical Analysis.* Second Edition. Prentice-Hall Int. Inc., England Cliffs, New Jersey.

Appendices

A	Background to the Project.
B	"Advertiser" Report, 30th November 1996.
C	The Rocky Intertidal Region: A General Review.
D	Oil: Characteristics and Properties.
E	Road Map 152 (UBD Street Directory Adelaide, 1994), used to locate Kingston Park, GSV
F	Road Map 164 (UBD Street Directory Adelaide, 1994), used to locate Marino Rocks, GSV
G	Road Map 175 (UBD Street Directory Adelaide, 1994), used to locate Hallett Cove & Port Stanvac sites, GSV
H	Road Map 185 (UBD Street Directory Adelaide, 1994), used to locate Witton Bluff, GSV
I	Road Map 195 (UBD Street Directory Adelaide, 1994), used to locate Port Noarlunga South & Robinson Point, GSV
J	Physical Parameter Assessment Sheet.
K	Biota Census Sheet.
L	Photographic Handbook of Common GSV Intertidal Species.
M	"Advertiser" Report, December 1995.
N	"GMAV5" Instructions.
O	"BMDP" V 5: Analysis of the 'Effluent' Data Set for Serial Correlation.
P	Animal Taxa Recorded at GSV Study Sites During Preliminary Monitoring.
Q	Pearson Matrix with Bonferroni Corrections (Taxa *vs* SSH MDS Ordination Axes).
R	Pearson Matrix with Bonferroni Corrections (Environmental Variables *vs* SSH MDS Ordination Axes).
S	"The FLOWC Model" (Bye and Ng 1994).
T	"The FLOWM Model".
U	Amendments to "The FLOWM Model".
V	Final Report to Mobil.
W	Project Summary.
X	Final Field Data Sheets.
Y	Final Data: Collected as the Initial Ongoing Monitoring Program Data.

Appendix A: Background to the Project

A.1 The Study Area in Gulf St Vincent (GSV)

A.1.1 Overview of GSV

GSV lies within the Flindersian biogeographical province which extends westward from southern New South Wales to approximately Geraldton in Western Australia (Womersley 1990). GSV is an *inverse estuary* with limited open ocean water exchange due to the presence of Kangaroo Island at its mouth (Lewis 1982). It is connected with the Southern Ocean via Investigator Strait (to the west) and Backstairs Passage (to the south-east) (Bye 1976).

Extensive studies of GSV are limited but it is considered to be of biological significance due to its seagrass beds and the presence of *Avicennia marina* mangrove stands to the north of Adelaide which are important fish nursery areas (Grzechnik 1995, Paxinos and Clarke 1996). The Gulf supports a local fishing industry which targets Western King prawns, King George whiting, snapper, garfish and blue-swimmer crabs, many of which breed on the north-eastern coast (Lewis 1982). An overview of current commercial and recreational fishing in GSV is given by Paxinos and Clarke (1996).

Adelaide is situated on the eastern side of GSV and its population of greater than one million people impact on the coast via such mechanisms as effluent, industrial and stormwater discharges to its waters, and recreational activities on its shores.

A.1.2 Physical Oceanography of GSV

South Australia's Coastal Waters

The coastal waters of South Australia are less than 200m deep and overlie the continental shelf. Deeper water is found beyond this region, reaching depths of 5,000m at about 500km from the coast (Bye 1976). A region of water encompassing 100,000 km^2 and referred to as the South Australian Sea (Fig. A.1) stretches from the east of Cape Carnot (on the tip of Eyre Peninsula) to the Victorian border and includes Spencer Gulf, GSV, Investigator Strait and Encounter Bay (Bye 1976). GSV forms a shallow marine basin with an average water depth of 21m, a maximum depth of about 40m and a surface area of about 6,800km^2 (Bye 1976, Petrusevics 1990). It is roughly triangular in shape, 60km wide at its entrance and approximately 150km wide from north to south.

Tides

Water level fluctuations along the South Australian coast are mainly astronomically driven but are also influenced by meteorological tides (Bye 1976). Astronomical tides are of two types; a diurnal tide which travels to the west, and a semi-diurnal tide which travels to the east, but is almost normally incident on the coast (Irish & Snodgrass 1972). Tides are primarily semi-diurnally dominated but show a diurnal inequality with the range typically 1 m in the south of GSV and 3.3 m in the north under spring tidal conditions (de Silva Samarasinghe and Lennon 1987). Semi-diurnal tidal energy enters GSV centrally and then spreads to the coasts where it is strongly dissipated. Diurnal tidal energy is not as strongly dispersed but spreads inwards in the south of Investigator Strait and Backstairs Passage, and outwards in the north of Investigator Strait (Bye 1976).

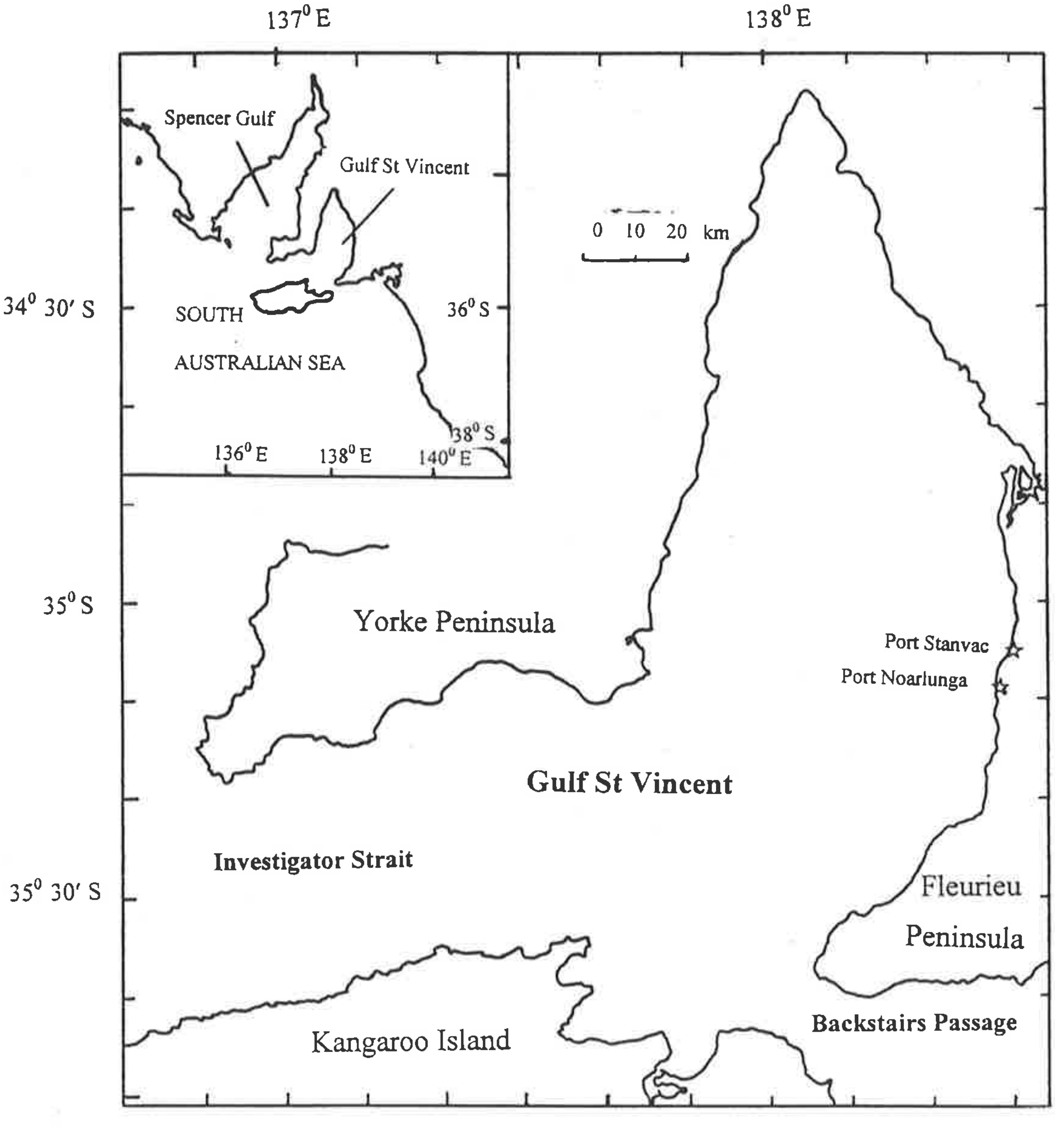


Fig. A.1 The position of GSV and Port Stanvac in relation to Backstairs Passage, Investigator Strait and Kangaroo Island. *Inset*: The position of GSV within the South Australian Sea (After Bye 1976).

GSV has a large spring to neap tidal range. During neap regimes the diurnal tide dominates and the semidiurnal tide is virtually absent, while at equinoxes the diurnal tide vanishes resulting in a 'dodge' tide (de Silva Samarasinghe and Lennon 1987, Underwood and Chapman 1995). Apart from 'dodge' tidal conditions, two tidal cycles (each including a high and a low tide) occur in a day, with the morning tide generally having a greater amplitude than its afternoon counterpart from mid-October to mid-February, while the reverse occurs for the rest of the year (Bye 1976). General seasonal trends in GSV include higher mean sea levels in winter compared with summer, with differences being as great as 15-20 cm (Womersley and Edmonds 1958).

Winds are known to influence tidal range and general water circulation. In GSV the predominant wind directions range between south and west (but see Petrusevics 1990), which tends to raise the sea level, but a change in general wind direction in summer can result in a lower sea level (Womersley and Edmonds 1958). Tidal elevation produces tidal currents which have been recorded at 1-2m/s in Backstairs Passage (Shepherd and Sprigg 1976) and 0.02-0.5m/s (at a depth of 5m) at the crude marine berth at Port Stanvac in February 1995 (pers. comm. Cove).

In order to better understand the physical oceanography of GSV mathematical computer models have been used to simulate tidal elevations and currents. Such work has continued at Flinders University (through Dr Bye) and Adelaide University (through Professor Noye and his student Marcus Grzechnik). An oceanographic model ('FLOWM') for GSV, designed by Dr Bye, was used to model and predict likely sites where oil spilt from the Port Stanvac Oil Refinery would ground (see Chapter 5).

Circulation

Patterns of non-tidal circulation in GSV rely on the combined effects of local wind, heat and water exchange across the water-air interface as well as deep oceanic movement adjacent to the South Australian Sea (Bye 1976). However, wind is believed to be the primary determinant of general water circulation, with west to east moving synoptic pressure systems, modulated in summer by sea breezes, being a major force in GSV. In general, wind direction tends to be mainly south to south-east in summer and predominantly south-west to north in winter (Petrusevics 1990).

Modelling of wind driven water circulation patterns in GSV (Fig. A.2) has predicted water inflow along the west coast, outflow in the central regions and an 'anti-cyclonic' pattern of water movement (the Myponga Eddy) close to the Fleurieu Peninsula (Bye 1976). This pattern is most pronounced in summer (Fig A.2a) and is important in GSV as it affects transportation processes along the metropolitan coast (Bye 1976). Deep oceanic water enters the Gulf along the coast of lower Yorke Peninsula before continuing north along the western coast and then moving in a south-easterly direction along the opposing coast. Water movement is an eastward outflow through Backstairs Passage or a counter-current which returns via Investigator Strait (Bye 1976).

Seasonal comparisons of computer generated simulations of mean circulation due to wind and density gradients are shown in Fig. A.2. Based on these simulations a coastal northerly horizontal velocity of 4 cm/s at Port Stanvac is predicted for January, while a southerly horizontal velocity of 6 cm/s is predicted in the same region for July. In April and October the Myponga Eddy has a more pronounced effect, but in general an inshore northerly current and an offshore southerly current exist (Bye 1976).

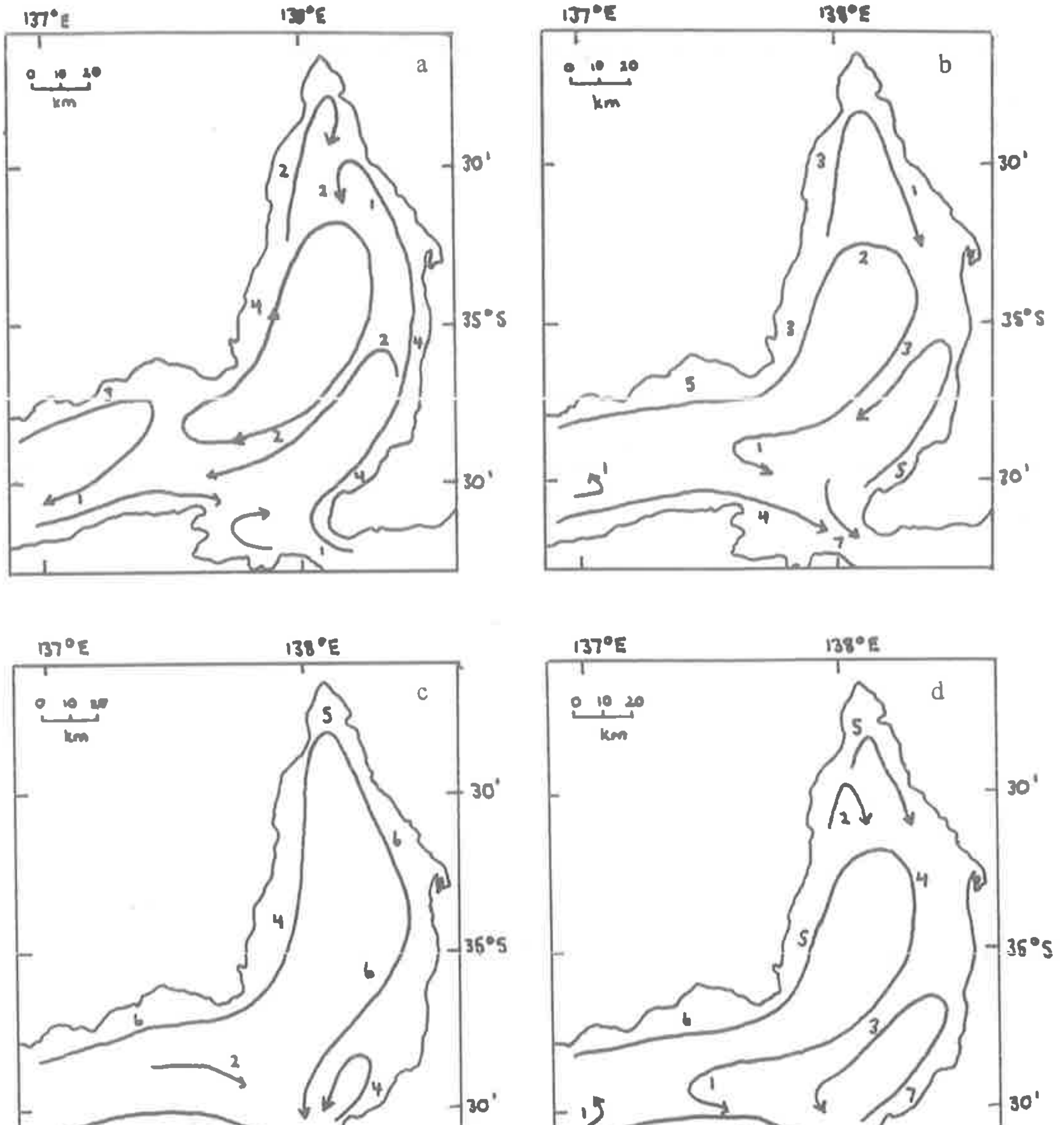


Fig. A.2 Simulated patterns of seasonal wind and density generated water circulation in GSV derived from the modelling work of Bye (1976): a) January; based on wind stress components (0.0053N/m^2, 0.0167 N/m^2); b) April, based on wind stress components (0.0350N/m^2, 0.0129 N/m^2); c) July, based on wind stress components (0.0950N/m^2, -0.0255 N/m^2); d) October, based on wind stress components (0.0694N/m^2, 0.0189 N/m^2). Wind stress components are recorded in brackets and are towards the east and north respectively. Numbers shown in the figures represent the average horizontal velocities in the water column , while units are: Newtons per metre^2 (N/m^2) & centimetres per second (c/s) (After Bye 1976).

Vertical mixing within the water column tends to remove any marked gradients in salinity, temperature and density which could occur with depth (Bye 1976). However, the closed nature of GSV results in increasing horizontal salinity towards the head of the Gulf, particularly in summer (Bye 1976, de Silva Samarasinghe and Lennon 1987). An offshore increase in salinity is attributed to land based run-off, while the Myponga Eddy is believed to be responsible for the salinity increase to the north (Bye 1976). Water temperature similarly shows a horizontal gradient, increasing from Hallett Cove to Largs Bay (in a northerly direction) by about 2 degrees Celcius in summer and 1 degree in winter (at a depth of approximately 1m) (Bye 1976). Overall, the salinity range in GSV lies between 35.5‰-42‰ while the temperature range is 12.0°C-25.9°C (de Silva Samarasinghe and Lennon 1987).

The wave energy typical of the coast tends to promote supersaturated oxygen levels in coastal waters. However, rock pools and shallow water on calm nights, especially in combination with high organism densities and/or dodge tides, may result in reduced water oxygenation.

Wave action

The eastern coast of GSV is relatively sheltered in the north and more exposed to the south, with the region from Black Cliff to Port Stanvac being categorised as moderately exposed (Womersley and Clarke 1979). To the south of Port Stanvac the steeper coastal gradient typically results in higher energy exposure and stronger current velocities, particularly in winter (Womersley and Clarke 1979, Coast Protection Board 1984). However, coastal exposure can be modified by topography, examples being the breakwater and reef at Port Stanvac and offshore reefs at Port Noarlunga which decrease the wave energy experienced by these shores (Womersley and Clarke 1979). It should be noted that wind direction can be of greater importance than wind strength in determining the local wavefield and in GSV the roughest conditions are experienced when the wind direction is between the southern and western quarters where the fetch is longest (Bye 1976).

A.1.3 Sediment, Coastal Topography and Substrata Types

Sediment

A noteworthy feature of GSV is the accumulation of more than seven metres of sediment over the bedrock base at the mouth of the Onkaparinga River (an accretional area), while at Hallett Cove (where erosion dominates) the sediment layer is less than half a metre thick (Coast Protection Board 1984). Sediments in GSV are mainly 'carbonate' of biological origin (Shepherd and Sprigg 1976). However, some terrestrial erosional debris in the form of quartz and clay enters coastal waters from hard rock cliffs and outwash.

GSV sediments tend to be fine grained and less than 0.1mm in diameter in the deeper water of the central northern Gulf basin and at the eastern end of Investigator Strait, but are coarser, ranging from 1-2 mm in diameter, in the southern headlands of the Gulf, across the western section of Investigator Strait, and in the sublittoral zone of the eastern coastal beaches (Shepherd and Sprigg 1976). Factors controlling the supply of coarse sand and silt include tidal and wave action, and proximity to headlands or erosional rip channels. Finer sediment is predominantly transported by tidal currents and enters the Gulf from the south, tending to settle out into deeper, quieter water, or become entrapped by seagrasses, mangrove roots or supratidal flats (Shepherd and Sprigg 1976). However, at Port Stanvac it is reported that coarser sands are associated with higher seagrass densities and deeper waters (Cheshire and Kildea 1993). During winter the combined effects of wind, strong wave activity and mixing within the water column interact to increase sediment movement and water turbidity (Coast Protection Board 1984).

Coastal Topography and Substrata

GSV is characterised by a series of stranded cliffs, raised seashores, and prominent erosional areas extending from western Kangaroo Island, via Cape Jervis to Marino (Shepherd and Sprigg 1976). Along the eastern coastline rocky headlands are interspersed by irregular wave cut platforms and sandy beaches, with a sloping platform consisting of remnant layers of resistant rocks running parallel to the shore north of Black Cliff and south of Hallett Cove and extending to Port Stanvac (Womersley and Clarke 1978). Landward of this platform are cliffs up to 75m high comprised of dark reddish-purple quartzites and slates (Paxinos and Clarke 1996). The cliffs continue to the south but are reduced in height by Christies Beach and are of more recent (Tertiary) origin (Womersley and Clarke 1978).

Submerged shorelines extend approximately 1 km offshore from Hallett Cove South and a few kilometres off Marino. Extensive submarine Tertiary limestone outcrops extend seaward for about 5 km from Port Noarlunga, while a limestone reef (called Horseshoe Reef) is emergent at low tide and lies off Christies Beach (Shepherd and Sprigg 1976). Port Noarlunga also has another offshore reef which lies parallel to the shore, is connected to Horseshoe Reef in the north, and is believed to be composed of consolidated Pleistocene sand deposits (Womersley and Clarke 1978).

The southerly and south-easterly margins of GSV and its approaches consist primarily of hard rock cliffs of consolidated Cambrian and Precambrian rocks, while the rest of the coast typically consists of soft, sand and clay sediments of Permian, Tertiary or Quaternary Age (Shepherd and Sprigg 1976). Another feature of the coastline is the presence of boulder and cobble littoral deposits at the bases of many of the cliffs at, or above, modern beach level (Shepherd and Sprigg 1976). This type of substrata can impact on intertidal community structure (McGuiness 1987a & b, Underwood and Chapman 1995).

A.1.4 Nutrient Status

South Australian waters have a relatively poor nutrient status due to limited inflow from the nutrient rich waters of the sub-Antarctic and low rates of terrestrial input (Connell 1983, Bell and Andrew 1995, Brodie 1995). Terrestrial input is low due to sparse rainfall and consequently low surface run-off, combined with the paucity of phosphorous found in South Australian soils (Connell 1983, Bell and Andrew 1995, Brodie 1995). Seasonal variability in rainfall and run-off introduces a high degree of temporal variability to nutrient input into GSV from point and diffuse natural and anthropogenic sources (March 1996).

In 1981 coastal nutrient concentrations in the vicinity of Port Stanvac were examined (Clarke 1986; cited by March 1996). This study found elevated levels of nitrogen in winter, with trough levels occurring in summer, and peak levels of total phosphorous occurring in winter and early spring. The main sources of nutrients into the Port Stanvac region were from Christies Creek and the Onkaparinga River systems but the relative contributions by each were extremely temporally variable.

A.1.5 Marine Biology

The plant taxa occurring in GSV between Port Noarlunga and Hallett Cove are extensive and are listed in Womersley and Clarke (1979), Womersley (1988) and Clarke (1993). Mobile epifauna found in the Gulf in association with seagrass have also been described (Sergeev *et al.* 1988). However, it is the intertidal region (particularly the rocky intertidal area) and its associated fauna and flora which is of most relevance to this study. An overview of the dominant species found in the rocky intertidal and sandy beach areas within the region of interest in GSV is given by Paxinos and Clarke (1996) and broadly examined in section A.2.4.

A.2 History and Operation of the Port Stanvac Oil Refinery

Mobil Petroleum Industries have a refining plant at Lonsdale, Port Stanvac, which is situated within GSV, South Australia (34^{0}61′S 138^{0}27′N). This plant together with its sister plant at Altona (Melbourne), jointly operate to manufacture approximately 25% of Australia's petroleum product requirements (Mobil Career Pamphlet). The Port Stanvac Oil Refinery began operation in 1963 and now has the capacity to meet almost all the petroleum product needs of South Australia. The lube plant came into operation in 1975, was expanded in 1981, and produces lubricating base stocks. Mobil's Port Stanvac Oil Refinery receives crude oil for refinement within the plant and exports refined oil and other products, such as lubricants.

One of the potential problems associated with refinery operation is accidental release of oil into the marine environment. The primary points where this can occur are the two mooring sites referred to as the 'Deep Ocean Point' (or crude marine berth) and the 'Wharf Point', and from the pipeline that feeds into the refinery (Fig. A.3). Two cargoes of 100,000 tonnes and one cargo of 150,000 tonnes of crude oil are imported on a monthly basis via the 'Deep Ocean Point', and 25,000 tonnes of refined fuel oil are exported from this point twice a week. Wharf operation involves exports of 50,000 tonnes of refined fuel oil and 15,000 tonnes of lubricating oil per month, and twice a year 35,000 tonnes of light oils and related products are sent from the refinery.

Without establishment of a monitoring program and a baseline assessment of existing conditions it would not be possible to determine (except intuitively) the extent to which an oil spill impacts the area. Advice from Mobil and the South Australian Environmental Protection Authority (EPA) and a preliminary site assessment supports the likelihood of oil accumulating intertidally if an oil spill occurs at Port Stanvac.

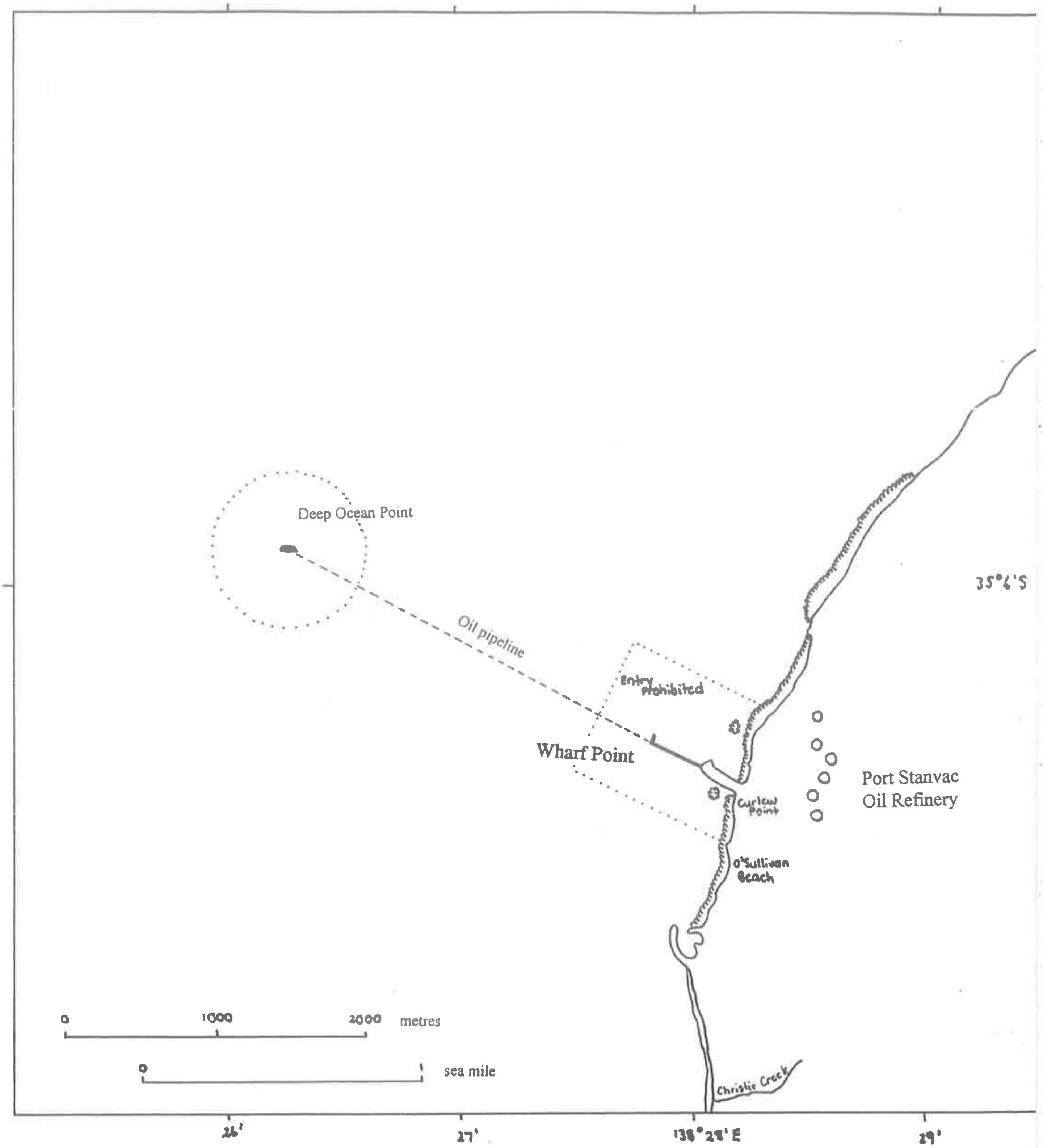


Fig. A.3 The position of the two mooring points; the 'Wharf Point' and the 'Deep Ocean Point', within the Port Stanvac Oil Refinery. These are the primary sites where oil enters and leaves the refinery and from where an operational spillage could occur (After Navigational Map No. AUS 125, Pub. Hydrographic Service, R.A.N. Wollongong, New South Wales, 1994).

A.3 Disturbances in the Vicinity of Port Stanvac

A.3.1 Background

A number of other factors (besides an oil spill) potentially impact the Port Stanvac coastline. These include natural northward sand drift in winter and spring, the E&WS secondarily treated sewage discharge from Christies Beach, and the addition of pollutants to the coastal waters south of Port Stanvac from Christies Creek and the Onkaparinga River. Localised dredging within the refinery and the discharge of treated refinery effluent towards the northern refinery boundary may also impact on the coastline within or immediately adjacent to the refinery. Another potential effect of the refinery, arising from its private ownership, is the partial protection of intertidal animals from the trampling and collection pressure experienced in similar, but publicly accessed, areas. The Mitsubishi storm water outfall which gives an intermittent discharge of seasonal water runoff at close proximity to the northern boundary of the refinery (Plate A.1), dredging (currently being investigated by the University of Adelaide) and beach replenishment may also potentially impact the area. The positions of a number of disturbances and point sources of pollution in GSV adjacent to Port Stanvac are shown in Fig. A.4.

Plate A.1 The position of the Mitsubishi stormwater outfall and Mobil's treated effluent outfall adjacent to the northern refinery boundary (marked by the fence). The effluent pipe is in the foreground of the plate and the stormwater outfall pipe can be seen on the rising edge of the cliff in the background.

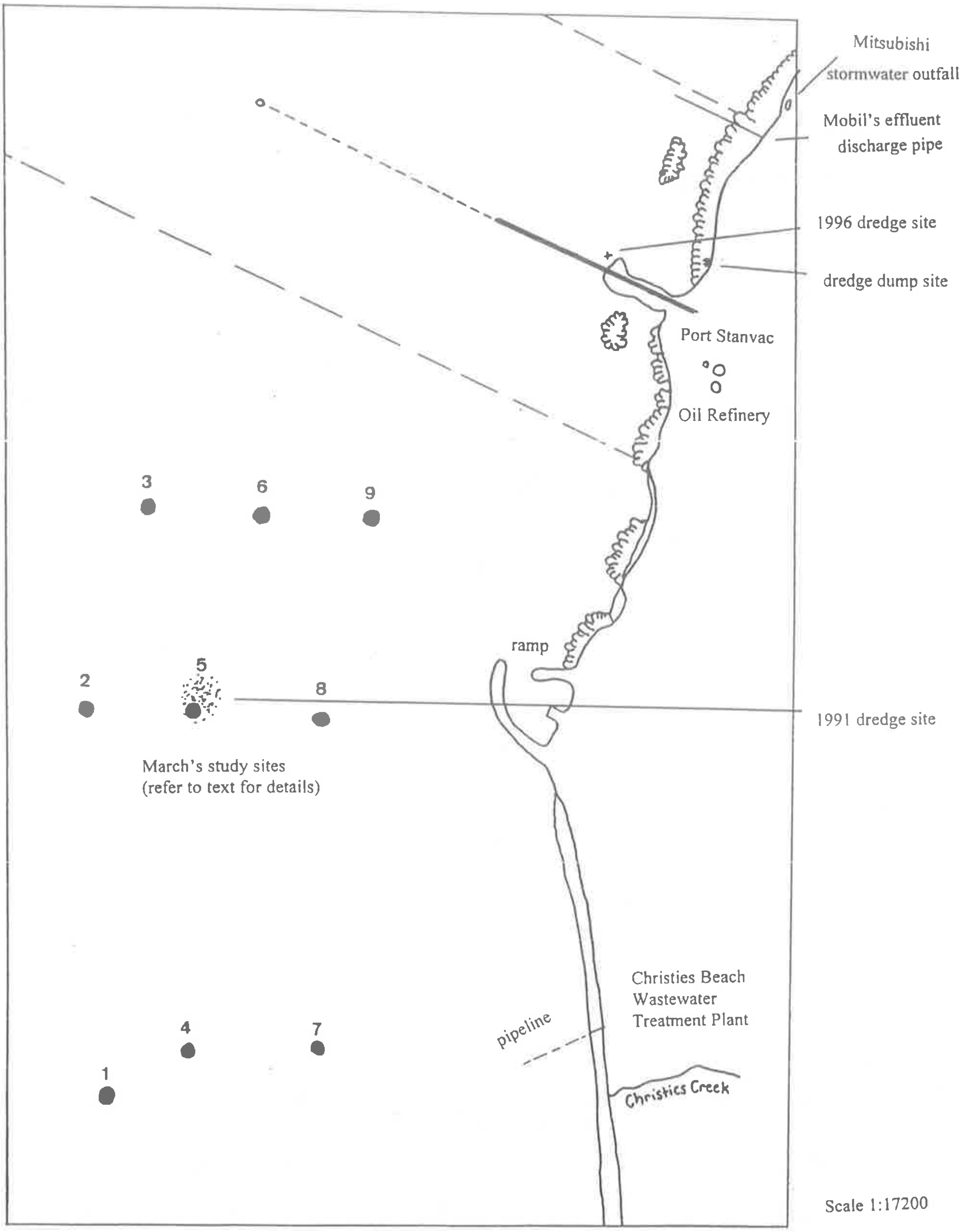


Fig A.4 The position of the Port Stanvac Oil Refinery in relation to some of the point sources and disturbances which impact the coastline. The nine study sites used in the "effects of dredging study" (section A.3.4) are shown, with site 5 situated close to the 1991 dredge site, and site 7 being 400m from the Christies Beach Wastewater outfall (After March 1996).

A.3.2 The Christies Beach Wastewater Outfall

The Christies Beach Wastewater Treatment Plant was established in 1971 and continuously discharges treated wastewater from a pipe 200m offshore at a depth of approx 7m (Steffensen 1985). The volume of effluent discharge has increased eight fold in the 19 years from 1974 to 1993. The wastewater is subjected to secondary treatment which leaves it high in nutrients but strips it of coarse particles and materials which are toxic to humans (AEC 1987). March (1996) has compared point source discharges in the Port Stanvac region (Table A.1). It is apparent that the major contribution of nutrients and contaminants to the area is from the Christies Beach wastewater outfall which exhibits elevated levels of nitrogen containing compounds, total phosphate and several metals, but shows lower turbidity than Christies Creek water. However, analysis of the quality of the wastewater involved assessment of only one water sample per month and may not be representative of actual levels (Steffenson 1985).

A.3.3 River and Creek Discharges

Christies Creek has an annual flow of 4,900 megalitres and is a possible source of sediment and pollutants to GSV. The Noarlunga City Council performs monthly monitoring of the creek waters (see Table A.1). This monitoring indicates that Christies Creek contributes more dissolved solids to GSV than any other source (March 1996). However, analysis is based on low replication and so data must be viewed with caution (March 1996). The Onkaparinga River also contributes significant amounts of organic and inorganic material to the Port Stanvac region. The relative contribution varies significantly in response to release of water from the Mt. Bold Reservoir (Lewis 1975). Chemical analysis of the Onkaparinga water indicates it contributes less nutrients but more suspended solids than the Christies Beach wastewater outfall (Manning and Associates 1985).

Table A.1 Some of the primary sources of point discharges into GSV adjacent to Port Stanvac are shown. Numbers in **bold** represent discharges above schedule 1 or chronic levels listed in "Guidelines for Licensing Discharges to the Marine Environment" (Office of the EPA 1993) (After March 1996).

Source	SA Limits	Mobil	Mitsubishi	Christies	Creek		Christies Beach Effluent Outfall					Sediment
						Total/Mth	Discharge water		*Total/mth*	Surface water	near outfall	*ppm*
Year	1993.00	1994	1994	1974	1993-94	1993-94	1974	1993-94	1993-94	1978	1981	1993
Flow (ML/mth)		101.6	1 379	250	408	4,896	96.7	806.04	736			
Suspended solids (mg/L)	80.00	62	404.6					4	33,690	12		
Turbidity (NTU)										17		18
Total dissolved solids (mg/L)					4841.6	23,723,840		888.8	8,596,918			
BOD (mg/L)		128						5	43,363			
pH	6.5-8.5	6.9	6.6		8.17	40,033		7.1	63,675			8
DO (mg/L)	>6											
Oil	40-70	12	2.89					6000	58,035,000			
Aluminium				275			330	626	6,054,985			960
Arsenic	36-50		2					1	9,673			3.75
Barium												20
Chromium	50.00	0.2-2.2	8	15			0.04		0			6
Chromium IV	50.00	0.37										
Boron												640
Cadmium	9.30		1	10			2	0.2	,935			0.1-0.5
Calcium												
Chloride												
Chlorine	7.50											
Cobalt									164,433			2
Copper	2.90		**56**	26			**43**	60	500,350			3
Iron	50.00							149	1,441,203			0.09
Lead	5.60		**277**	54			**33**	4	38,690			5
Magnesium												
Manganese	100.00		25	19			67	37	357,883			65
Mercury	0.10		**16**					0.5	4,836			
Molydenum								18	174,105			1.4
Nickel	8.30		**10**	40			**20**	65	628,713			2
Phenol	50.00	1.2						60	500,350			
Phosphorous												80
Potassium												
Selenium	70.00		1					<1				2
Silver	1.00			10			2	1.8	17,411			0.1
Sulphate												
Sulphide	2.00	0.03-1										
Tin	0.00											<5
Zinc	50-86		**364**				80	120	1,160,700			8.5
Antimony	500.00							1	9,673			
Total organic C								22200	214 729,500			
NH4 +	<5							18600	179 908,500	**60**		
NO3 & NO2-	22190.00		**1330**		1100	5,390,000	**31360**	14300	138 316,750	**610**	**290790**	
Total Keldar Nitrogen (TKN)								21500	207 958,750	**1700**	**450450**	
Total phosphate	35704.00		**308**		130	637,000	**5622**	8200	79,314,500	**160**	**62132**	
Soluble Phosphate (bioavailable)										**156**	**53123**	
Elemental Phosphate (P)	0.10											

A.3.4 The Port Stanvac Oil Refinery

The Oil Spill

A procedural oil spill occurred from the 'Deep Ocean Point' at the refinery on September 23rd 1996. It was initially reported that about 10,000 litres of Arabian light crude oil was spilt as it was being unloaded into the refinery (see Appendix B). Much of the oil beached intertidally and contaminated a relatively large stretch of the coastline to the south of the refinery. However, the manual cleanup was rapid and no obvious acute effects on intertidal species were recorded at the time of the spill or in the week following it (see Chapters 4, 5 & 6 for details).

Sand Dredging

Sand dredging within the refinery commenced near the 'Wharf Point' (see Fig. A.4) on the 2nd of January 1996 and continued until the 23rd of January. Further dredging was carried out on the 28th and 29th of January (pers. comm. Cove). The aim of the dredging was to increase the depth of the harbour to the west of the breakwater adjacent to the wharf. The dredging spoil was discharged via a pipe onto the rocky shore to the north of the wharf (Fig. A.5).

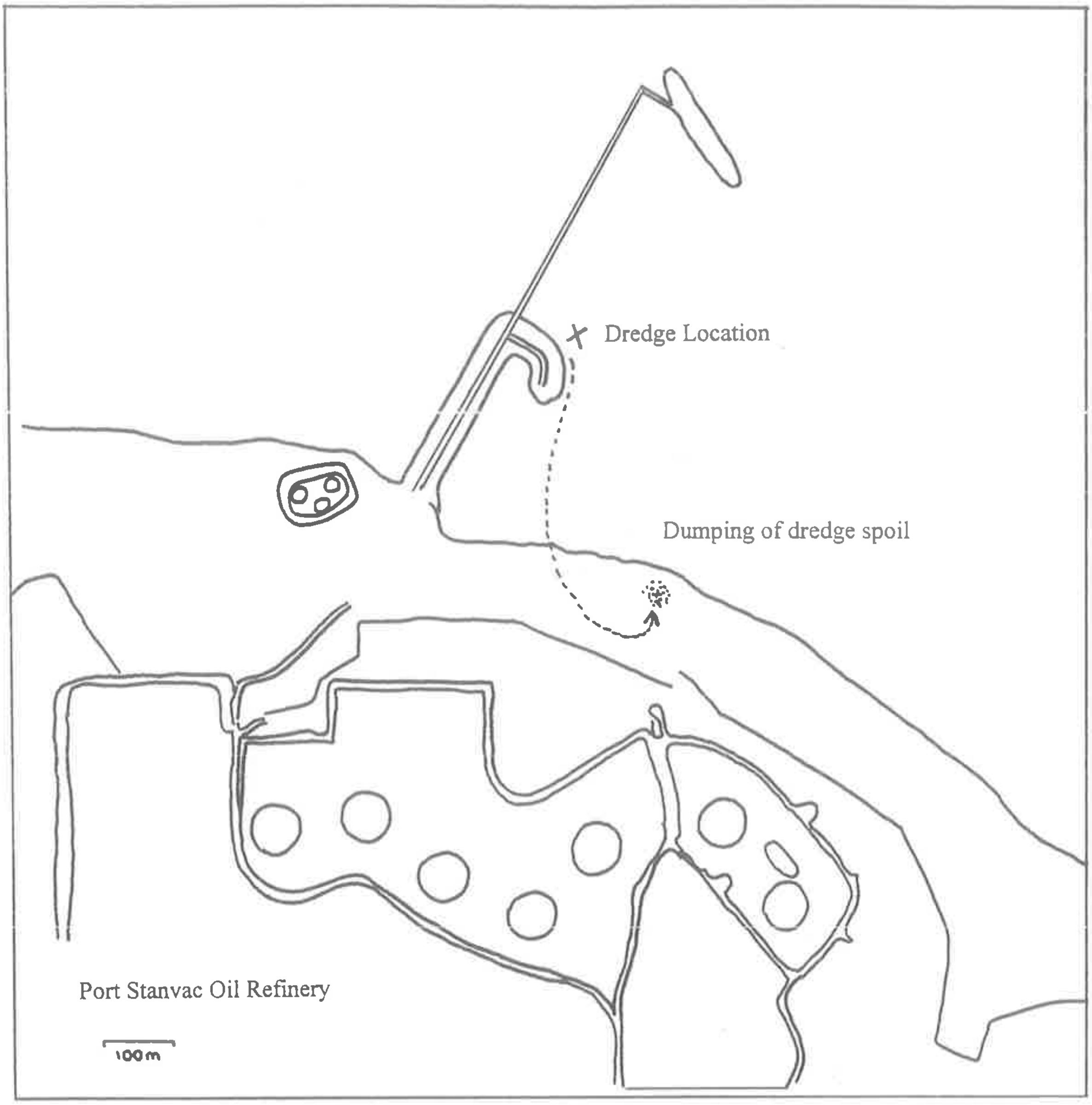


Fig. A.5 The dredge position adjacent to the wharf within the boundaries of the Port Stanvac Oil Refinery. Dredging was carried out in January 1996 to increase the depth of the harbour. The dredged area is marked with a cross and the speckled area signifies the dredging spoil dump site. The wharf juts out into the harbour and the dredge site is slightly north-west of its end. (Original figure supplied by the EPA).

Refinery Effluent

Treated refinery effluent flows into a concrete junction box where it mixes with water from the North Collection Basin and the Ballast Water Holding Pond before its final discharge into the ocean at the northern boundary of the refinery (Plate A.1) (Cove 1994). Passage from the junction box is via a 200 mm rubber pipe to the point of high tide and then via a metal pipe for the final 120 metres to the point of discharge. The depth of the ocean at this point is 7m and a deflector plate is used to facilitate dispersion of the effluent (Cove 1994). All refinery effluent is monitored prior to discharge as described by Cove (1994). The level of oil in water, suspended solids and furfural are measured daily, and pH, biological oxygen demand (BOD), phenol, sulphides and chromium oxide are measured weekly (Cove 1994).

A rupture in a section of the effluent pipe was noted by myself on the 29th of August 1995. This was reported to refinery staff who instigated repair work. The final repairs to the pipe were completed on the 13th of September 1995. From the time the rupture was noted until the final repair of the pipe, refinery effluent was discharged onto the mid-eulittoral zone where it mixed with seawater at high tide. On the 11th of September I revisited the area and found that the original pipe had been connected to a flexible hose through which refinery effluent was being discharged onto the beach. On the 13th of September Transfield Company Staff were present on the beach and in the process of connecting the current outlet pipe to the old pipe. This effectively bypassed the damaged area of the old pipe and the effluent was once again discharged out to sea as previously described. An assessment of the local effects of this event on intertidal fauna is given in Chapter 4.

A.3.5 Mitsubishi Stormwater Discharge

Mitsubishi Motors Australia Pty Ltd has a manufacturing site at Lonsdale adjacent to the northern boundary of Port Stanvac. Runoff from the site is via a stormwater drain on the cliff very close to the border of the refinery (Plate A.1). Discharge tends to be intermittent and occurs in response to rainfall episodes. Monitoring by Mitsubishi during 1994 indicated that rain fell on 99 days scattered over 11 months of the year. The total annual rain for 1994 amounted to 307.6 mm (pers. comm. Pfennig). The average daily discharge from the stormwater pipe was 0.153 megalitres, and the average monthly discharge was 1.379 megalitres (using data from rainfall days only).

Monitoring by the Mitsubishi Plant compared the plant discharge (via the outfall pipe shown in Plate A.1) to water from a road drain. This enabled extraneous pollutant sources to be discriminated from pollutants originating within the Mitsubishi plant. The Mitsubishi outfall contained levels of suspended solids, copper, lead, mercury, nickel and zinc which were above recommended limits (see Table A.1), although the recorded levels were similar to those obtained from the road drain. The generally low flow from Mitsubishi implies that pollutant input to the coast from this source is likely to have little impact to the region. However, Port Stanvac and areas to the north could be affected if high rainfall events occurred in combination with calm conditions, resulting in retention of the discharged water and its pollutant load close to shore.

A.3.6 Sand Dredging

It is known that Adelaide's beaches are eroding, a situation which can be counteracted by sand replenishment. Dredging from a depth of 12m or more off Port Stanvac has been used as an economical way to replenish sand to the southern end of the metropolitan beach system (Cheshire *et al.* 1996). Dredging for this purpose was trialed in January and May 1991 by the Coast Protection Board and was repeated in 1994 and late 1995. The replenishment dredging involved removing an estimated 40 cm of overlying sand from an area about 1 km by 400 m. This disturbance is likely to cause environmental damage to animals that live in and on the dredged sand and could also impact on adjacent sensitive habitats, such as seagrass beds and associated fauna (Cheshire *et al.* 1996). Dredging activities are liable to result in increased sand drift to some coastal sites in addition to the natural sand drift which already occurs along the eastern shores of GSV.

A.4 Past Studies in the Vicinity of Port Stanvac

Port Noarlunga Reef and the Onkaparinga River Estuary

One of the first biological assessments in the vicinity of Port Stanvac was a survey undertaken by the Department of Agriculture and Fisheries. This took place between 1974 and 1975 and focused on organisms on and around the southern section of the Port Noarlunga Reef (Duyverman 1976). The plan was to implement ongoing monitoring of the reef and the conspicuous biota associated with it but repeat assessments were never carried out (March 1996).

The Onkaparinga River Estuary has been the subject of five reports covering the period between 1974 and 1985. The latest report investigated effects associated with maintenance dredging of the estuary (see Manning & Assoc. 1985).

The Intertidal Work of Womersley

The work which most directly pertains to the monitoring program is the intertidal work of Womersley (1988) who surveyed organisms directly around the refinery in 1979, 1980 and part of 1981. The surveys aimed to establish intertidal abundance and seasonal variation of dominant biota over two years and to provide baseline data against which future environmental changes could be compared. Surveys were carried out at two sites; the boat ramp at Port Stanvac, and a steeply sloping, slightly offshore rock at Curlew

Point. Surveys of two other sites (O'Sullivan Beach and Witton Bluff) were begun but were aborted for various reasons.

The supralittoral zone in rocky coastal sections near Port Stanvac was found to be dominated by *Littorina* spp., while the upper-eulittoral zone supported the barnacle *Chamaesipho*, with another barnacle species; *Chthamalus*, occurring less commonly. The mid-eulittoral zone was characterised by the appearance of a variety of molluscs (including *Nerita atramentosa*, *Austrocochlea* spp., *Bembicium nanum* and *Cellana tramoserica*), *Galeolaria* (tube worms), blue-green algae, and patchily distributed beds of *Xenostrobus pulex* mussels (Womersley and Thomas 1976, Womersley 1988).

In general it was concluded that Port Stanvac was rich in marine plants and animals compared to the adjacent coast, especially north of the refinery. This was attributed to the deeper inshore water at Port Stanvac and the protection from recreational pressure afforded by private ownership of the Port Stanvac site (Womersley 1988). It may also reflect the great diversity of habitat (natural; sandflats, boulders and reefs, and artificial; breakwater, jetty and moorings) and the variability in environmental conditions created by the interaction of these varied habitats with regular natural perturbations which occur in the area (Clarke 1993). It was also noted that biota tended to show high seasonal fluctuations and that abundance was generally greatest in winter. However, these apparent trends occurred against a high variability in biota abundance between years. On this basis, Womersley (1988) recommended that detailed long-term surveys (of perhaps up to 5 years) would be needed to establish seasonal trends in the area.

Sand Dredging

Dredging in GSV represents an intense pulse disturbance and is capable of interacting with press disturbances in the area (March 1996). The Botany Department at the University of Adelaide was commissioned to investigate the effects of dredging against background fluctuations which could arise due to other perturbations in the area.

Between 1992 and 1994 Cheshire and Kildea developed protocols to assess and quantify the impact of dredging on susceptible organisms. This work was followed by a further investigation of dredging which began in 1995 and is to continue over three years. This more intensive investigation is jointly run by A. Cheshire and A. Butler and aims to address local changes in sandy sections of the sea floor and concurrent changes in adjacent habitats (particularly seagrass) due to dredging (Cheshire *et al.* 1996). It will also consider if any sensitive or endangered species are likely to be affected by dredging activity, and attempt to establish a way of predicting likely effects at new dredging sites. A major difficulty with isolating dredge-related effects in the area is the high inherent natural variation and the confounding influence of other anthropogenic disturbances.

The results to date indicate that the effects of dredging appear to be small, with no apparent increase in dissimilarity between control and dredged areas. However, there does appear to be a short term increase in variability in patches of the sea floor within the dredged area (Cheshire *et al.* 1996). The study was made more difficult by large differences between study sites due, in part, to different dominant vegetation covers (e.g. seagrass *versus* algae).

Christies Beach Wastewater Treatment Plant

Chemical monitoring of the discharged Christies Beach wastewater is the primary mechanism of quality control used by the Christies Beach wastewater treatment plant (Gutteridge, Hastings & Davey Pty. Ltd. 1993). However, a concurrent study of biota close to the outfall to attempt to match chemical pollutant loads with biological changes has not been done (March 1996).

The only biological study in the region was a one-off study on the 13th of April 1978 which focused on the area surrounding the outfall and a small adjacent reef. This study identified four habitat types (reef, bare sand, outfall pipe and outfall pad) and collections were made of algae and sessile animals in each habitat (Steffensen 1985). The abundance of the main biota were subjectively ranked on a scale from 0 ("complete absent of a species") to 5 ("very abundant"). Water quality including nitrogen (as nitrate and total Kjeldahl nitrogen), total and soluble phosphorous, carbon, turbidity and suspended solids at varying distances from the outfall were also measured on the same day. Total phosphorous and total nitrogen levels were elevated, and remained so, within 100m of the outfall, after which they rapidly attenuated (Steffensen 1985).. However, the levels still remained above the maximum levels listed as acceptable for South Australian coastal waters (Office of the EPA 1993). This study reported a localised effect on water quality but failed to detect differences in biological communities which could be attributed to the wastewater discharge (Steffensen 1985). However, due to the limited extent of the study and a lack of pre-discharge monitoring the conclusions should be viewed with caution.

The only other survey of the area around the Christies Beach outfall was carried out by Clarke between 1980 and 1981 (March 1996). This study found elevated water nutrient levels but no obvious effects on macro-algal communities in the vicinity. The later survey by Cheshire and Kildea (1993) detected significant seagrass communities close to the Christies Beach outfall point, an important finding in view of the sensitivity of seagrass to this type of pollution. Clearly the need exists for more extensive, detailed and continued monitoring of the area.

Changes to the Environmental Protection Act which required compilation of an Environmental Improvement Plan for each sewage treatment plant, necessitated investigation of strategies for the future management of the Christies Beach Wastewater Treatment Plant. A report detailing such strategies was compiled by Gutteridge, Hastings & Davey Pty. Ltd. (1993). It was noted that biological and chemical data pertaining to the outfall area were sparse, but despite this no new monitoring was done prior to the final recommendations being made. The report recognised the reefs in the region as being important due to their high diversity compared with adjacent areas and recommended that the outfall be extended to protect those reefs which were close to the outfall point. However, it should be noted that areas with a lower biotic diversity may also be of biological significance (March 1996).

A recent study relating to the Christies Beach sewage outfall was conducted by March (1996). She used infauna and epibenthic abundance data collected by Cheshire and Kildea in 1992 and 1993 from 9 sites off the coast of Port Stanvac to investigate for a sewage related impact. The data she used was initially collected to address the effects of dredging and had not been intended for an investigation of sewage related changes. The sampling design involved using a 3 x 3 grid pattern of sites positioned parallel to the shore and encompassing a depth profile. Dredging occurred in the vicinity of site 5, while study site 7 was situated 400m from the sewage discharge point (refer to Fig. A.4) (March 1996). The study involved a temporal comparison of infaunal and epibenthic assemblages at the sewage perturbed site with assemblages in the eight control sites, but lacked pre-impact data (March 1996).

March (1996) found that most infauna taxa (particularly Crustacea and Echinodermata) decreased in abundance with increasing proximity to the wastewater outfall. This trend could be a response to the wastewater perturbation but could also be driven by other unknown environmental gradients (March 1996). In contrast to the trends seen with the infauna, epibenthic communities failed to show any changes which could be related to pollution and also displayed less response to the depth gradient than the infauna. In general, the results failed to show a definitive response to the wastewater outfall, perhaps because the sampling sites were too far from the outfall to detect effects. An ongoing investigation of the effects of the wastewater outfall on infauna is currently being performed by M. Loo at The University of Adelaide. Her work is still in its preliminary stage but early results support evidence of pollution based trends in infauna.

Sediment Transport Along the Coast

Several studies have looked at sediment transport along the Adelaide metropolitan coastline as effort was directed towards managing this recreational resource. These studies were not conclusive but generally indicated that sediment movement was primarily influenced by wind direction and strength, storm activity, sediment grain size, wave activity and off-shore topography (Coast Protection Board 1984). At Port Stanvac it would appear that there is little near-shore sand movement, with only a small northward drift and cyclic seasonal patterns of erosion from the beach in winter and deposition in summer (see March 1996). At greater depth, sediment movement is believed to be parallel to the shore and affected by wave transport and sea currents (Coast Protection Board 1984). General trends along the eastern coast of GSV were mentioned previously and will be discussed in Chapter 4.

Refinery Effluent Discharge

Experimental work commenced during 1997 on the effects of the discharged refinery effluent on sublittoral animals (pers. comm. Bidwell). This project is likely to involve the caging of animals (such as sea urchins) in the effluent stream, after which they will be assessed for physiological changes associated with exposure and compared to caged (unexposed) control animals. The results of this work are not known at this time.

References

AEC (1987) Nutrients in Australian Waters. *Australian Environmental Council Report* **19**. Australian Government Printing Service, Canberra.

Bell, J.D. and Andrew, N.L. (1995) Fisheries and aquaculture. **In:** *Coastal Marine Ecology of Temperate Australia.* A.J. Underwood and M.G. Chapman (eds). pp. 277-296. UNSW Press, New South Wales, Australia.

Brodie, J. (1995) The problems of nutrients and eutrophication in the Australian marine environment. Technical Annex 2. **In:** *State of the Marine Environment Report for Australia.* L.P. Zann and D.C. Sutton. (eds).

Bye, J.A.T. (1976) Physical oceanography of Gulf St Vincent and Investigator Strait. **In:** *Natural History of the Adelaide Region.* C.R. Twidale, M.J. Tyler and B.P. Webb (eds). pp. 143-160. Royal Society of South Australia (Inc.): Adelaide, South Australia.

Cheshire, A.C. and Kildea, T. (1993) *The impact of sand dredging on benthic community structure at the Port Stanvac trial dredge site: Project Report* (January 1992-July 1993). Botany Department, University of Adelaide, South Australia.

Cheshire, A.C., Butler, A.J., Westphalen, G., Bathgate, R. and Miller, D.J. (1996) The impact of sand dredging on benthic community structure at a Port Stanvac trial dredge site. *An Interim Report on the Results of Surveys 1992-1995.* Botany Department, University of Adelaide, South Australia.

Clarke, S.M. (1993) Port Stanvac intertidal and subtidal environment. *Report to Mobil Refining Australia, Port Stanvac Wastewater Study.*

Coast Protection Board (1984) *Adelaide Coast Protection Strategy Review.* Coastal Management Branch Conservation Programmes Division; South Australian Department of Environment and Planning.

Connell, D.W. (1983) *Water Pollution Causes and Effects in Australia and New Zealand.* (3rd Edition). University of Queensland Press, Queensland.

Cove, M.N. (1994) Effluent Water Quality Monitoring Program. *Adelaide Refinery Environment Management Handbook.* Unpublished Internal Adelaide Refinery Document. 13pp.

de Silva Samarasinghe, J.R. and Lennon, G.W. (1987) Hypersalinity, flushing and transient salt wedges in a tidal gulf; an inverse estuary. *Estuarine, Coastal and Shelf Science* **24**, 483-498.

Duyverman, H. (1976) Ecological surveys of the South Australian Aquatic Reserves: Port Noarlunga. *Technical Report No. 2.* Prepared for the Department of Agriculture and Fisheries. Adelaide, South Australia.

Grzechnik, M. (1995) *A tidal model of Gulf St. Vincent, South Australia, with particular attention to Outer Harbor and Port Stanvac.* Revised Honours Thesis. Department of Applied Maths, University of Adelaide, South Australia.

Gutteridge, Hastings and Davey Pty Ltd (1993) *Strategies for the future operation of the Christies Beach Wastewater Treatment Plant.* Prepared for the South Australian Engineering and Water Supply Department. Adelaide, South Australia.

Irish, J.D. and Snodgrass, F.E. (1972) Australian-Antarctic tides. *Antarctica Oceanology II, Antarctica Research Series* **19**, 101-116.

Lewis, R. (1975) *Report of the committee on the effects of land-based discharges from metropolitan Adelaide upon the marine environment of Gulf St Vincent.* Prepared for the South Australian Engineering and Water Supply Department. Adelaide, South Australia.

Lewis, R.K. (1982) A Statement to the Australian Marine Sciences and Technologies Advisery Committee on the South Australian Gulf System by the South Australian Department of Fisheries. **In:** *Australian Marine Sciences and Technologies (AMSTAC) Advisory Committee Seminar on the Research Needs for Management of the South Australian Gulfs.* (November 1982). pp. 11-18. Adelaide, South Australia.

Manning, P.F. and Associates (1985) *Onkaparinga River Estuary: maintenance dredging environmental effects, June 1985.* Report prepared by Manning, P.F. and Associates, and Fargher-Maunsell (S.A.) for the Department of Environment and Planning (DEP), South Australia.

March, W.A. (1996) *Assessing Anthropogenic Impacts on the Port Stanvac Macrobenthic Communities.* Unpublished Masters Thesis, Botany Department, University of Adelaide, South Australia.

McGuiness, K.A. (1987a) Disturbance and organisms on boulders I. Patterns in the environment and the community. *Oecologia* (Berlin) **71**, 409-419.

McGuiness, K.A. (1987b) Disturbance and organisms on boulders II. Causes of patterns in diversity and abundance. *Oecologia* (Berlin) **71**, 409-419.

Mobil Career Pamphlet. Pub. Employee Relations Department, Mobil Oil Australia, Victoria, Australia.

Navigational Map No. AUS 125, Pub. Hydrographic Service, R.A.N. Wollongong, New South Wales, 1994.

Office of the EPA (1993) *Guidelines for Licensing Discharges to the Marine Environment November 1993.* Department of Environment and Natural Resources. The Office of the Environmental Protection Authority, South Australia.

Paxinos, R. and Clarke, S. (1996) *Gulf St Vincent, South Australia: Marine Biogeography.* pp. 1-49. South Australian Research & Development Institute (SARDI) Aquatic Sciences, Adelaide, South Australia.

Petrusevics, P. (1990) Water circulation studies in Gulf St Vincent, South Australia. *Argos Newsletter*, **41**, 1-3.

Sergeev, V.N., Clarke, S.M. and Shepherd, S.A. (1988) Motile macroepifauna of the seagrasses *Amphibolis* and *Posidonia* and unvegetated sandy substrata in Holdfast Bay, South Australia. *Transactions of the Royal Society of South Australia* **112**, 97-108.

Shepherd, S.A. and Sprigg, R. C. (1976) Substrate, sediments and subtidal ecology of Gulf St Vincent and Investigator Strait. **In:** *Natural History of the Adelaide Region.* C.R. Twidale, M.J. Tyler and B.P. Webb (eds). pp. 161-174. Royal Society of South Australia (Inc.): Adelaide, South Australia.

Steffensen, D.A. (1985) *Gulf St Vincent Water Pollution Studies Phase II 1976-1983. Part 1 Southern and Central Metropolitan Zones.* Engineering and Water Supply Department, South Australia.

Underwood, A.J. and Chapman, M.G. (1995) Rocky shores. **In:** *Coastal Marine Ecology of Temperate Australia.* A.J. Underwood and M. G. Chapman (eds). pp. 55-82. Pub. University of New South Wales Press Ltd, Sydney, New South Wales.

Womersley, H.B.S. (1988) *Port Stanvac Marine Biology Survey: Project report, December 1988.* Botany Department, Adelaide University, South Australia.

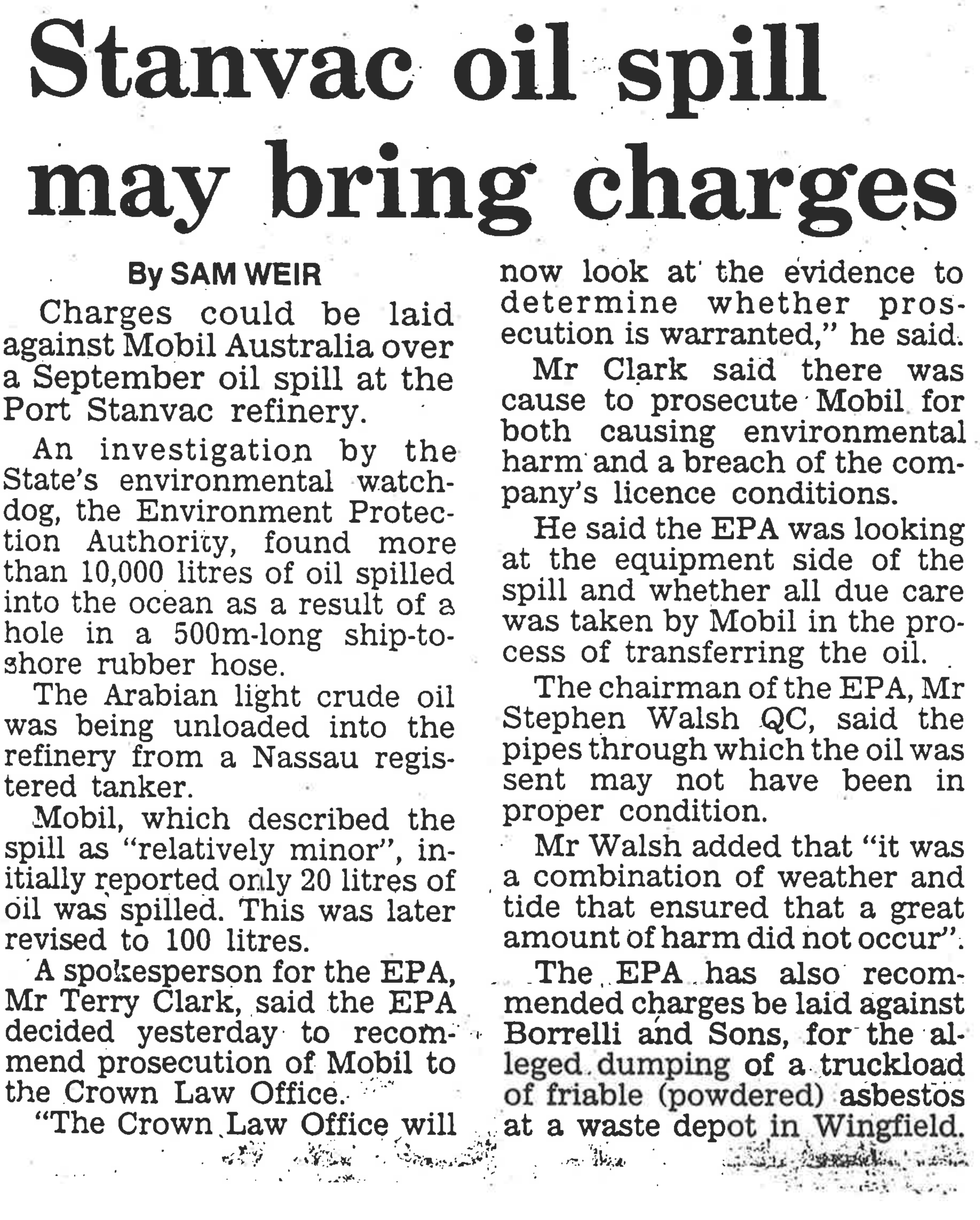
Womersley, H.B.S. (1990) Biogeography of Australian marine macroalgae. **In:** *Biology of Marine Plants.* M.N. Clayton and R.J. King (eds). pp. 367-381. Longman Cheshire Pty. Ltd., Sydney, New South Wales.

Womersley, H.B.S. and Clarke, S.M. (1979) *Port Stanvac Marine Survey I, December 1977-February 1978.* Report to the South Australian Coastal Protection Board and Port Stanvac Oil Refinery.

Womersley, H.B.S. and Edmonds, S.J. (1958) A general account of the intertidal ecology of South Australian coasts. *Australian Journal of Marine and Freshwater Research* **9**, 217-260.

Womersley, H.B.S. and Thomas, I.M. (1976) Intertidal ecology. **In:** *Natural History of the Adelaide Region.* C.R. Twidale, M.J. Tyler and B.P. Webb (eds). pp 175-185. Royal Society of South Australia (Inc.): Adelaide.

Appendix B: "Advertiser" Report, 30th November 1996



Stanvac oil spill may bring charges

By SAM WEIR

Charges could be laid against Mobil Australia over a September oil spill at the Port Stanvac refinery.

An investigation by the State's environmental watchdog, the Environment Protection Authority, found more than 10,000 litres of oil spilled into the ocean as a result of a hole in a 500m-long ship-to-shore rubber hose.

The Arabian light crude oil was being unloaded into the refinery from a Nassau registered tanker.

Mobil, which described the spill as "relatively minor", initially reported only 20 litres of oil was spilled. This was later revised to 100 litres.

A spokesperson for the EPA, Mr Terry Clark, said the EPA decided yesterday to recommend prosecution of Mobil to the Crown Law Office.

"The Crown Law Office will now look at the evidence to determine whether prosecution is warranted," he said.

Mr Clark said there was cause to prosecute Mobil for both causing environmental harm and a breach of the company's licence conditions.

He said the EPA was looking at the equipment side of the spill and whether all due care was taken by Mobil in the process of transferring the oil.

The chairman of the EPA, Mr Stephen Walsh QC, said the pipes through which the oil was sent may not have been in proper condition.

Mr Walsh added that "it was a combination of weather and tide that ensured that a great amount of harm did not occur".

The EPA has also recommended charges be laid against Borrelli and Sons, for the alleged dumping of a truckload of friable (powdered) asbestos at a waste depot in Wingfield.

Appendix C: The Rocky Intertidal Region: A General Review

C.1 Habitat Variability in the Rocky Intertidal Zone

The intertidal region is an extreme and dynamic habitat largely influenced by the action of tides and waves (Carefoot and Simpson 1977, Menge and Farrell 1989, Underwood 1994, Underwood and Chapman 1995). Tidal ebb and flow result in varied periods of immersion and emersion and thus air exposure and desiccation for intertidal biota (Womersley and Thomas 1976, Underwood and Chapman 1995, Chapman and Underwood 1996). Tides and waves create temporal intertidal variability over a range of scales (days, months and seasons) which, in turn, may be modified spatially on local (micro and meso) and regional scales (Black 1979, Underwood and Chapman 1995).

Physical hard habitat types within the intertidal region are also variable. They include natural substrata such as boulders (often interspersed with cobble, pebble or sand), reefs, rocky extensions of land masses and tidal pools (Fairweather and Underwood 1991, Metaxas and Scheibling 1993 & 1994, Metaxas *et al.* 1994, van Tamelen 1996), and artificial substrata; such as wharfs, breakwaters and boat ramps (Jan *et al.* 1994, Underwood and Chapman 1995). Different geological rock types can also introduce additional physical variability to intertidal habitats. For example, soft rock (such as sandstone or shale) is readily eroded to form rock platforms that are typically broad and steeply sloped at their seaward end and marked at their landward end by a cliff, while basalt and granite rocks are subjected to less pronounced erosion, resulting in very steep shores (Underwood and Chapman 1995).

Boulder shores are an important rocky intertidal habitat which occurs in GSV. These form where ambient wave action is sufficiently strong to prevent formation of a sandy beach but is not strong enough to displace the boulders (Underwood and Chapman 1995).

Assemblages (particularly sessile assemblages) utilising them are less stable than those occupying fixed substratum and are primarily structured by disturbance, which overrides other factors such as competition and grazing (Sousa 1979a & b, Lieberman *et al.* 1984, McGuiness 1987a & b). Three unique microhabitats can be identified within the larger boulder habitat; the upper surfaces of boulders, the area beneath the boulders, and the area between the boulders which may include entrapped sand (see Underwood and Chapman 1995).

The rocky intertidal area is spatially extremely variable due to major differences in the dominant substrata types on rocky shores and the percentage contribution of secondary substrata. The degree of shelter afforded to a reef can also modify physical conditions faced by intertidal biota, while micro-scale topographic variations in substrata complexity such as fissures and eroded holes, and the presence of rock pools can provide refuge to biota and further modify local conditions. Temporal variation in physical structuring forces (wind, wave and tide) interacting at a range of scales with biotic processes and spatial variability can stamp additional layers of complexity and variability on the rocky intertidal zone.

C.2 Rocky Intertidal Flora and Fauna

The flora and fauna of the intertidal zone display intriguing vertical patterns of distribution. With the aim of enabling world-wide inter-shore comparisons Stephenson and Stephenson (in 1949) divided the rocky shore into five major biota-defined zones (Russell 1991). This was later modified (see Lewis 1961 & 1964) and the scheme now widely used, and which I have adopted, is that of Womersley and Thomas (1976), which recognises four main zones;

1. <u>Supralittoral zone</u> ('splash' zone). This zone is situated above the average level of high tide and receives salt water from splash or wind-driven spray. Littorinid snails, various lichens and, in some cases, thin sheets of blue-green algae dominate this region (Underwood 1972).

2. Eulittoral zone ('littoral' or 'mid-littoral' zone). This is the largest zone, receiving varying degrees of water coverage throughout the tidal cycle. In some regions three distinct sub-zones can be identified: the upper eulittoral zone (often dominated by small barnacles on rocky coasts); the mid-eulittoral zone (generally dominated by larger barnacles and/or molluscs such as limpets, and often blue-green algae); and the lower eulittoral zone (closest to low water mark and typified by an algal mat or turf and, in South Australia, often the sea grape, *Hormosira*).
3. Sublittoral zone. This zone extends from the mean low tide mark and is always covered with water except when exposed during extremely low tides or by interpeak wave action at low tide. It is typified by the presence of large brown algae on its upper boundary.
4. Sublittoral fringe zone. This can only be identified on coasts exposed to extremely strong wave action and is emergent only as waves recede at low tide.

Although zonation is a simple way of looking at broad intertidal patterns a number of quantitative studies have questioned the existence of true zonation (consisting of sets of coexisting species with upper and lower boundaries of the same tidal height), instead believing that it is the presence of overlapping patterns of large, dominant, or (in some other way) conspicuous species which create the illusion of zonation (Underwood 1994). However, species do tend to be restricted in their distribution by an upper and lower limit which is defined by their physical ability to cope with the abiotic conditions rather than the presence or absence of other species (Underwood 1972, 1973 & 1975a, Underwood and Chapman 1995).

In general, five main floral elements occur on rocky shores; encrusting algae, foliose algae, macroalgae, lichens and the plant component of biofilms. Encrusting (or crustose) algae tends to be restricted in size and distribution at lower shore levels, and is typically tightly adherent, calcareous and extensively distributed at upper shore levels (Underwood 1991). Foliose algae may provide a food source for herbivores and can modify local conditions for smaller organisms by providing shelter from waves and protection from sun exposure (and desiccation) at low tide (Underwood 1980). It typically adopts one of two functional forms; tough and wiry, or soft and flexible (Underwood and Chapman 1995). Lichen occurs in the supralittoral zone and can be a food source for littorinid gastropods (Quinn *et al.* 1992). Canopy-forming macro-algal species can also occur on rocky shores but are generally not extensive in southern Australia (Underwood 1994). Biofilms are living films comprised of varying proportions of diatoms, bacteria, protozoans, cyanobacteria, and macroalgal propagules (Anderson 1995). They provide a food source for herbivores (Underwood 1975b) and their presence has been shown to affect the settlement of marine larvae (Anderson 1995, Kennish *et al.* 1996).

Gastropods are frequently the most conspicuous and diverse group of animals seen on rocky shores (Womersley and Edmonds 1958, Underwood 1975a & 1979, Underwood and Chapman 1995). Typically, littorinids dominate at high levels due to their tolerance of prolonged air exposure (Underwood 1972 & 1979, Chapman 1994), while larger herbivorous gastropods occur at lower levels where they may co-exist with crustose algal-forms under sheltered conditions (Underwood 1991). The majority of intertidal herbivores graze on biofilms and consequently can influence the settlement and establishment of algae on bare rock (Underwood 1979 & 1984a, b & c). Predatory snails (or whelks) are found at midshore levels (see Connell 1970, Black 1978 & Underwood 1979 for feeding and related details), as are limpets which may also be found higher on the shore (Underwood 1979). Sessile animals such as bivalve mussels and barnacles often form a conspicuous intertidal component and can be the chief occupiers of space on rocky shores (Womersley and Edmonds 1958, Underwood 1979).

C.3 Natural Processes Affecting Patterns of Distribution

Zonation on rocky shores is influenced by an array of physical factors. These include tides, waves, currents, horizontal elevation and microtopography of rocks, shore slope, dominant substrata type and size, the degree of protection afforded by seaward structures such as rocky outcrops, and varying amounts of sun exposure and shade provision (Stephenson and Stephenson 1949, Dakin 1950, Womersley and Edmonds 1958, Lewis

1964, Stephenson and Stephenson 1972, Morton and Miller 1973, Underwood 1973, Emson and Faller-Fritsch 1976, Carefoot and Simpson 1977, Underwood 1978a & b & 1979, Underwood and Denley 1984, Underwood and Chapman 1989, Russell 1991, Jan *et al.* 1994, Schoch and Dethier 1996). However, physical factors are not the only structuring forces influencing the patterns of occurrence and distribution extremes of a particular species (Underwood 1985). The work of Connell (1961a & b and 1970) and Paine (1966, 1971, 1974 & 1984) established the importance of biological factors (for example, competition and predation) in the distribution patterns of rocky intertidal biota. Other studies have identified disturbance, recruitment limitation and the interaction of these factors as important factors influencing the structure of intertidal assemblages (Dayton 1971, Peterson 1979, Sousa 1979a & b, Paine 1984, Sousa 1984a, Gaines and Roughgarden 1985, Sutherland 1987).

Succession is an important process affecting the distribution of species in intertidal communities which are frequently exposed to patchy disturbance at a range of spatial and temporal scales. This process can be defined as the non-seasonal, directional and continuous pattern of colonisation and species replacement occurring as a direct or indirect response to site disturbance (Connell and Slayter 1977, Farrell 1991). Succession can be influenced by season, predation, competition and mutualism, wave exposure, nutrient and light availability, tidal height, recruitment and the individual growth rates of organisms (Underwood 1981, Jara and Moreno 1984, Farrell 1991, Underwood and Chapman 1995). Patchy disturbance creates a mosaic of habitats at different successional stages, maintaining species diversity and providing colonisation opportunities for new recruits (Sousa 1984b).

Most intertidal organisms reproduce by pelagic, planktonic dispersal of eggs, young, spores or other immature lifestages (Underwood 1994, Richards *et al.* 1995). The transport and dispersal of plankton is a passive process at large scales, and is primarily influenced by ocean currents, tidal activity, wind and waves (Gaines and Roughgarden 1985, Underwood and Fairweather 1989, Underwood and Chapman 1995). However, at smaller spatial scales organisms arriving at a site may display active site selection in response to a number of species-specific cues, such as shade, the presence of adult conspecifics, and altered water flow (see Underwood 1994).

Time spent in the plankton varies widely between organisms. In general, longer planktonic time reflects greater dispersal opportunities and avoidance of local extinction but introduces a higher risk of planktonic mortality (Underwood and Chapman 1995). Planktonic dispersal is both spatially and temporally variable and unpredictable and the number of new recruits arriving at a site is not influenced by conspecific adults or juveniles already present, nor by competition, predation or physical disturbance on the shore (Underwood and Fairweather 1989, Underwood 1994, Underwood and Chapman 1995).

Recruitment is extremely variable and this reflects such factors as fertilisation success, planktonic events, larval choice and post-settlement mortality (Gaines and Roughgarden 1985, Underwood 1994). Planktonic dispersal, settlement and recruitment have major effects on adult population dynamics (Butler 1987, Possingham and Roughgarden 1990, Gaines and Bertress 1992, Underwood 1994, Richards *et al.* 1995). Following recruitment, post-settlement success is influenced by the availability of food, ambient physical conditions and the densities of competing species (Underwood and Chapman 1995). Grazing is a significant structuring force within an intertidal community (see Castenholz 1961, May *et al.* 1970, Nicotri 1977, Raffaelli 1979, Underwood 1980 & 1981, Underwood and Jernakoff 1981, Hawkins and Hartnoll 1983, Jernakoff 1985, Petraitis 1987, Underwood 1991, Beovich and Quinn 1992) and it may alter the settlement surface for larvae (see Slattery 1992, Matthews and Cook 1995).

Competition for spacc also influences distribution patterns as sessile animals and plants require attachment sites and motile animals require grazing space (Underwood and Chapman 1995). This often results in the domination of space by the superior competitor (Menge 1976, Lubchenco and Menge 1978, Peterson 1979). However, when the situation is modified by frequent disturbance or predators are present, less-effective competitors are able to gain and hold space (Connell 1961a & b, Paine 1966, 1974, 1984, Dayton 1971, Denley and Underwood 1979, Sousa 1984a & b). Thus, predation also influences the observed distribution patterns of intertidal biota. A diverse array of predators occur on rocky shores including whelks, crabs, octopi, fish, birds and humans (Black 1978, Parry 1982, Chilton and Bull 1984, Underwood and Chapman 1995). High densities of organisms can be found coexisting with large numbers of their predators in situations where high pulse recruitment of an alternative prey in previous years has lifted predation pressure and allowed the original species to become established (Fairweather 1985). This situation highlights the interactive nature of many processes (such as competition, predation and herbivory) operating in communities and stresses the importance of investigating a suite of structuring factors when attempting to find underlying explanations for observed patterns of intertidal species abundance and distribution (Petraitis 1987).

C.4 Anthropogenic Activities and the Intertidal Zone

Many human activities perturb coastal systems and influence the distribution patterns of intertidal plants and animals (Ghazanshahi *et al.* 1983, Connell and Keough 1985, Sousa 1985, Liddle and Kay 1987, Castilla and Bustamante 1989, Underwood 1993, Grigg 1994, Kaly and Jones 1994). Activities such as selective foraging for bait and aquarium specimens (Blake 1979, Fairweather 1991b, Kingsford *et al.* 1991, Wynberg and Branch 1994), commercial and recreational fishing, and food gathering all impact heavily on the distribution and abundance of organisms in the intertidal zone (Durán *et al.* 1987, Underwood and Kennelly 1990, Keough *et al.* 1993, Underwood 1993, Underwood 1995a & b).

Isolating human impacts from natural disturbances is difficult. An experimental approach involving manipulation of the human activity of interest, the use of controls, and adequate replication is required to establish a causal relationship between an investigated activity (such as recreational shore use) and the observed biological patterns (Stewart-Oaten *et al.*

1986, Underwood and Peterson 1988, Keough and Quinn 1991). The lack of an experimental focus has meant that although a number of studies have investigated patterns of human activity along the coasts of NSW and Victoria (see Underwood and Kennelly 1990, Kingsford *et al.* 1991), they were only able to identify the species which were favoured by collectors and the most frequent recreational activities carried out on these shores, but not the relationship between these activities and any apparent trends (see Underwood 1993 for a review).

Underwood and Kennelly (1990) essentially conducted a pilot study to determine the optimal design appropriate to larger scale surveys investigating intertidal activities. They reported that the predation impact by humans on rocky shores in coastal NSW was affected by temporal factors including prevalent weather conditions. The study highlighted the importance of variability in recreational activities due to the time of day, the state of the tide, weather, and various spatial and temporal scales, and the need to factor these variables into experimental or survey designs.

Human Predation (or Collection)

In South and Central America and South Africa human predation on intertidal biota (particularly the collection of molluscs) can critically influence intertidal communities (e.g. Moreno *et al.* 1984 & 1986, Castilla and Durán 1985, Hockey and Bosman 1986, Olivia and Castilla 1986, Hockey *et al.* 1988, Durán and Castilla 1989). The link between human predation and intertidal change is evident (Ghazanshahi *et al.* 1983, Underwood 1993b) although many studies focusing on this topic suffer with inadequate replication and/or a lack of control areas which makes establishment of a cause-and-effect link between human predation and a perceived intertidal change difficult (but see Bosman 1986 & Hockey *et al.* 1988).

Human exploitation of coastal species can directly result in loss of individuals and the potential loss of breeding populations. Indirect effects arising from human predation in the intertidal zone include a change in the ecological balance of predators, competitors and food supply, alteration or loss of habitat, or loss of optimal breeding conditions for non-exploited species (Ghazanshahi *et al.* 1983, Underwood 1993). Predation (either natural or anthropogenic) is important in controlling the abundance of dominant competitors for primary space, an intertidal resource which is often limited (refer to Paine 1971 & 1974). For example, predation behaviours which tend to remove all animals from an area or target large animals are likely to have impacts on species diversity and general space occupancy patterns (Underwood and Kennelly 1990, Keough *et al.* 1993). This superimposes extra scales of patchiness on the natural patchiness which is a characteristic of intertidal systems.

An indirect consequence of human predation upon and removal of herbivorous gastropods is a lifting of grazing pressure, resulting in increased growth of the algae they graze (Underwood 1980, Underwood and Jernakoff 1981, Hockey and Bosman 1986, Durán *et al.* 1987, Godoy and Moreno 1989). This can result in changes in population and ultimately community dynamics (Underwood and Jernakoff 1981, Underwood *et al.* 1983, Godoy and Moreno 1989).

Human Trampling

Human trampling has long been known to produce deleterious changes in terrestrial systems (Liddle 1975, Nickerson and Thibodeau 1983, Kuss 1986, Kay and Liddle 1989, Liddle 1991). However, intertidal regions such as coral reefs (Woodland and Hooper 1977, Liddle and Kay 1987, Liddle 1991) and rocky shores (Beauchamp and Gowing 1982, Ghazanshahi *et al.* 1983, Cole *et al.* 1990, Kingsford *et al.* 1991, Povey and Keough 1991) are also prone to damage from recreational trampling. Trampling may remove all or part of an individual through crushing and dislodgment, weaken the attachments of organisms and increase their risk of dislodgment, or alter competition, predation or habitat provision (Suchanek 1978, Brosnan and Crumrine 1994). The differential survival of species under trampled conditions can be a function of their position in the intertidal zone, the conditions they are exposed to, and their morphology (Anderson *et al.* 1981, Kay and Liddle 1989, Liddle 1991, Brosnan and Crumrine 1994).

Microtopography has also been reported as an important modifier of trampling effects (Beauchamp and Gowing 1982, Brosnan and Crumrine 1994).

C.5 Overview of Processes

The observed biotic patterns on rocky intertidal shores represent the interactions of a number of processes. Chance elements such as recruitment, resource partitioning and disturbance shape intertidal assemblages in combination with predation, grazing, competition, and physical stresses, such as wave and tidal action and associated challenges. Studies of intertidal communities have generated hypotheses that identify natural disturbance (Connell 1978, Connell and Keough 1985), food web regulation, competition for space (Paine 1984), recruitment limitation (Gaines and Roughgarden 1985, Sutherland 1987), or a combination of these factors, as being of prime importance in structuring these communities. Although these factors may be of major importance to the coexistence of organisms they may act differentially in time and space, and their relative importance in shaping community structure and its complexity will similarly fluctuate temporally and spatially.

References

Anderson, M.J. (1995) Variations in biofilms colonising artificial surfaces: seasonal effects and effects of grazers. *Journal of the Marine Biological Association of the U.K.* **75**, 705-714.

Anderson, G.R.V., Ehrlich, A.H., Roughgarden, P.R., Russel, J.D. and Talbot, F.H. (1981) The community structure of coral reef fishes. *American Naturalist* **117**, 476-495.

Beauchamp, K.A. and Gowing, M.M. (1982) A quantitative assessment of human trampling effects on a rocky intertidal community. *Marine Environmental Research* **7**, 279-293.

Beovich, E.K. and Quinn, G.P. (1992) The grazing effect of limpets on the macroalgal community of a rocky intertidal shore. *Australian Journal of Ecology* **17**, 75-82.

Black, R. (1978) Tactics of whelks preying on limpets. *Marine Biology* **46**, 157-162.

Black, R. (1979) Competition between intertidal limpets: an intrusive niche on a steep resource gradient. *Journal of Animal Ecology* **48**, 401-411.

Blake, R.W. (1979) Exploitation of a natural population of *Arenicola marina* (L.) from the north-east coast of England. *Journal of applied Ecology* **16**, 663-670.

Bosman 1986, - not in ref list

Brosnan, D.M. and Crumrine, L.L. (1994) Effects of trampling on marine rocky shore communities. *Journal of Experimental Marine Biology and Ecology* **177**, 79-97.

Butler, A.J. (1987) Ecology of *Pinna bicolor* gmelin (Mollusca:Bivalvia) in Gulf St Vincent, South Australia: density, reproductive cycle, recruitment,growth and mortality at three sites. *Australian Journal of Marine and Freshwater Research* **38**, 743-769.

Carefoot, T. H. and Simpson R. D. (1977) *Seashore Ecology*. University of Queensland Press: Queensland.

Castenholz, R.W. (1961) The effect of grazing on marine littoral diatom populations. *Ecology* **42**, 783-794.

Castilla, J.C. and Bustmante, R.H. (1989) Human exclusion from rocky intertidal of Las Cruces, central Chile: effects on *Durvillaea antarctica* (Phaeophyta, Durvilleales). *Marine Ecology Progress Series* **50**, 203-214.

Castilla, J.C. and Durán, L.R. (1985) Human exclusion from the rocky intertidal zone of central Chile: the effects on *Concholepas concholepas* (Gastropoda). *Oikos* **45**, 391-399.

Chapman, M.G. (1994) Small- and broad-scale patterns of distribution of the upper-shore littorinid *Nodilittorina pyramidalis* in New south Wales. *Australian Journal of Ecology* **19**, 83-95.

Chapman, M.G. and Underwood A.J. (1996) Influences of tidal conditions, temperature and desiccation on patterns of aggregation of the high-shore periwinkle, *Littorina unifasciata*, in New South Wales, Australia. *Journal of Experimental Marine Biology and Ecology* **196**, 213-237

Chilton, N.B. and Bull, C.M. (1984) Influence of predation by a crab on the distribution of the size-groups of three intertidal gastropods in South Australia. *Marine Biology* **83**, 163-170.

Cole, R.C., Ayling, A.M. and Creese, R.G. (1990) Effects of marine reserve protection at Goat Island, northern New Zealand. *New Zealand Journal of Marine and Freshwater Research* **24**, 197-210.

Connell, J.H. (1961a). Effects of competition, predation by *Thais lapillus* and other factors on natural populations of the barnacle *Balanus ballanoides*. *Ecological Monographs* **31**, 61-104.

Connell J.H. (1961b). The influence of interspecific competition and other factors on the distribution of the barnacle *Chthamalus stellatus*. *Ecology* **42**, 710-723.

Connell J.H. (1970). A predator-prey system in the marine intertidal region. I. *Balanus glandula* and several predatory species of *Thais*. *Ecological Monographs* **40**, 49-78.

Connell, J.H. (1978) Diversity in tropical rain-forests and tropical reefs. *Science* **199**, 1302-1310.

Connell, J.H. and Keough, M.J. (1985) Disturbance and patch dynamics of subtidal marine animals on hard substrata. **In**: *The ecology of natural disturbance and patch dynamics*. S.T.A. Pickett and P.S. White (eds). (pp. 125-151). Academic Press, New York, USA.

Connell, J.H. and Slayter, R.O. (1977) Mechanisms of succession in natural communities and their role in community stability and organization. *American Naturalist* **111**, 1119-1143.

Dakin, W.J. (1950). *Australian Seashores.* 372 pp. Angus and Robertson, Sydney, Australia.

Dayton, P.K. (1971) Competition, disturbance and community organization: the provision and subsequent utilization of space in a rocky intertidal community. *Ecological Monographs* **41**, 351-389.

Denley, E.J. and Underwood, A.J. (1979) Experiments on factors influencing settlement, survival and growth of two species of barnacle in NSW. *Journal of Experimental Marine Biology and Ecology* **36**, 269-293.

Durán, L.R. and Castilla, J.C. (1989) Variation and persistence of the middle rocky intertidal community of central Chile, with and without human harvesting. *Marine Biology* **103**, 555-562.

Durán, L.R., Castilla, J.C. and Oliva, D. (1987) Intensity of human predation on rocky shores at Les Cruces in central Chile. *Environmental Conservation* **14**, 143-149.

Emson, R.H. and Faller-Fritsch, R.J. (1976) An experimental investigation into the effect of crevice availability on abundance and size-structure in a population of *Littorina rubis* (Maton): Gastropoda: Prosobranchia. *Journal of Experimental Marine Biology and Ecology* **23**, 285-297.

Fairweather, P.G. (1985) Differential predation on alternative prey, and the survival of rocky intertidal organisms in New South Wales. *Journal of Experimental Marine Biology and Ecology* **89**, 135-156.

Fairweather, P.G. (1991) A conceptual framework for ecological studies of coastal resources: an example of a tunicate collected for bait on Australian seashores. *Ocean and Shoreline Management* **15**, 125-142.

Fairweather, P.G. and Underwood, A.J. (1991) Experimental removals of a rocky intertidal predator: variations within two habitats in the effects on prey. *Journal of Experimental Marine Biology and Ecology* **154**, 29-75.

Farrell, T.M. (1991) Models and mechanisms of succession: an example from a rocky intertidal community. *Ecological Monographs* **61**, 95-113.

Gaines, S.D. and Bertress, M.D. (1992) Dispersal of juveniles and variable recruitment in sessile marine species. *Nature* **360**, 579-580.

Gaines, S.D. and Roughgarden, J. (1985) Larval settlement rate: a leading determinate of structure in an ecological community of the marine intertidal zone. *Proceedings of the National Academy of Science U.S.A.* **82**, 3707-3711.

Ghazanshahi, J., Huchel, T.D. and Devinny J.S. (1983) Alteration of southern California rocky shore ecosystems by public recreational use. *Journal of Environmental Management* **16**, 379-394.

Godoy, C. and Moreno, C.A. (1989) Indirect effects of human exclusion from the rocky intertidal in southern Chile: a case of cross-linkage between herbivores. *Oikos* **54**, 101-106.

Grigg, R.W. (1994) Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. *Marine Ecology Progress Series* **103**, 25-34.

Hawkins, S.J. and Hartnoll, R.G. (1983) Grazing of intertidal algae by marine invertebrates. *Oceanography and Marine Biology: Annual Review* **21**, 195-282.

Hockey, P.A.R. and Bosman, A.L. (1986) Man as an intertidal predator in Transkei: Disturbance, community convergence and management of a natural food resource. *Oikos* **46**, 3-14.

Hockey, P.A.R., Bosman, A.L. and Siegfried, W.R. (1988) Patterns and correlates of shellfish exploitation by coastal people in Transkei: An enigma of protein production. *Journal of Applied Ecology* **25**, 353-363.

Jan, R.Q., Dai, C.F. and Chang, K.H. (1994). Monitoring of hard substrate communities. **In**: *Biomonitoring of Coastal Waters and Estuaries*. K.J..M. Kramer (ed.). pp 285-310. CRC Press, Boca Raton, F.L.

Jara, H.F. and Moreno, C.A. (1984) Herbivory and structure in a midlittoral rocky community: a case in southern Chile. *Ecology* **65**, 28-38.

Jernakoff, P. (1985) Interactions between the limpet *Patelloida latistrigata* and algae on an intertidal rock platform. *Marine Ecology Progress Series* **23**, 71-78.

Kaly, U.L. and Jones, G.P. (1994) Long-term effects of blasted boat passages on intertidal organisms in Tuvalu: a meso-scale human disturbance. *Bulletin of Marine Science* **54**, 164-179.

Kay, A.M. and Liddle, M.J. (1989) Impact of human trampling in different zones of a coral reef flat. *Environmental Management* **13**, 509-520.

Kennish, R., Williams, G.A., and Lee, S.Y. (1996) Algal seasonality on an exposed rocky shore in Hong Kong and the dietary implications for the herbivorous crab *Grapsus albolineatus*. *Marine Biology*.**125**, 55-64.

Keough, M.J. and Quinn, G.P. (1991) Causality and the choice of measurements for detecting human impacts in marine environments. *Australian journal of Marine and Freshwater Research* **42**, 539-554.

Keough, M.J., Quinn, G.P. and King, A. (1993) Correlations between human collecting and intertidal mollusc populations on rocky shores. *Conservation Biology* **7**, 378-390.

Kingsford, M.J., Underwood, A.J. and Kennelly, S.J. (1991) Humans as predators on rocky reefs in New South Wales, Australia. *Marine Ecology Progress Series* **72**, 1-14.

Kuss, F.R. (1986) A review of major factors influencing plant responses to recreation impacts. *Environmental Management* **10**, 637-650.

Lewis, J.R. (1961) The littoral zone on rocky shores- a biological or physical entity? *Oikos* **12**, 280-301.

Lewis, J.R. (1964) *The Ecology of Rocky Shores.* 323 pp. English Universities Press, London.

Liddle, M.J. (1975) A selective review of the ecological effects of human trampling on natural ecosystems. *Biological Conservation* **7**, 17-36.

Liddle, M.J. (1991) Recreational ecology: effects of trampling on plants and corals. *Trends in Ecology and Evolution* **6**, 13-17.

Liddle, M.J. and Kay, A.M. (1987) Resistance, survival and recovery of trampled corals on the Great Barrier Reef. *Biological Conservation* **42**, 1-18.

Lieberman, M., John, D.M. and Lieberman, D. (1984) Factors affecting algal species assemblages on reef and coral substrata of Ghana. *Journal of Experimental Marine Biology and Ecology* **75**, 129-143.

Lubchenco, J. and Menge, B.A. (1978) Community development and persistence in a low rocky intertidal zone. *Ecological Monographs* **48**, 67-94.

Matthews, I. and Cook, P.A. (1995) Diatom diet of abalone post-larvae (*Haliotis midae*) and the effect of pre-grazing the diatom overstorey. *Marine Freshwater Research* **46**, 545-548.

May, V., Bennett, I., and Thompson, T.E. (1970) Herbivore-algal relationships on a coastal rock platform (Cape Banks, N.S.W.). *Oecologia* (Berlin) **6**, 1-14.

McGuiness, K.A. (1987a) Disturbance and organisms on boulders I. Patterns in the environment and the community. *Oecologia* (Berlin) **71**, 409-419.

McGuiness, K.A. (1987b) Disturbance and organisms on boulders II. Causes of patterns in diversity and abundance. *Oecologia* (Berlin) **71**, 409-419.

Menge, B.A. (1976) Organization of the New England rocky intertidal community: role of predation, competition and environmental heterogeneity. *Ecological Monographs* **46**, 355-393.

Menge, B.A. and Farrell, T.M. (1989) Community structure and interaction webs in shallow marine hard-bottom communities: test of an environmental stress model. ***Advances in Ecological Research*** **19**, 189-262.

Metaxas, A. and Scheibling, R.E. (1993) Community structure and organization of tidepools. *Marine Ecology Progress Series* **98**, 187-198.

Metaxas, A. and Scheibling, R.E. (1994) Spatial and temporal variability of tidepool hyperbenthos on a rocky shore in Nova Scotia, Canada. *Marine Ecology Progress Series* **108**, 175-184.

Metaxas, A., Hunt, H.L. and Scheibling, R.E. (1994) Spatial and temporal variability of macrobenthic communities in tidepools on a rocky shore in Nova Scotia, Canada. *Marine Ecology Progress Series* **105**, 89-103.

Moreno, C.A., Lunecke, K.M. and Lépez, M.I. (1986) The response of an intertidal *Concholepas concholepas* (Gastropoda: Muricidae) to protection from man in southern Chile and its effects on benthic-sessile assemblages. *Oikos* **46**, 359-364.

Moreno, C.A., Sutherland, J.P. and Jara, H.F. (1984) Man as a predator in the intertidal zone of southern Chile. *Oikos* **42**, 155-160.

Morton, J.E. and Miller, M.C. (1973). *The New Zealand Seashore.* (2nd Edn). 653 pp. Collins, Glasgow.

Nickerson, N.H. and Thibodeau, F.R. (1983) Destruction of *Ammophila breviligulata* by pedestrian traffic: quantification and control. *Biological Conservation* **27**, 277-287.

Nicotri, M.E. (1977) Grazing effects of four marine intertidal herbivores on the microflora. *Ecology* **58**, 1020-1032.

Oliva, D. and Castilla, J.C. (1986) The effect of human exclusion on the population structure of Key-hole Limpets *Fisurella crassa* and *F. limbata* on the coast of central Chile. *Marine Ecology* **7**, 201-217.

Paine R.T. (1971) A short term experimental investigation of resource partitioning in New Zealand rocky intertidal habitat. *Ecology* **52**, 1096-1106.

Paine R.T. (1974) Intertidal community structure: experimental studies on the relationship between a dominant competitor and its principle predator. *Oecologia (Berlin)* **15**, 93-120.

Paine, R.T. (1966). Food web complexity and species diversity. *American Naturalist* **100**, 65-75.

Paine, R.T. (1984) Ecological determinism in the competition for space. *Ecology* **65**, 1339-1348.

Parry, G.D. (1982) The evolution of the life histories of four species of intertidal limpets. *Ecological Monographs* **52**, 65-91.

Peterson, C.H. (1979) The importance of predation and competition in organizing the intertidal epifaunal communities of Barnegat Inlet, New Jersey. *Oecologia (Berlin)* **39**, 1-24.

Petraitis, P.S. (1987) Factors organizing rocky intertidal communities of New England: herbivory and predation in sheltered bays. *Journal of Experimental Marine Biology and Ecology* **109**, 117-136.

Possingham, H.P. and Roughgarden, J. (1990) Spatial population dynamics of a marine organism with a complex life cycle. *Ecology* **71**, 973-985.

Povey, A. and Keough, M.J. (1991) Effects of trampling on plant and animal populations on rocky shores. *Oikos* **61**, 355-368.

Quinn, G.P., Wescott, G.C., and Synnot, R.N. (1992) *Life on The Rocky Shores of South-Eastern Australia.* Victorian National Parks Association, Melbourne.

Raffaelli, D. (1979) The grazer-algae interaction in the intertidal zone on New Zealand Rocky shores. *Journal of Experimental Marine Biology and Ecology* **38**, 81-100.

Richards, S.A., Possingham, H.P. and Noye, B.J. (1995) Larval dispersal along a straight coast with tidal currents: complex distribution patterns from a simple model. *Marine Ecology Progress Series* **122**, 59-71.

Russell, G. (1991). Vertical Distribution. **In**: *Ecosystems of the World 24. Intertidal and Littoral Ecosystems.* D.W. Goodall (Editor in Chief). A.C. Mathieson and P.H. Nienhuis (eds). pp 43-66. Pub. Elsevier Science, London.

Schoch, G.C. and Dethier, M.N (1996) Scaling up: the statistical linkage between organismal abundance and geomorphology on rocky intertidal shorelines. *Journal of Experimental Marine Biology and Ecology* **201**, 37-72.

Slattery, M. (1992) Larval settlement and juvenile survival in the red abalone (*Haliotis rufescens*): an examination of inductive cues and substrate selection. *Aquaculture* **102**, 143-153.

Sousa, W. (1979a) Disturbance in marine intertidal boulder fields: the non-equilibrium maintenance of species diversity. *Ecology* **60**, 1225-1239.

Sousa, W. (1979b) Experimental investigations of disturbance and ecological succession in a rocky intertidal algal community. *Ecological Monographs* **49**, 227-254.

Sousa, W.P. (1984a) Intertidal mosaics: patch size, propagule availability, and spatially variable patterns of succession. *Ecology* **65**, 1918-1935.

Sousa, W. (1984b) The role of disturbance in natural communities. *Annual Review of Ecology and Systematics* **15**, 353-392.

Sousa, W.P (1985) Disturbance and patch dynamics on rocky intertidal shores. **In**: ***The ecology of natural disturbance and patch*** *dynamics*. S.T.A. Pickett and P.S. White (eds). pp. 101-124. Academic Press, New York, USA.

Stephenson, T.A. and Stephenson, A. (1949). The universal features of zonation between tide-marks on rocky coasts. *Journal of Ecology* **37**, 289-305.

Stephenson, T.A. and Stephenson, A. (1972). *Life Between Tidemarks on Rocky Shores.* W.H. Freeman and Co., San Francisco, USA.

Stewart-Oaten, A., Murdoch, W.W. and Parker, K.R. (1986) Environmental impact assessment: 'pseudoreplication' in time? *Ecology* **67**, 929-940.

Suchanek, T.H. (1978) The ecology of *Mutilus edulis* L. in exposed rocky intertidal communities. *Journal of Experimental Marine Biology and Ecology* **31**, 105-120.

Sutherland, J.P. (1987) Recruitment limitation in a tropical intertidal barnacle: *Tetraclita panamensis* (Pilsbry) on the Pacific coast of Costa Rica. *Journal of Experimental Marine Biology and Ecology* **113**, 267-282.

Underwood, A.J. (1972) Tide-model analysis of the zonation of intertidal prosobranchs. I. Four species of *Littorina* (L.). *Journal of Experimental Marine Biology and Ecology* **9**, 239-255.

Underwood, A.J. (1973) Studies of zonation of intertidal prosobranch molluscs in the Plymouth region. *Journal of Animal Ecology* **42**, 353-372.

Underwood, A.J. (1974) The reproductive cycles and geographical distribution of some common eastern Australian prosobranchs (Mollusca: Gastropoda). *Australian Journal of Marine and Freshwater Research* **25**, 63-88.

Underwood, A.J. (1975a) Intertidal zonation of prosobranch gastropods: analysis of densities of four coexisting species. *Journal of Experimental Marine Biology and Ecology* **19**, 197-216.

Underwood, A.J. (1975b) Comparative studies of the biology of *Nerita atramentosa* Reeve, *Bembicium nanum* (Lamarck) and *Cellana tramoserica* (Sowerby) (Gastropoda: Prosobranchia) in SE Australia. *Journal of Experimental Marine Biology and Ecology* **18**, 153-172.

Underwood, A.J. (1978a) The refutation of critical tidal levels as determinants of the structure of intertidal communities on British shores. *Journal of Experimental Marine Biology and Ecology* **33**, 261-276.

Underwood, A.J. (1978b) An experimental evaluation of competition between three species of intertidal prosobranch gastropods. *Oecologia* (Berlin) **33**, 185-202.

Underwood, A.J. (1979) The ecology of intertidal gastropods. *Advances in Marine Biology* **16**, 111-210.

Underwood, A.J. (1980) The effects of grazing by gastropods and physical factors on the upper limits of distribution of intertidal macroalgae. *Oecologia* (Berlin) **46**, 201-213.

Underwood, A.J. (1981) Structure of a rocky intertidal community in New South Wales: patterns of vertical distribution and seasonal changes. *Journal of Experimental Marine Biology and Ecology* **51**, 57-85.

Underwood, A.J. (1984a) The vertical distribution and seasonal abundance of intertidal microalgae on a rocky shore in New South Wales. *Journal of Experimental Marine Biology and Ecology* **78**, 199-220.

Underwood, A.J. (1984b) Microalgal food and the growth of the intertidal gastropods *Nerita atramentosa* Reeve and *Bembicium nanum* (Lamarck) at four heights on a shore. *Journal of Experimental Marine Biology and Ecology* **79**, 277-291.

Underwood, A.J. (1984c) Vertical and seasonal patterns in competition for microalgae between intertidal gastropods. *Oecologia* (Berlin) **64**, 211-222.

Underwood, A.J. (1985). Physical factors and biological interactions: the necessity and nature of ecological experiments. **In**: *The Ecology of Rocky Shores.* P.G. Moore and R. Seed (eds). pp. 372-390. (467 pp) Hodder and Stoughton, London.

Underwood, A.J. (1991) Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* **42**, 569-587.

Underwood, A.J. (1993) Exploitation of species on the rocky coast of New South Wales (Australia) and options for its management. *Ocean and Coastal Management* **20**, 41-62.

Underwood, A.J. (1994) Rocky intertidal shores. **In**: *Marine Biology*. L.S. Hammond and R.N. Synot (eds). pp. 272-296. Longman Cheshire Pty. Ltd. Melbourne.

Underwood, A.J. (1995a) Detection and measurement of environmental impacts. **In**: *Coastal Marine Ecology of Temperate Australia*. A.J. Underwood and M.G. Chapman (eds). pp. 311-324. University of New South Wales Press Ltd. Sydney.

Underwood, A.J. (1995b) Ecological research and (research into) environmental management. *Ecological Applications* **5**, 232-247.

Underwood, A.J. and Chapman, M.G. (1989) Experimental analyses of the influences of topography of the substratum on movements and density of an intertidal snail, *Littorina unifasciata*. *Journal of Experimental Marine Biology and Ecology* **134**, 175-196.

Underwood, A.J. and Chapman, M.G. (1995) Rocky shores. **In**: *Coastal Marine Ecology of Temperate Australia*. A.J. Underwood and M.G. Chapman (eds). pp. 55-82. Pub. University of New South Wales Press Ltd, Sydney.

Underwood, A.J. and Denley, E.J. (1984). Paradigm, explanations and generalisations in models for the structure of intertidal communities on rocky shores. **In**: *Ecological Communities:conceptual issues and the evidence*. D.R. Strong Jr, D. Simberloff, L.G. Abele and A.B. Thistle (eds). pp. 151-180. Princeton University Press, New Jersey, U.S.A.

Underwood, A.J. and Fairweather, P.G. (1989) Supply-side ecology and benthic marine assemblages. *Trends in Ecology and Evolution* **4**, 16-20.

Underwood, A.J. and Jernakoff, P. (1981) Effects of interactions between algae and grazing gastropods on the structure of a low-shore intertidal algal community. *Oecologia (Berlin)* **48**, 221-233.

Underwood, A.J. and Kennelly, S.J. (1990) Pilot Studies for designs of human disturbance of intertidal habitats in New South Wales. *Australian Journal of Marine and Freshwater Research* **41**, 165-173.

Underwood, A.J. and Peterson, C.H. (1988) Towards an ecological framework for investigating pollution. *Marine Ecology Progress Series* **46**, 227-234.

Underwood, A.J., Denley, E.J. and Moran, M.J. (1983) Experimental analyses of the structure and dynamics of midshore rocky intertidal communities in New South Wales. *Oecologia* **56**, 202-219.

van Tamelen, P.G. (1996) Algal zonation in tidepools: experimental evaluation of the roles of physical disturbance, herbivory and competition. *Journal of Experimental Marine Biology and Ecology* **201**, 197-231.

Womersley, H.B.S. and Edmonds, S.J. (1958) A general account of the intertidal ecology of South Australian coasts. *Australian Journal of Marine and Freshwater Research* **9**, 217-260.

Womersley, H.B.S. and Thomas, I.M. (1976) Intertidal ecology. **In**: *Natural History of the Adelaide Region*. C.R. Twidale, M.J. Tyler and B.P. Webb (eds). pp. 175-185. Royal Society of South Australia (Inc.): Adelaide.

Woodland, D.J. and Hooper, J.N.A. (1977) The effect of human trampling on coral reefs. *Biological Conservation* **11**, 1-4.

Wynberg, R.P. and Branch, G.M. (1994) Disturbance associated with bait-collection for sandprawns (*Callianassa kraussi*) and mudprawns (*Upogebia africana*): long-term effects on the biota of intertidal sandflats. *Journal of Marine Research* **52**, 523-558.

Appendix D: Oil

D.1 The Specific Physical and Chemical Nature of Oil

Oil is naturally formed from the decomposition of biogenic material (Overton *et al.* 1994). It consists of a complex mix of hydrocarbon molecules, each with different molecular structures and therefore unique physical and chemical properties and toxicities, which result in a similar variability in properties of the bulk oil (Ward *et al.* 1980, Essaid *et al.* 1993, Suchanek 1993, Overton *et al.* 1994). Such variability extends to crude oils from different fields of origin, as well as oils from a single field harvested at different times (Nelson-Smith 1973, Baker 1983, Clark 1989, Gary and Handwerk 1994, Overton *et al.* 1994).

Crude oils are used for the production of fuels and lubricants and for feedstocks in the petrochemical industry (Overton *et al.* 1994). Refining the crude product involves distillation to remove and separate the constituent products sequentially according to their different boiling point ranges (or volatilities), and catalytic cracking processes which use thermal energy to convert a large hydrocarbon into smaller molecules (Clark 1989, Chang 1991, Gary and Handwerk 1994, Overton *et al.* 1994). The refined products show the same physical, chemical and toxicological variability as crude oil, and include light gasoline (used as the basis of petrol), bunker fuels, naphtha and tars (Baker 1983, Clark 1989, Gary and Handwerk 1994).

The Chemical Structure of Oil

Hydrocarbons can be described as a mix of many organic compounds of natural origin and low water solubility and are the most important constituents of oils, accounting for up to 98% of some crude oils and as much as 100% of many oil products (Nelson-Smith 1973a, Overton *et al.* 1994). Other constituents present in crude oils are hydrocarbon derivatives which contain elements such as oxygen, sulphur, nitrogen or vanadian. The additional elements can influence the properties exhibited by the oil (Clark 1989, Suchanek 1993, Gary and Handwerk 1994, Overton *et al.* 1994).

Hydrocarbons contain hydrogen and carbon atoms arranged in straight, branching or cyclic chains (Nelson-Smith 1973a, Clark 1989). They fall into four main classes; paraffins, naphthenes, olefins and aromatics (Nelson-Smith 1973a, Chang 1991, Gary and Handwerk 1994, Overton *et al.* 1994).

1. Paraffins (alkanes) are arranged in straight or branching chains and are stable compounds with single, covalent, saturated bonds and the general formula C_nH_{2n+2} where 'n' is a whole integer.
2. Naphthenes (cycloparaffins or cycloalkanes) are also saturated and differ from paraffins in that two hydrogen atoms are eliminated which results in a ring structure. In addition, some hydrogen atoms may be replaced by alkyl groups. The general formula of this compound is C_nH_{2n} where 'n' is a whole integer ≥ 3.
3. Olefins (or alkenes) are unsaturated non-cyclic (branching or chain) structures with at least one carbon-carbon double bond and no more than two hydrogen atoms per carbon molecule. They occur in some petroleum products but never in crude oil and have the same general formula as the naphthenes except that 'n' is a whole integer ≥ 2.
4. Aromatics are unsaturated cyclic compounds containing one or more benzene rings. Within these compounds, some of the hydrogen atoms can be replaced by halogens (e.g. chlorine, fluorine and iodine) and alkyl groups which will confer different properties to the hydrocarbon. When benzene rings are fused together, the resultant compounds are termed polycyclic aromatic hydrocarbons.

In addition to the four main groups, two other groups can be defined. The first of these consists of asphaltenes and resins; colloidal aggregates found in crude oil which have the highest individual molecular weight of all crude oil components, are generally solids at 'normal' temperatures and are structured as large cyclic and planar molecules (Overton *et al.* 1994). The second additional group of oil components are called porphyrins. These are complex cyclic carbon structures derived from chlorophyll which can contain a central metal atom (Overton *et al.* 1994).

Physical Properties of Oils

The physical characteristics of oil, such as density, specific gravity (sg), viscosity, pour point and flash point (see Table D.1) will have a major impact on the transport and ultimate fate of oil spilt at sea. For example, the density of an oil is a major factor influencing whether it will float. Since crude oils and refined products (Table D.2), are typically less dense than seawater (which has a density ranging from 1.0 to 1.03 x 10 kg m^{-3}), oil tends to float on the water surface unless other factors, such as wave agitation, oppose this (Farmer and Li 1994).

Oil viscosity is a way of quantifying its resistance to flow (Gary and Handwerk 1994). The more viscous the oil, the more force is required for it to move a specified distance and the greater its tendency to aggregate. In general, viscosity will decrease with increasing API sg (see Table D.1) (Overton *et al.* 1994). Pour points for crude oils generally lie between 7^0 to 43^0C (Overton *et al.* 1994). This parameter is important as an oil with a pour point above the ambient environmental temperature will tend to aggregate rather than spread as a liquid (Gary and Handwerk 1994, Overton *et al.* 1994). Another important physical property of an oil is its flash point which is determined by the composition of its more volatile components (Overton *et al.* 1994). If the compound has volatile components of low molecular weight the flash points will be low, and vice versa (Overton *et al.* 1994).

Table D.1 Important physical properties of oil. Degrees API sg is a scale for specific gravity established by the American Petroleum Institute (API), where sg = 141.5/(131.5 + degrees API) (After Overton *et al.* 1994).

Characteristic	Definition	Units
Density	weight per unit volume of a substance	g cm^{-3} (liquids or solids) g L^{-1} (gases)
Specific Gravity (sg)	relates the density of a substance to the density of a standard substance such as water (sg = 1.000)	degrees API
Viscosity	Resistance to flow or internal friction.	
Absolute Viscosity	Force required to move a 1cm^2 planar surface area over another planar surface at a rate of 1 cm s^{-1} when the two surfaces are separated by a layer of fluid 1cm thick.	poise
Kinematic Viscosity	Ratio of absolute viscosity to density	stokes (St) or centistokes (cSt)
Pour Point	Lowest temperature at which a liquid can be poured. Recorded as 5^{0}F above the solid phase temperature (when no fluid movement occurs)	^{0}C
Flash Point	Temperature at which a liquid or volatile solid gives off enough vapours to form an ignitable mixture with air near its surface or in a test vessel	^{0}C

Table D.2 Properties of some crude and refined oil products ([1] From Bobra 1989, cited in Overton *et al.* 1994, [2] information from Mobil, Adelaide Refinery) (After Overton *et al.* 1994).

a) Crude Oil Properties

	Crude Oil Types		
Parameter	California [1]	Prudhoe Bay [1]	Arabian Light Crude [2]
Physical Properties			
API gravity	10.30	27	33.3
Density (20°C)	0.998	0.893	
Pour Point (°C)	0.0	27	-51
Flash Point (°C)	28.00	30	-18
Composition (wt %)			
Saturates	13.7	61.2	
Aromatics	29.8	35.6	
Polars	31.4	2.9	
Asphaltenes	24.8	1.2	
Sulfur (%)	3.3	0.82	

b) Refined Oil Properties

	Refined Oil Types			
Parameter	Gasoline[1]	Kerosene [1]	# 2 Fuel Oil [1]	# 6 Fuel Oil[1]
Physical Properties				
API gravity	60	37	31.6	10
Density (20°C)	0.734	0.83	0.84	0.966
Pour Point (°C)	< -40	-18.0	-20	6
Flash Point (°C)	-40	38.0	55	80
Composition (wt %)				
Saturates	39.6	85	61.8	24.4
Aromatics	46.2	15	38.2	54.6
Polars	-	-	0.0	14.9
Asphaltenes	N/A	N/A	0.0	6.2
Sulfur (%)	0.07	0.5	0.32	2.0

The physical characteristics displayed by oils provide information on their collective molecular composition and *vice versa* (Table D.2). A 'light' crude oil, for example, will have a high API sg, low viscosity and low pour point compared to other oils (Overton *et al.* 1994). Such physical characteristics generally indicate the oil contains a higher percentage of saturates in combination with lower percentages of asphaltene and polar components (Overton *et al.* 1994). In contrast, oils with a high asphaltene content are very viscous, have a high pour point and are non-volatile in nature (Gary and Handwerk 1994).

The physical characteristics of the individual components within a particular oil can be used to determine water solubility and vapour pressure, both of which have important implications on the persistence of oil in the environment (Overton *et al.* 1994). Water solubility is affected by the functional groups present in an oil e.g. phenol has an -OH functional group and a solubility of 8.2×10^4 ng μl^{-1} while benzoic acid has a functional group of -COOH and a lower solubility of 2.9×10^3 ng μl^{-1} (Overton *et al.* 1994). The pressure exerted by a vapour in equilibrium with the liquid from which it was derived, at a particular temperature (usually 20^0C), is termed the vapour pressure (Overton *et al.* 1994). Oils with a higher vapour pressure are the most volatile hydrocarbons, and if a light petroleum product is subjected to increased temperature and pressure, its volatility increases and it can form an explosive mix in the air (Overton *et al.* 1994).

D.2 The Oil Types Handled at Mobil, Port Stanvac

The two major types of oil handled at Mobil's Port Stanvac Oil Refinery are gasoline (petroleum) and Arabian light crude oil. Some of the properties exhibited by these two oils are presented in Table D.3.

Table D.3 A comparison of properties of gasoline and Arabian light crude oil, the most common crude oil received and processed at the Port Stanvac Oil Refinery. Values provided by [1]Overton *et al.* (1994) and [2]Eilman (pers. comm.).

	Oil Product	
Properties	Gasoline[1]	Arabian Light Crude[2]
API gravity	60	33.3
Pour Point (^{0}C)	<-40	-51
Flash Point (^{0}C)	-40	-18

D.3 Oil as a Coastal Disturbance

Oil can enter the ocean from a range of sources (see Burns and Smith 1980, Gunkel and Gassmann 1980, Clarke 1989, Volkman *et al.* 1992, Ehrhardt and Burns 1993, Ritchie 1993), including coastal oil refineries, and result in a variety of effects on coastal areas and their resident biota (Nelson-Smith 1973a & b, Ward *et al.* 1980, Hayes *et al.* 1993, Krupp and Jones 1993, Kureishy 1993, Literathy 1993, Sauer *et al.* 1993, Suchanek 1993). Oil is a mixture of complex compounds with varying properties and toxicities (Suchanek 1993), and its composition, in particular the ratio of carbon to hydrogen atoms, will influence its physical properties and determine how it will behave when spilt at sea (Gary and Handwerk 1994, Overton *et al.* 1994).

D.3.1 The Fate of Oil Spilt at Sea

Initially, oil tends to float and form a thin surface film or slick, but physical environmental factors such as water turbulence can lead to the formation of smaller globules or droplets (Farmer and Li 1994). Close to the water surface wind driven counter-rotating concentric vortices (termed Langmuir circulation) can form producing downwelling zones which disperse oil droplets beneath the surface (Farmer and Li 1994).

The spread of oil on a still sea is affected by gravity, inertia, surface tension and viscosity. Initially gravity is the primary force promoting spreading of an oil slick and this is opposed by inertia (Hoult 1972). However, once a critical thickness of approximately 8 mm is reached, surface tension becomes the major force affecting spread (Fay 1969, cited by Hoult 1972). As the oil spreads it carries with it a thin layer of water, and when the thickness of the two fluid layers are equal, viscosity becomes the dominant retarding force and spreading slows (Hoult 1972). In a large volume oil spill it is expected that viscosity would be the dominant force in as little as one hour. However, under 'real' conditions, wind, wave, tide and currents (both tidal and non-tidal) will be the major factors affecting the spread of oil and its transport as well as influencing the rate and way in which it weathers.

Weathering

Weathering refers to the physical and chemical changes which oil undergoes as it interacts with the environment. Weathering processes are primarily influenced by mechanical energy; such as wind, waves and currents, and thermal energy; such as oil, water and air temperature (Nounou 1980, Baker 1983, Overton *et al.* 1994) (see Fig. D.1). As the oil spreads, rapid evaporation of the light, low molecular weight components, mixing of the more water soluble components with the water column, and emulsification of the insoluble components to form droplets, occurs (Nelson-Smith 1973a, Clark 1989, Suchanek 1993, Overton *et al.* 1994, Douglas *et al.* 1996). These processes continue over time scales ranging from hours to days and result in the formation of a surface layer containing lighter oil components and displaying different characteristics to the underlying layer in which the oil has become dispersed within the water column (Nounou 1980). It has been estimated that during this phase around 10% of heavy oils or oil products and up to 75% of light fuel oil will be lost via evaporation (Nounou 1980). In addition, aerosol formation can occur at the surface of an oil slick (Fig. D.1) and remove more of the volatile components. As volatile components are lost and the slick spreads, the oil becomes more viscous and its pour point increases, retarding further spreading (Hoult 1972) and weathering (Overton *et al.* 1994).

In the open ocean an oil slick generally breaks up after a few days and oil can reach the beach at varying stages of weathering (Gunkel and Gassmann 1980). Physical processes such as high energy storms can act to increase the dispersion of oil and its surface area, therefore decreasing the persistence of the oil in the environment (Farmer and Li 1994, Overton *et al.* 1994). Oil spread is a self retarding process, which can be further complicated by the development of oil-water emulsions.

Emulsification and Mousse Formation

Oil emulsification occurs when the mechanical agitation of oil and water, which are each insoluble in the other, produces a dispersed phase which becomes suspended as droplets in the continuous phase (Nelson-Smith 1973a, Suchanek 1993, Overton *et al.* 1994). Two types of emulsions can form, an 'oil-in-water' emulsion and a 'water-in-oil' emulsion, either of which can be induced by natural or added surfactants in the oil and stabilised or destabilised by suspended particles in the sea (Nounou 1980). Aerated 'water-in-oil' emulsions form naturally with crude oils under agitated conditions and are very stable. A 'water-in-oil' emulsion with a 30-50% water content will flow freely and can appear to be pure oil, while a water content of 50-80% gives the emulsion the consistency of pale chocolate coloured grease, termed a 'mousse' (Nelson-Smith 1973a, Baker 1983). In this form it can be stable for some months, depending on the composition of the original oil, has an increased volume and viscosity which increases its smothering capacity, but provides a reduced surface area for degradative activity (Overton *et al.* 1994). It can also form thick pancakes on the water and adherent sticky masses on shore which tend to be resistant to physical and chemical breakdown but are less able to penetrate substrata (Baker 1983).

Tar Balls

Hydrocarbons which have not been degraded and which remain pelagic for an extended time can form stabilised agglomerates of heavy oil residues (ranging from 1 mm-20 cm) known as tar balls (Nounou 1980, Baker 1983). These can accumulate in living organisms or on mobile substrata and are slow to weather and degrade (Gunkel and Gassmann 1980).

Degradation

Degradation occurs as a consequence of chemical oxidation, primarily due to exposure to ultra-violet light, and biological processes (Baker 1983, Sauer *et al.* 1993, Essaid *et al.* 1995). The rate at which these processes occur is determined by the oil composition and its physical properties, exposure to physical processes, the presence and quantity of pre-existing hydrogen degrading microorganisms and exposure to abiotic environmental factors, such as temperature, pH, nutrient and oxygen availability, and mineral salt composition (Nounou 1980, Ward *et al.* 1980, Overton *et al.* 1994, Essaid *et al.* 1995). Both chemical and biological degradation act over periods ranging from a few weeks to several years, but can begin within days of an oil spill (Sauer *et al.* 1993).

Adherence and Sedimentation

Hydrocarbons can become attached to particles such as clay, organic matter, the remains of plankton and living microbes. If this occurs they eventually settle to the bottom of the ocean or accumulate in shore sediment, where degradation rates are then determined by the interaction of local physical and chemical conditions with the type of hydrocarbons involved (Baker 1983 & 1991).

References

Baker, J.M. (1983) Impact of oil pollution on living resources. *The Environmental Supplement* **3**, 5-48.

Baker, J.M. (1991) Guidelines on biological impacts of oil pollution. *International Petroleum Industry Environmental Conservation Association (IPIECA) Report Series.* Volume **1**, 1-15.

Burns, K.A. and Smith, J.L. (1980) Hydrocarbons in Victorian coastal waters. *Australian Journal of Marine and Freshwater Research* **31**, 251-256.

Chang, R. (1991) *Chemistry.* Fourth Edition. McGraw-Hill Inc., Sydney.

Clark, R.B. (1989) *Marine Pollution.* 2nd Edition. pp 33-64. Oxford Scientific Publications, Clarendon Press, Oxford.

Douglas, G.S., Bence, A.E., Prince, R.C., McMillan, S.J. and Butler, E.L. (1996) Environmental stability of selected petroleum hydrocarbon source and weathering ratios. *Environmental Science and Technology* **30**, 2332-2339.

Ehrhardt, M.G. and Burns, K.A. (1993) Hydrocarbons and related photo-oxidation products in Saudi Arabian Gulf coastal waters and hydrocarbons in underlying sediments and bioindicator bivalves. *Marine Pollution Bulletin* **27**, 187-197.

Essaid, H.I., Bekins, B.A., Godsy, M., Warren, E., Baedecker, M.J. and Cozzarelli, I.M. (1995) Simulation of aerobic and anaerobic biodegradation processes at a crude oil spill site. *Water Resources Research* **31**, 3309-3327.

Essaid, H.I., Herkelrath, W.N. and Hess, K.M. (1993) Simulation of fluid distributions observed at a crude oil spill incorporating hysteresis, oil entrapment, and spatial variability of hydraulic properties. *Water Resources Research* **29**, 1753-1770.

Farmer, D. and Li, M. (1994) Oil dispersion by turbulence and coherent circulations. *Oceanographic Engineering* **21**, 575-586.

Gary, J.H. and Handwerk, G.E. (1994) *Petroleum Refining. Technology and Economics.* Third Edition. pp 23-32. Marcel Dekker Inc., New York.

Gunkel, W. and Gassmann, G. (1980) Oil, oil dispersants and related substances in the marine environment. *Helgolander Meeresuntersuchungen* **33**, 164-181.

Hayes, M.O., Michel, J., Montello, T.M., Aurand, D.V., Al-Mansi, A.M., Al-Moamen, A.H., Sauer, T.C. and Thayer, G.W. (1993) Distribution and weathering of shoreline oil one year after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 135-142.

Hoult, D.P. (1972) Oil spreading on the sea. *Annual Review of Fluid Mechanics* **4**, 341-368.

Krupp, F. and Jones, D.A. (1993) The creation of a marine sanctuary after the 1991 Gulf War oil spill. *Marine Pollution Bulletin* **27**, 315-323.

Kureishy, T.W. (1993) Concentration of heavy metals in marine organisms around Qatar before and after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 183-186.

Literathy, P. (1993) Considerations for the assessment of environmental consequences of the 1991 Gulf War. *Marine Pollution Bulletin* **27**, 349-356.

Nelson-Smith, A. (1973a) Effects of oil on marine organisms. *Oil Pollution and Marine Ecology.* pp 71-98. Plenum Press, New York.

Nelson-Smith, A. (1973b) Benthic invertebrates. *Oil Pollution and Marine Ecology.* pp 116-132. Plenum Press, New York.

Nounou, P. (1980) The oil spill age. Fate and effects of oil in the marine environment. *Ambio* **9**, 297-302.

Overton, E.B., Sharp, W.D. and Roberts, P. (1994) Toxicity of Petroleum. **In**: *Basic Environmental Toxicology.* L.G. Cockerham and B.S. Shane (eds). pp 133-156. CRC Press Inc., London.

Ritchie, W. (1993) Environmental impacts of the *Braer* oil spill and development of a strategy for the monitoring of change and recovery. *Marine Policy* **17**, 434-448.

Sauer, T.C., Brown, J.S., Boehm, P.D., Aurand, D.V., Michel, J. and Hayes, M.O. (1993) Hydrocarbon source identification and weathering characterization of intertidal and subtidal sediments along the Saudi Arabian coast after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 117-134.

Suchanek, T.H. (1993) Oil impacts on marine invertebrate populations and communities. *American Zoologist* **33**, 510-523.

Volkman, J.K., Holdsworth, D.G., Neill, G.P. and Bavor H.J.Jr (1992). Identification of natural, anthropogenic and petroleum hydrocarbons in aquatic sediments. *The Science of the Total Environment*, **112**, 203-219.

Ward, D.M., Atlas, R.M., Boehm, P.D. and Calder, J.A. (1980) Microbial biodegradation and chemical evolution of oil from the Amoco spill. *Ambio* **9**, 277-283.

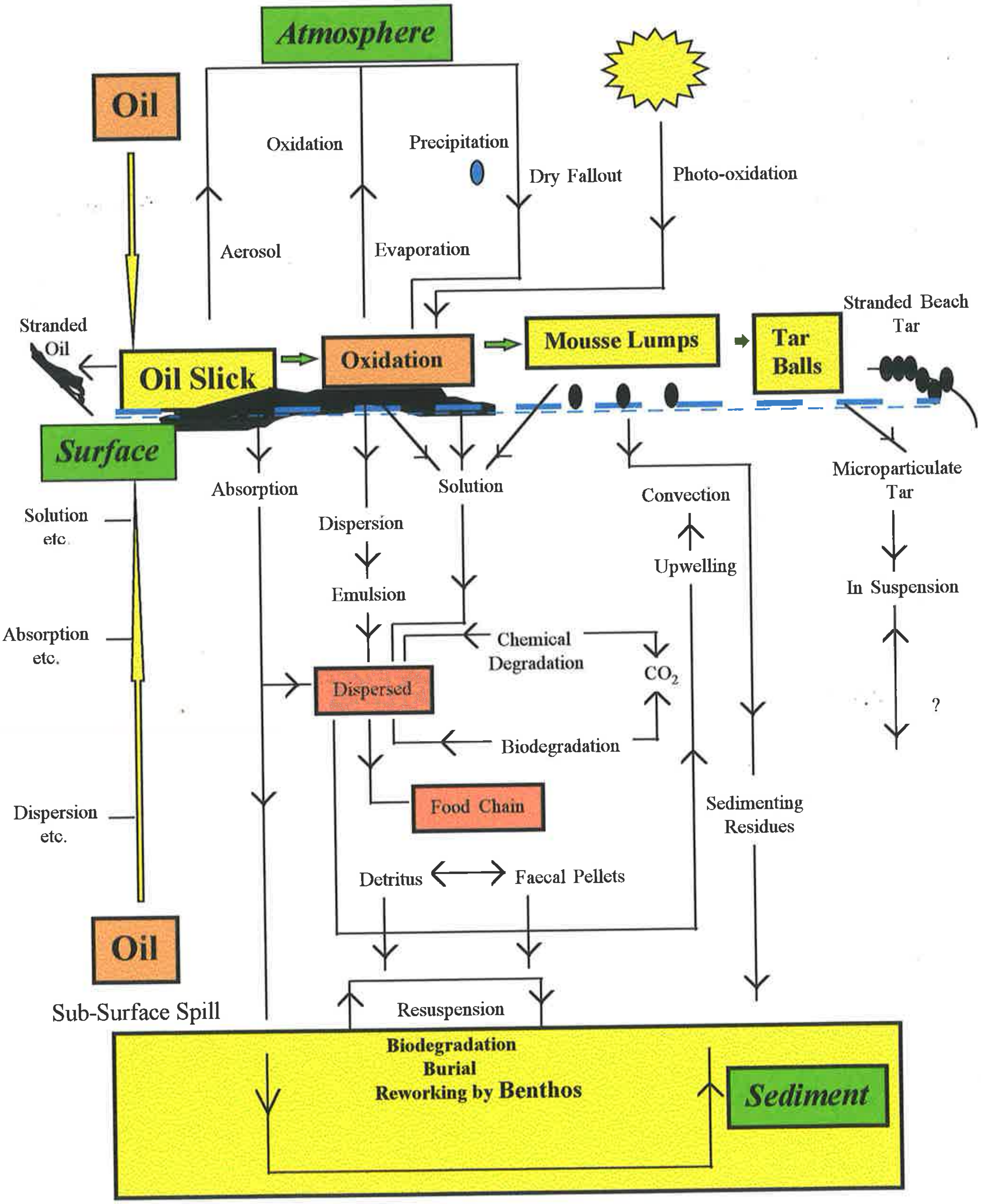
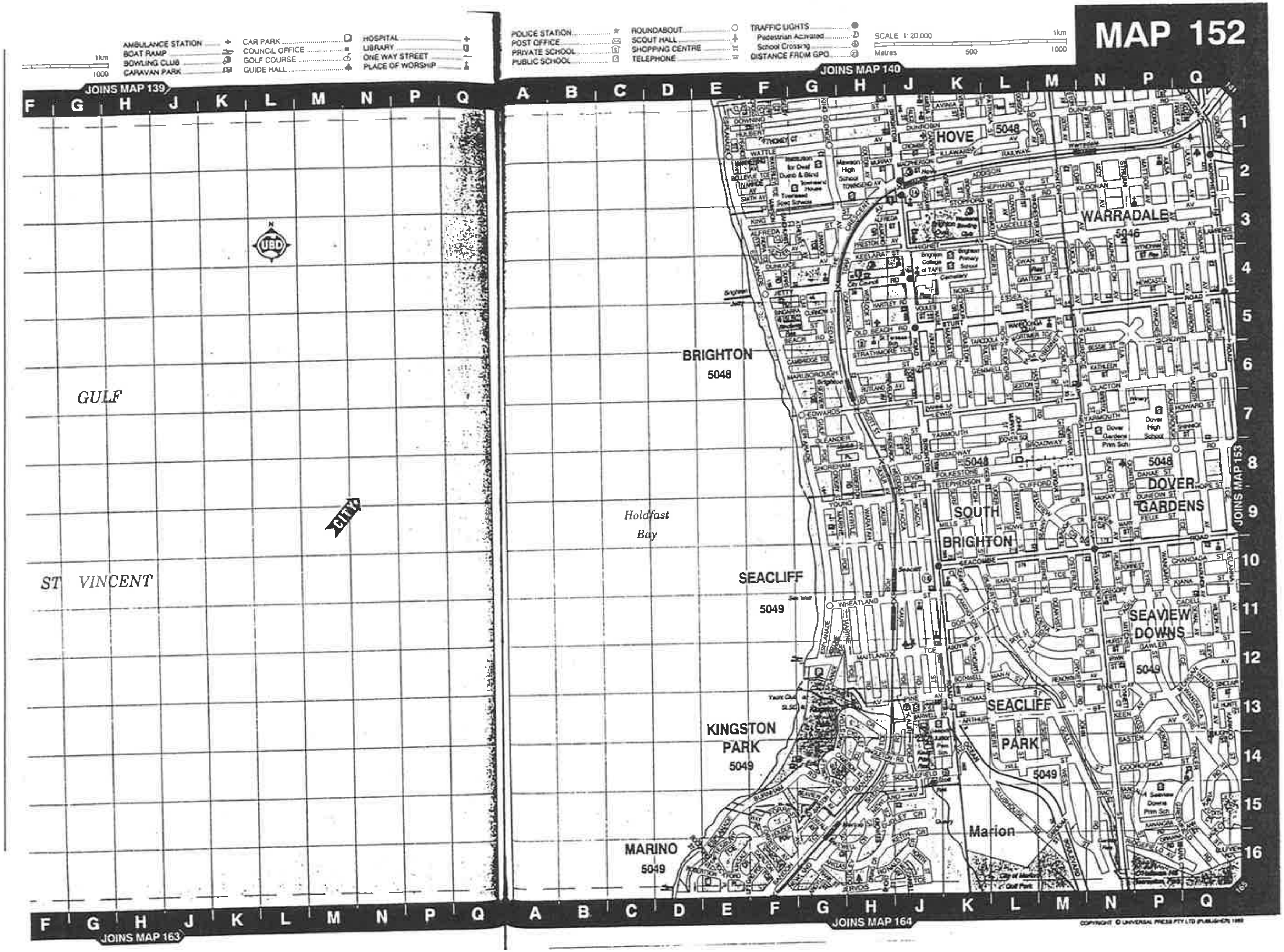
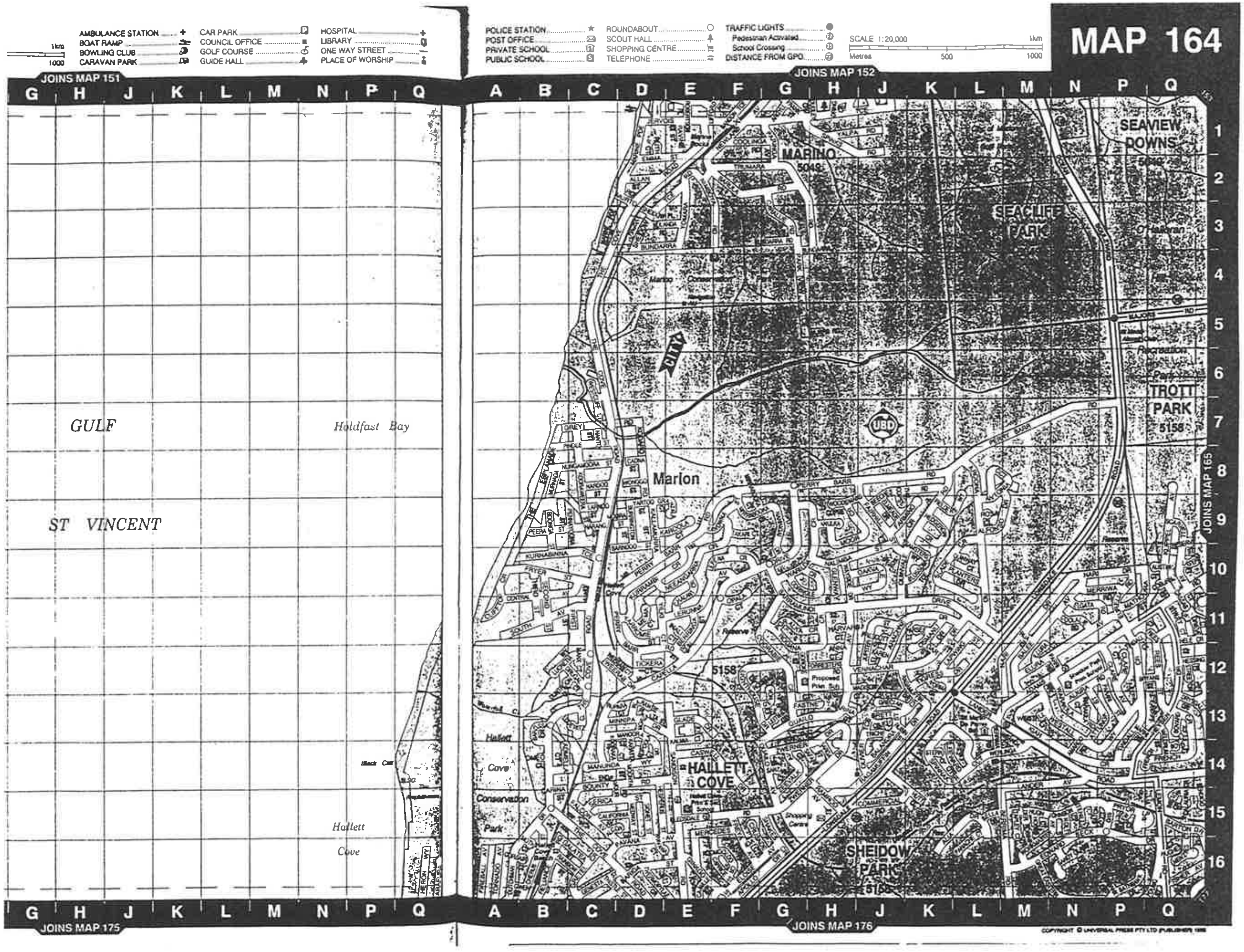


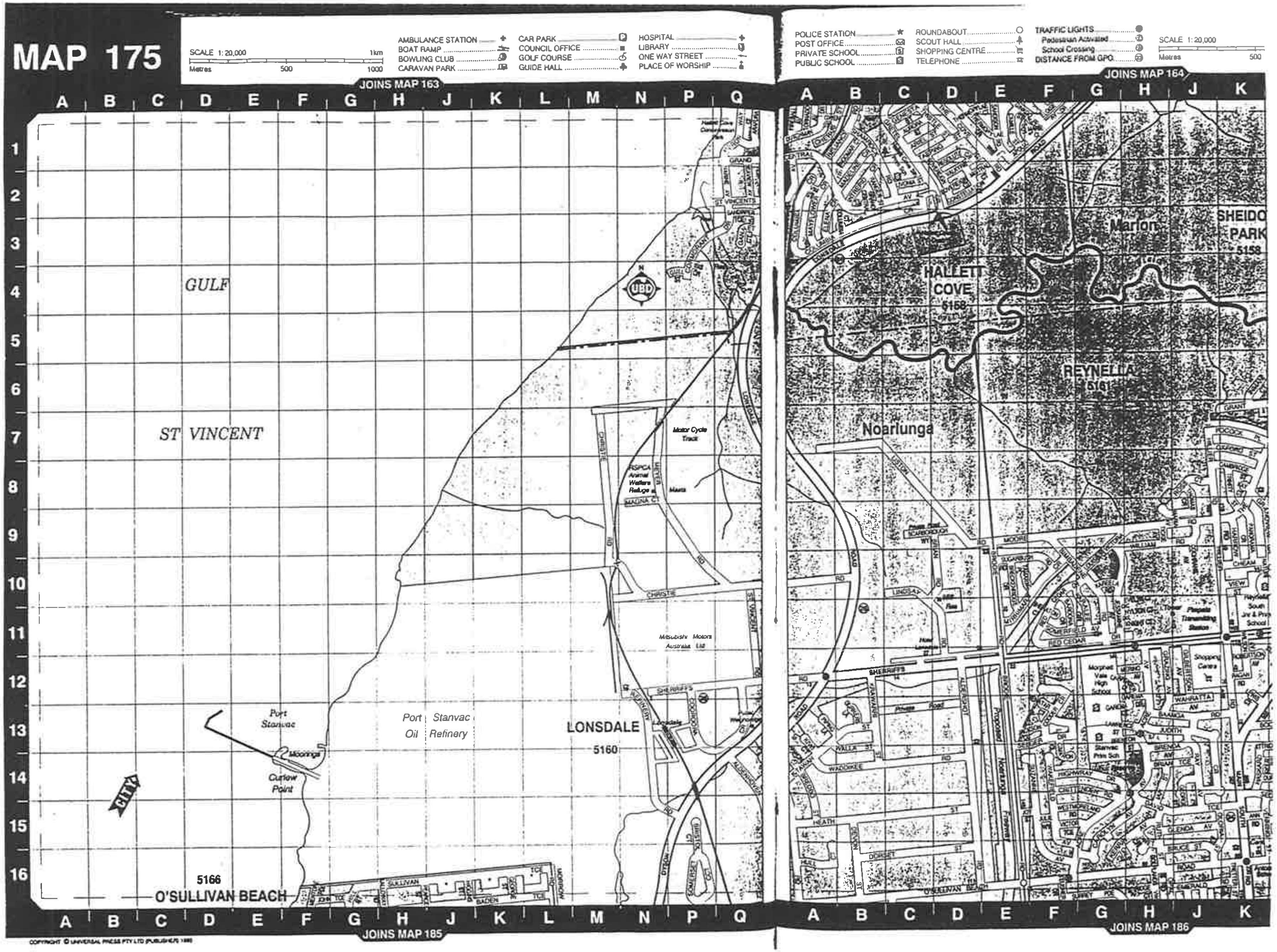
Fig. D.1 An overview of the dominant natural processes involved in oil weathering in the marine environment (modified after Gunkel and Gassmann 1980).

Appendix E: Road Map 152 ("UBD Street Directory Adelaide, 1994), used to locate Kingston Park, GSV



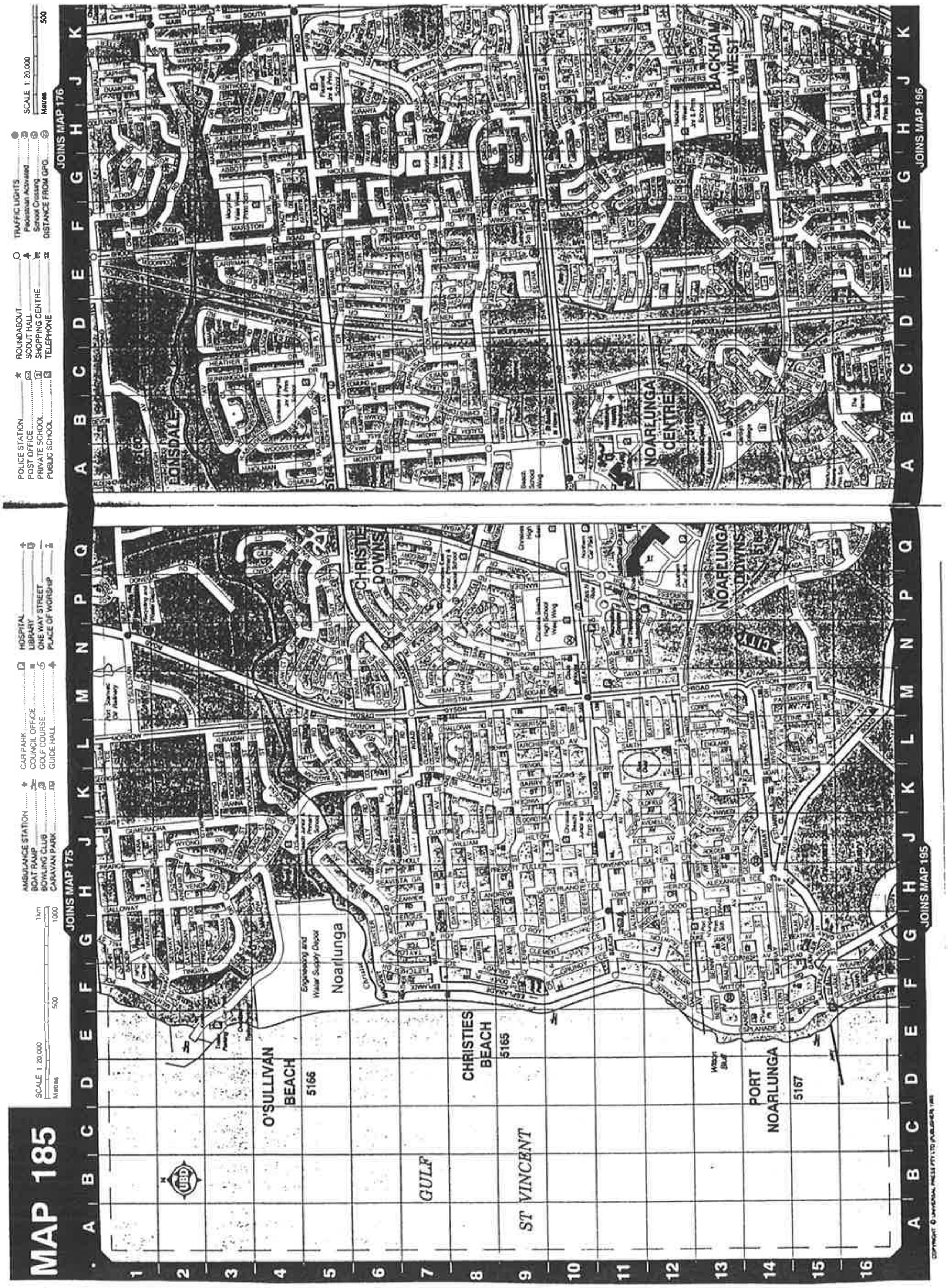


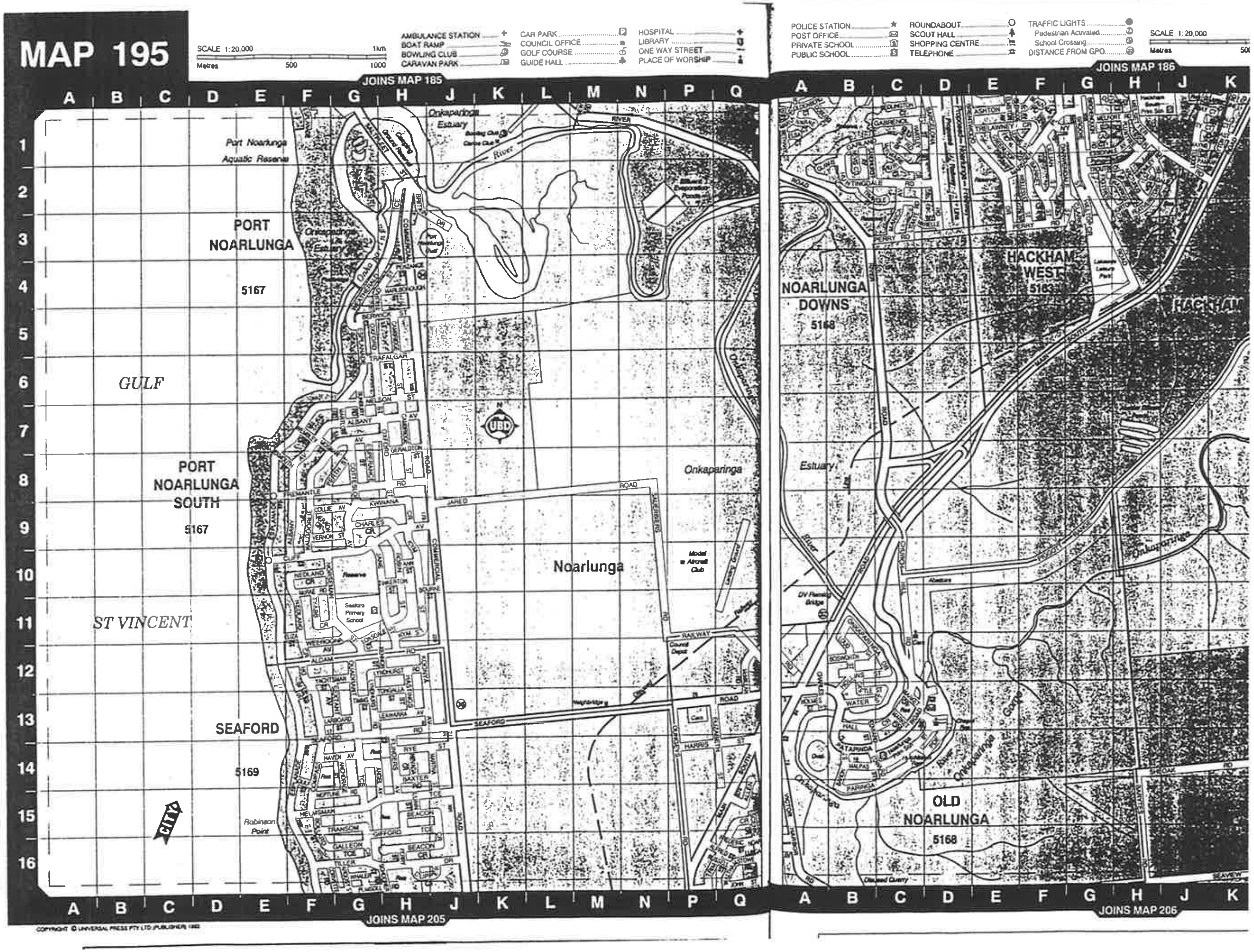
Appendix F: Road Map 164 ("UBD Street Directory Adelaide, 1994), used to locate Marino Rocks, GSV



Appendix G: Road Map 175 ("UBD Street Directory Adelaide, 1994), used to locate Hallett Cove & Port Stanvac sites, GSV

Appendix H: Road Map 185 ("UBD Street Directory Adelaide, 1994), used to locate Witton Bluff, GSV





Appendix I: Road Map 195 ("UBD Street Directory Adelaide, 1994), used to locate Port Noarlunga South & Robinson Point sites, GSV

Appendix J: Physical Parameter Assessment Sheet

DATA SHEET 1. PHYSICAL CHARACTER OF SITE								
SITE				DATE		TIME	ht L W M	
					COND.			
TEMP	AIR		pH				time L W	
	WATER							
WEATHER	CLOUD	RAINY(O,L,M,H)	CLEAR	FINE	WIND DIRECTN	WIND(0-4)	WAVE(0-4	**NOTES**
								OIL
ZONE NUMBER	CHAIN	ROCK TYPE	% ROCK TYPE	SHADE	ELEVATN	RETAINED WATER		(O-4)
1								
2								
3								
4								
5								
6								
7								
ZONE								
1								
2								
3								
4								
5								
6								
7								

BR=bedrock (or embedded reef rock), B=Boulder, C=Cobble,
P=Pebble, G=Gravel, S=Sand

Appendix K: Biota Census Sheet

DATA SHEET 2. INTERTIDAL ANIMALS PRESENT AT SITE

SITE	**ZONE**		**DATE**	**SITE**	**ZONE**		**DATE**	**SITE**	**ZONE**		**DATE**
	TIME				**TIME**				**TIME**		
QUAD SIZE	**NO.**			**QUAD SIZE**	**NO.**			**QUAD SIZE**	**NO.**		
	small	med	large		small	med	large		small	med	large
Galeolaria caesp.				Galeolaria caesp.				Galeolaria caesp.			
Scutus antipodes				Scutus antipodes				Scutus antipodes			
Cellana tramoser.				Cellana tramoser.				Cellana tramoser.			
Patelloida alticos.				Patelloida alticos.				Patelloida alticos.			
Patelloida latistrig.				Patelloida latistrig.				Patelloida latistrig.			
Notoacmea spp				Notoacmea spp				Notoacmea spp			
Siphonaria diem.				Siphonaria diem.				Siphonaria diem.			
Austrocochlea c.				Austrocochlea c.				Austrocochlea c.			
Austrocochlea o.				Austrocochlea o.				Austrocochlea o.			
Turbo undulatus				Turbo undulatus				Turbo undulatus			
Nerita atrament.				**Nerita atrament.**				**Nerita atrament.**			
Bembicium nanum				Bembicium nanum				Bembicium nanum			
Littorina unifasc.				Littorina unifasc.				Littorina unifasc.			
Littorina praeterm.				Littorina praeterm.				Littorina praeterm.			
Xenostrobus pulex				**Xenostrobus pulex**				**Xenostrobus pulex**			
Catomerus polym.				Catomerus polym.				Catomerus polym.			
Chthamalus ant				Chthamalus ant				Chthamalus ant			
Chamaesipho tas.				Chamaesipho tas.				Chamaesipho tas.			
Elminius spp				Elminius spp				Elminius spp			
Ulva spp				Ulva spp				Ulva spp			
Enteromorp. int.				Enteromorp. int.				Enteromorp. int.			
Homosera bank.				Homosera bank.				Homosera bank.			
Cystophora spp				Cystophora spp				Cystophora spp			
Sargassum spp				Sargassum spp				Sargassum spp			

Appendix L: Photographic Handbook of Common GSV Intertidal Species

Appendix A selection of animal species found in GSV.

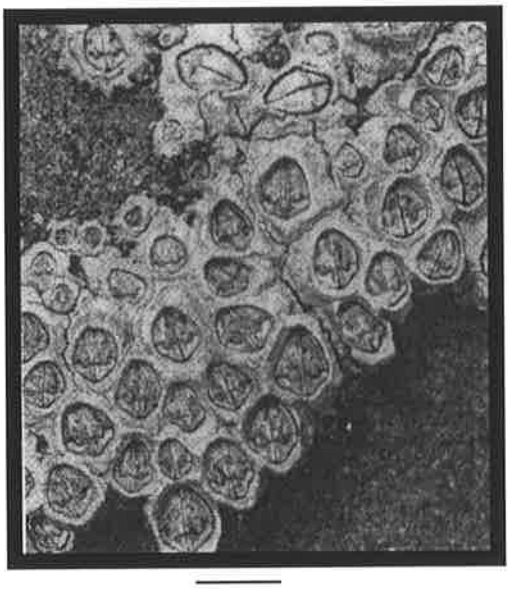
Chthamalus antennatus

1 cm

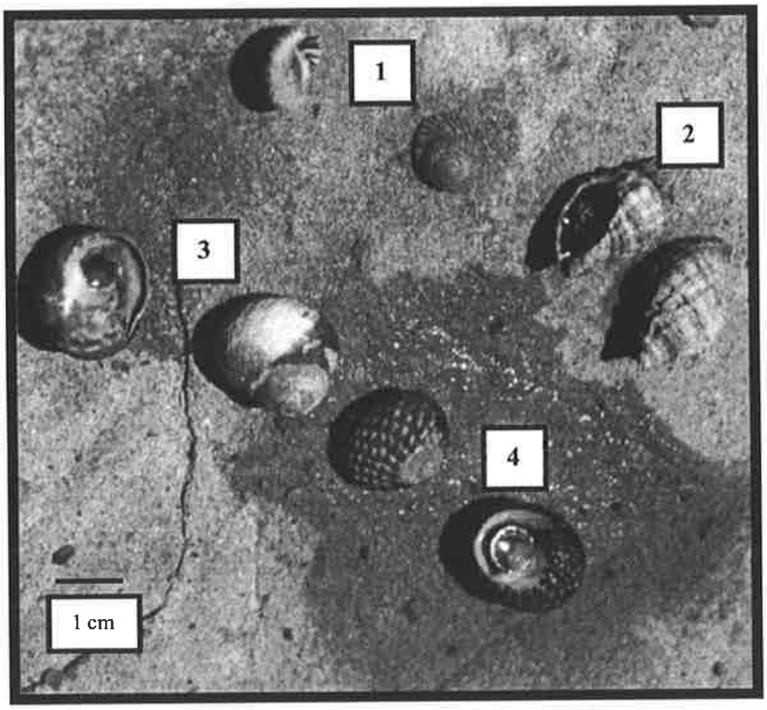
Catomerus polymerus

1 cm

Chamaesipho tasmanica

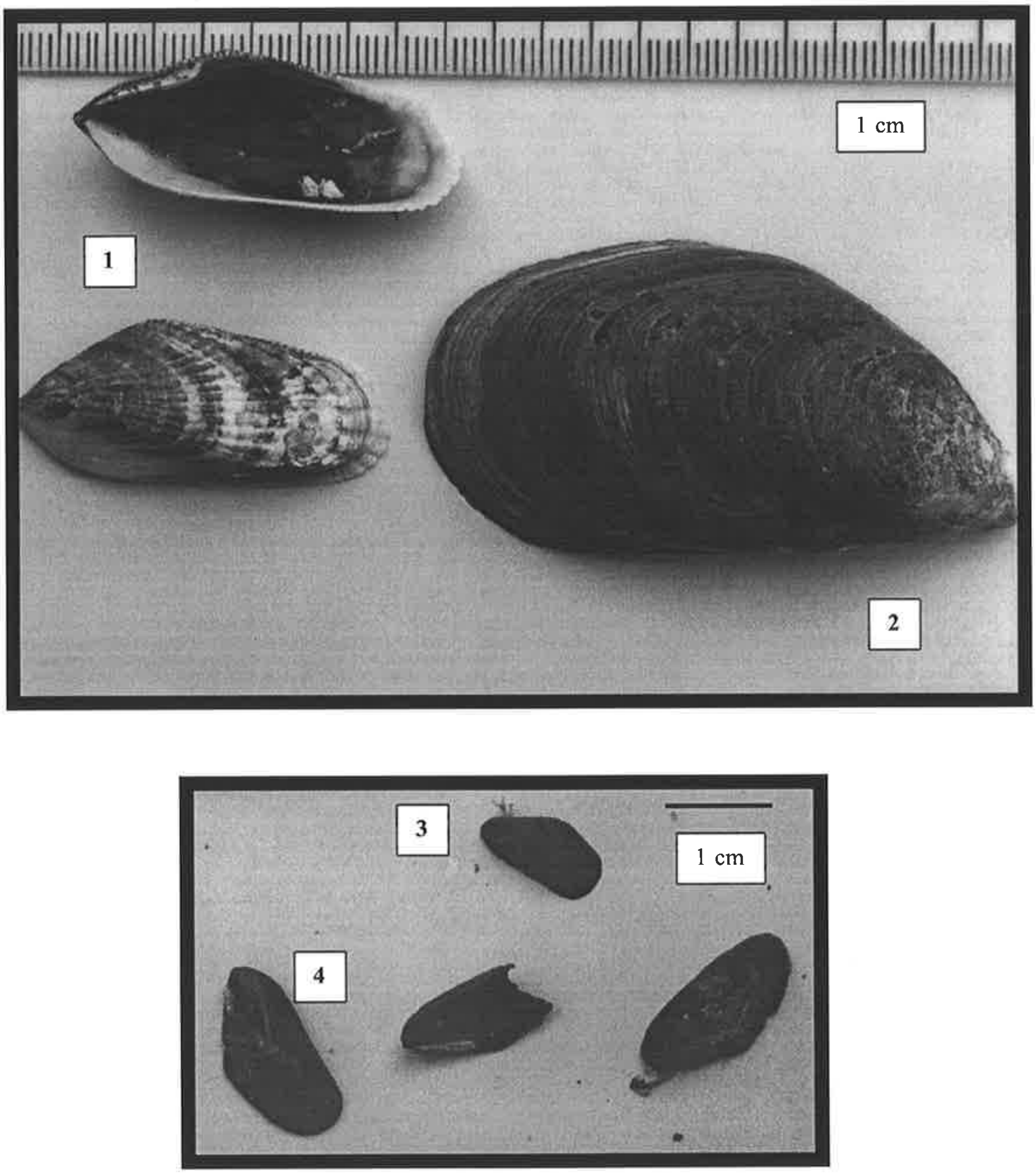


1 cm



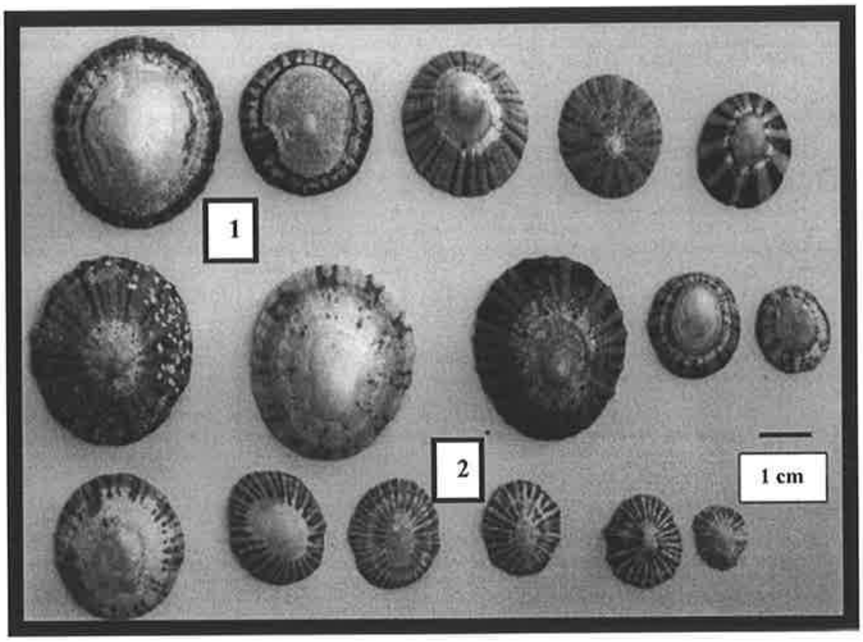
Bembicium nanum (1), *Lepsiella vinosa* (2),
Austrocochlea constricta (3) & *Austrocochlea concamerata* (4).

Appendix A selection of animal species found in GSV.

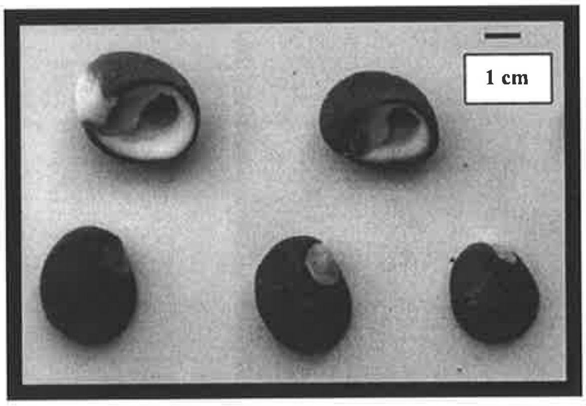


Brachidontes rostratus (1), *Mytilus edulis planulatus* (2), *Xenostrobus pulex* (3) & *Brachidontes erosus* (4).

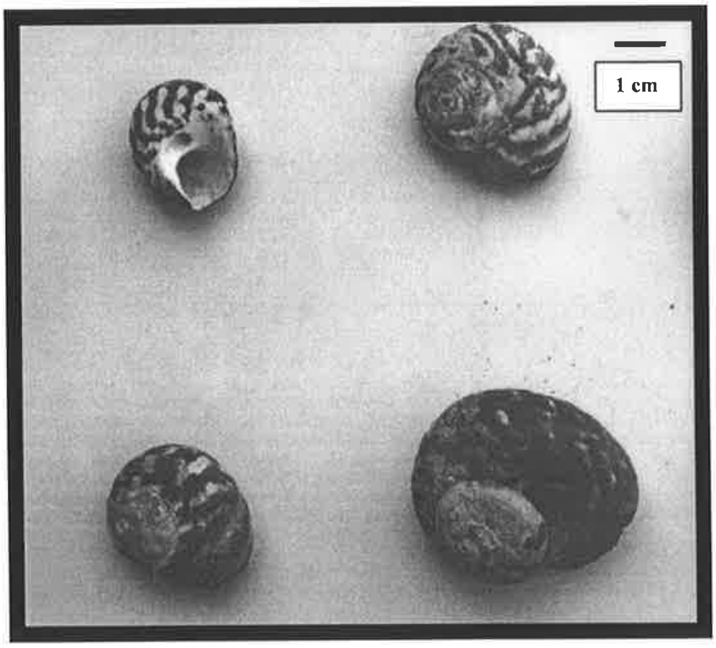
Appendix A selection of animal species found in GSV.

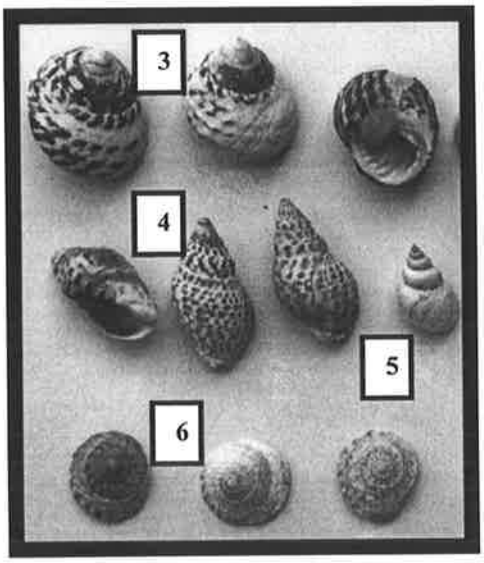


Nerita atramentosa



Turbo undulatus





Cellana tramoserica (1), *Siphonaria diemenensis* (2), *Austrocochlea constricta* (3), *Cominella lineolata* (4), *Littorina unifasciata* (5) & *Bembicium nanum* (6).

1 cm

Appendix M: "Advertiser" Report, December 1995

Shellfish scavengers face fines

SHELLFISH scavengers face fines of up to $2000 from tomorrow under tough new measures to preserve the State's molluscs.

The moves means barnacles, shrimps, snails, crabs, coral, abalone, periwinkles, limpets, worms, mussels and other shellfish cannot be taken from intertidal reefs.

These reefs are defined as any rocky reef area between the high tide mark to a depth of 2m.

The Primary Industries Minister, Mr Kerin, said molluscs were vital to the food chain but were threatened by over-exploitation.

"This is not aimed at stopping young children from fossicking but it does aim to stop those people who deliberately strip the reefs of shells and other crustaceans and who have in the past had too much freedom to do so," he said.

About 3000 homes along the coast have received letters alerting residents to the change and signs will be placed along the coast.

Mr Kerin

Appendix N: "GMAV5 Instructions"

Instructions for the use of GMAV5

INSTRUCTIONS FOR RUNNING GMAV5

November 3, 1995

GMAV5 is a 5 Factor Analysis of Variance program for any complex model of orthogonal or nested, xed or random factors. Heterogeneity of variances are tested using Cochran's test and means compared using udent-Newman-Keuls tests.

There are a few restrictions on the models allowed.

1. Data must be balanced.

2. All hierarchical factors must be nested within those above them in the hierarchy.

rst Steps

In order to run this application, it is necessary to have the following programs and files in the same irectory. They can be on a floppy disk drive or on a hard disk drive, but must be accessed through the same ath.

GMAV5.EXE
GMSNK.EXE
BRUN61ER.EXE
COCH1TAB.SNK
COCH5TAB.SNK
DATAFOR.SNK
Q1TAB1.SNK
Q1TAB2.SNK
Q5TAB1.SNK
Q5TAB2.SNK

It is not necessary to run this program with a printer because the results of the analysis can be output to printer or the screen.

If you are printing the results to a printer, it must be plugged into LPT1 and it must be turned on. If the rinter is not plugged into LPT1 or not turned on, you will get a "device fault" or other erroneous message and ne program will break. You will then need to start again.

You MUST answer prompts from the keyboard using CAPITAL LETTERS, or you may get a onsensical message and the program will break. To make this easier, switch Caps Lock on before you start.

You start the program by switching to the directory containing the above files and typing GMAV5. You an do this straight out of DOS or via another application such as WINDOWS. Do not change the names of any f the above files or programs.

ata Entry

The program will read data filenames or header filenames up to 8 letters, but it does need extensions on nese. The default extensions are "filename.hed" for header files, "filename.dta" for data files of raw data and ilename.mva" for data files of means and variances or totals and variances for each cell. If you are using these efault extensions, the program will add them to the filenames automatically. Therefore, it is only necessary for ou to type the filename without an extension if default extensions are used. You can add your own extensions hen you enter the filenames. These will override the default extensions.

The data and header information can be entered via the keyboard or via the disk drive. If entered via he disk drive, they do not have to have the same path as each other nor the same path as the programs and files isted above.

NOTE. The path must be included in the filename for the header and data files, e.g. "a:filename" if th data come from the "a" drive or "c:\data\filename" if the data come from a directory called "data" on the "c" drive.

Header File

The header file supplies information about the design of the analysis. These data can be entered via t keyboard in answer to prompts, or from a disk. The program allows a header to be saved once entered from t keyboard, so that it can be used for future analyses.

If the header file is entered from the disk, it must be entered as a sequential ASCII file with the follow information:

Datum 1	1 or 2 or 3 (1 = data being entered as raw data, 2 = data being entered as means and variances = data being entered as totals and variances).
Datum 2	Number of factors, 1 - 5.
Data 3 -	For each factor in turn: i) name of the factor ii) the number of levels of this factor iii) "O" if the factor is orthogonal; otherwise the number of the factor it is nested in, e.g. "1" this factor is nested in factor 1 or "13" if this factor is nested in the Factor 1 X Factor 3 interaction iv) this is left blank or has the number of the factor which is nested in it, e.g. "3" if Factor 3 i nested within this factor v) "F" if this is a fixed factor; "R" if it is a random factor.
Final datum	The number of replicates. This analysis only deals with balanced sets of data.

Data file

Data can be entered in three different forms. Data can be entered from a disk as a sequential ascii file. They can also be entered from the keyboard in answer to screen prompts. If an error is made entering data fro the keyboard, one can step back through the sequence by entering "e". This allows one to move back through a series of data to correct the error. All data after that point must, however, be entered again.

(i) RAW DATA are entered as a continuous set of numbers with no labels and no spaces. They must entered in the following orders:

1 Factor	Level 1	Replicates 1........n, then
	Level 2	Replicates 1........n, then
	Level 3	Replicates 1........n,
	....	
	Last Level	Replicates 1........n.

2 Factors	Factor 1	Level 1	Factor 2	Level 1	Replicates 1........n, then
		Level 1		Level 2	Replicates 1........n, then
		Level 1		Level 3	Replicates 1........n, then
		Level 2		Level 1	Replicates 1........n, then
		Level 2		Level 2	Replicates 1........n, then
		Level 2		Level 3	Replicates 1........n

3 Factors	Factor 1	Level 1	Factor 2	Level 1	Factor 3	Level 1	Replicates 1........n, then
		Level 1		Level 1		Level 2	Replicates 1........n, then
		Level 1		Level 2		Level 1	Replicates 1........n, then
		Level 1		Level 2		Level 2	Replicates 1........n, then
		Level 2		Level 1		Level 1	Replicates 1........n, then

Level 2	Level 1	Level 2	Replicates 1........n, then
Level 2	Level 2	Level 1	Replicates 1........n, then
Level 2	Level 2	Level 2	Replicates 1........n

d so on for 4 Factor and 5 Factor analyses.

(ii) The data can also be entered as a sequential file of MEANS (or TOTALS) and VARIANCES for each l. When the data are entered from the disk, all of the means (or totals) are entered, followed by the variances. us:

actor	Level 1	mean, then
	Level 2	mean, then
	.....	
	Last level	mean, then
	Level 1	variance, then
	Level 2	variance, then
	.....	
	Last level	variance

actor	Factor 1	Level 1	Factor 2	Level 1	mean, then
		Level 1		Level 2	mean, then
		Level 2		Level 1	mean, then
		Level 2		Level 2	mean, then
		Level 1		Level 1	variance, then
		Level 1		Level 2	variance, then
		Level 2		Level 1	variance, then
		Level 2		Level 2	variance.

If means (or totals) and variances are entered from the keyboard, the prompt asks for the mean (or total) then the variance for each cell in turn.

NOTE. Data that are entered as means (or totals) obviously cannot be transformed. You would need to ack to the raw data.

imal Points

The default value is 4 decimal points. This can be altered in response to a screen prompt if desired.

ısformation

The data can be transformed after Cochran's test and before an analysis or after analysis and before the are re-analysed, as required. Eight different transformations are available as indicated in the program.

ng data -

Before or after the analysis, one has the following options:

on 1	Save data to the disk if they were entered via the keyboard.
on 2	Print data on the screen or a printer.
on 3	Print means and variances on the screen or printer.
on 4	Save the means (or totals) and variances to the disk.
on 5	Save the header file to a disk.

Analysis

After the analysis, one has the option of printing the analysis on the screen and then to the printer or a disk. The analysis gives the Sums of Squares, Degrees of Freedom, Mean Squares, *F*-ratios and exact Probablities for each term in the model and prints out the model. If the *F*-ratio cannot be calculated for any term, then it prints "NO TEST".

One can then transform the data and re-analyse them, do S.N.K. tests on the existing data, run the program again on a different set of data or finish.

One is also given the choice of printing out the algebraic variance components from the linear model, as estimated by each Mean Square value in the analysis so that it is easy to determine which terms can be pooled to obtain appropriate or more powerful tests for higher order terms.

S.N.K. tests

If you do S.N.K. tests, then the program will automatically load and run GMSNK.EXE. This program cannot run alone because the correct models and values are handed across from GMAV5.EXE. All S.N.K. tests must, therefore, be done at the time of analysis, or the data will need to be analysed again.

The different sources of variation or terms in the model are listed and you can choose which one to do. After you have finished, choose 0 to quit S.N.K. tests and return to GMAV5 tor run another analysis or to quit altogether.

The results of the S.N.K. tests are printed on the printer or the screen. This is determined by your selection when running GMAV5. NOTE - you cannot change from selecting no printer to selecting a printer between doing the analysis and doing the S.N.K. tests. The format of these tests is as follows:

```
FACTOR      2                 S.E. = 2.7115

MEANS       12.1000           6.9000
S.E.        3.4496            1.8791

RANKS       2 - 1                               (i.e. Rank Order)
MEANS       1 - 2                               (i.e. Number of the two levels being compared)
             **
```

This shows that the means of all levels of Factor 2 were compared. The standard error used to calculat Q was 2.7115. There were two levels of Factor 2; Level 1 had a mean of 12.1 (S.E. 3.4); Level 2 had a mean of 6. (S.E. 1.9). The largest mean was in Level 1, the smallest mean was in Level 2, and the difference was significant *P* < 0.01 (hence, **).

```
FACTOR       3(1)              S.E. =2.6169
LEVEL          1

MEANS        5.3300            18.3300           7.2121
S.E.         3.4496             1.8791           2.1211

RANKS        3 - 1
MEANS        2 - 1
             *

2 - 1        3 - 2
3 - 1        2 - 3
              **
```

In this example, 3(1) indicates that the means of the different levels of Factor 3 within each level of Factor 1 are going to be compared (because Factor 3 was nested in Factor 1). The "1" underneath indicates that the means of Factor 3 in the first level of Factor 1 are being compared. The standard error used to calculate Q w 2.6169. There were three levels of Factor 3; in the first level of Factor 1, Level 1 of Factor 3 had a mean of 5.3 an a S.E. of 3.4; Level 2 had a mean of 18.3 and a S.E. of 1.9; Level 3 had a mean of 7.2 and a S.E. of 2.1. The difference between the largest and smallest means (Levels 1 and 2) was significant at $P < 0.05$ (hence, *). The difference between means 1 and 3 was not significant; the difference between means 2 and 3 was significant at $P < 0.01$ (hence, **).

The above procedure would be repeated for Factor 3 within each level of Factor 1.

When analysing interactions, you are asked if you want to proceed with all comparisons of every level of each factor in every level of the other factor(s) that with which it interacts. So, you can choose to examine only levels of Factor B in each level of Factor A, levels of Factor A in each level of Factor B or both. Answer the questions when you are asked.

Appendix O: “BMDP” V 5; Analysis of the ‘Effluent’ Data Set for Serial Correlation

'Effluent-impact' data set

```
 BMDP5V - UNBALANCED REPEATED MEASURES MODELS
          WITH STRUCTURED COVARIANCE MATRICES
 Copyright 1977, 1979, 1981, 1982, 1983, 1985, 1987, 1988, 1990
                     by BMDP Statistical Software, Inc.

        BMDP Statistical Software, Inc.| BMDP Statistical Software
        1440 Sepulveda Blvd            | Cork Technology Park, Model Farm Rd
        Los Angeles, CA 90025 USA      | Cork, Ireland
           Phone (213) 479-7799        |    Phone +353 21 542722
           Fax   (213) 312-0161        |    Fax   +353 21 542822
           Telex 4972934 BMDP UI       |    Telex 75659 SSWL EI

 Version: 1990    (SUN/UNIX)      DATE:Tue Dec  3 10:46:46 1996
  Manual: BMDP Manual Vol. 1 and Vol. 2 (1990).
  Digest: BMDP User's Digest (1990).
 Updates: State NEWS. in the PRINT paragraph for summary of new features.

 PROGRAM INSTRUCTIONS
```

effluent file   effluent impact.

```
 /problem         title='leanne piller test data'.
 /input           file='data1'.
                  format='(9i8/(24x,6i8))'.
                  variables=45.
 /variables       names=group,period,time.
 /categories      codes(group)=1,2.
                  names(group)=B,A.
                  codes(period)=1,2.
                  names(period)=P1,P2.
                  codes(time)=1 to 3.
                  names(time)=T1,T2,T3.
 /design          repeated=rep,loc.
                  level=7,6.
                  dpname=y.
                  dpvar=4 to 45.
                  grouping=group,period,time.
 /model           y='group*period+group*time+group*loc+period*time+period*loc
                  +time*loc'.
 /print           linesize=80.
 /end
```

```
 PROBLEM TITLE IS
 leanne piller test data

 NUMBER OF VARIABLES TO READ . . . . . . . . . .        45
 NUMBER OF VARIABLES ADDED BY TRANSFORMATIONS. .         0
 TOTAL NUMBER OF VARIABLES . . . . . . . . . . .        45
 CASE FREQUENCY VARIABLE . . . . . . . . . . . .
 CASE WEIGHT VARIABLE. . . . . . . . . . . . . .
 CASE LABELING VARIABLES . . . . . . . . . . . .
 NUMBER OF CASES TO READ . . . . . . . . . . . . TO END
 MISSING VALUES CHECKED BEFORE OR AFTER TRANS. . NEITHER
 BLANKS IN THE DATA ARE TREATED AS     . . . . . MISSING
 INPUT FILE. . .data1
 REWIND INPUT UNIT PRIOR TO READING. . DATA. . .     YES
 NUMBER OF INTEGER WORDS OF MEMORY FOR STORAGE . 1279998
 NUMBER OF CASES DESCRIBED BY INPUT FORMAT . . .       1

 VARIABLES TO BE USED
      1 group         2 period       3 time          4 X(4)          5 X(5)
      6 X(6)          7 X(7)         8 X(8)          9 X(9)         10 X(10)
     11 X(11)        12 X(12)       13 X(13)        14 X(14)        15 X(15)
     16 X(16)        17 X(17)       18 X(18)        19 X(19)        20 X(20)
     21 X(21)        22 X(22)       23 X(23)        24 X(24)        25 X(25)
     26 X(26)        27 X(27)       28 X(28)        29 X(29)        30 X(30)
     31 X(31)        32 X(32)       33 X(33)        34 X(34)        35 X(35)
     36 X(36)        37 X(37)       38 X(38)        39 X(39)        40 X(40)
     41 X(41)        42 X(42)       43 X(43)        44 X(44)        45 X(45)

 DATA FORMAT:
 (9i8/(24x,6i8))

 THE LONGEST RECORD MAY HAVE UP TO    72 CHARACTERS.

 I N P U T   V A R I A B L E S . . . . .
  VARIABLE  RECORD  COLUMN  INPUT     VARIABLE  RECORD  COLUMN  INPUT
 NO.   NAME    NO.  BEG  END FORMAT   NO.   NAME    NO.  BEG  END FORMAT
 --- -------- ---  ---  --- ------   --- -------- ---  ---  --- ------
   1 group      1    1    8   F8.0    19 X(19)      3   49   56   F8.0
   2 period     1    9   16   F8.0    20 X(20)      3   57   64   F8.0
   3 time       1   17   24   F8.0    21 X(21)      3   65   72   F8.0
   4 X(4)       1   25   32   F8.0    22 X(22)      4   25   32   F8.0
   5 X(5)       1   33   40   F8.0    23 X(23)      4   33   40   F8.0
   6 X(6)       1   41   48   F8.0    24 X(24)      4   41   48   F8.0
   7 X(7)       1   49   56   F8.0    25 X(25)      4   49   56   F8.0
   8 X(8)       1   57   64   F8.0    26 X(26)      4   57   64   F8.0
   9 X(9)       1   65   72   F8.0    27 X(27)      4   65   72   F8.0
  10 X(10)      2   25   32   F8.0    28 X(28)      5   25   32   F8.0
  11 X(11)      2   33   40   F8.0    29 X(29)      5   33   40   F8.0
  12 X(12)      2   41   48   F8.0    30 X(30)      5   41   48   F8.0
  13 X(13)      2   49   56   F8.0    31 X(31)      5   49   56   F8.0
  14 X(14)      2   57   64   F8.0    32 X(32)      5   57   64   F8.0
  15 X(15)      2   65   72   F8.0    33 X(33)      5   65   72   F8.0
  16 X(16)      3   25   32   F8.0    34 X(34)      6   25   32   F8.0
  17 X(17)      3   33   40   F8.0    35 X(35)      6   33   40   F8.0
  18 X(18)      3   41   48   F8.0    36 X(36)      6   41   48   F8.0
```

```
PAGE    3  5V leanne piller test data


 I N P U T   V A R I A B L E S . . . . .
  VARIABLE   RECORD   COLUMN   INPUT      VARIABLE   RECORD   COLUMN   INPUT
 NO.    NAME    NO.   BEG   END FORMAT    NO.    NAME    NO.   BEG   END FORMAT
 --- -------- ---   ---   --- ------     --- -------- ---    ---   --- ------
  37 X(37)       6    49    56  F8.0      42 X(42)       7    41    48  F8.0
  38 X(38)       6    57    64  F8.0      43 X(43)       7    49    56  F8.0
  39 X(39)       6    65    72  F8.0      44 X(44)       7    57    64  F8.0
  40 X(40)       7    25    32  F8.0      45 X(45)       7    65    72  F8.0
  41 X(41)       7    33    40  F8.0
 ALGORITHM NAME. . . . . . . . . . . . . .NR
 MAXIMUM NUMBER OF ITERATIONS. . . . . .  15
 MAXIMUM NUMBER OF STEP HALVINGS . . . .  10
 CONVERGENCE CRITERION . . . . . . . . .LOG
 TOLERANCE FOR CONVERGENCE . . . . . . .    0.10000E-04
 TOLERANCE FOR PIVOTING. . . . . . . . .    0.10000E-04


 DESIGN SPECIFICATIONS

          GROUP  =    1   2   3
          DEPEND =    4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
                     19  20  21  22  23  24  25  26  27  28  29  30  31  32  33
                     34  35  36  37  38  39  40  41  42  43  44  45
          LEVEL  =    7   6

 RECORDS FOR EACH CASE:    7


   VARIABLE         STATED VALUES FOR               GROUP CATEGORY     INTERVALS
  NO.   NAME      MINIMUM MAXIMUM MISSING   CODE   INDEX   NAME      .GT.   .LE.
  ---- --------   ------- ------- -------  ------  ----- --------   ------ -------

    1  group                                1.000    1  B
                                            2.000    2  A

    2  period                               1.000    1  P1
                                            2.000    2  P2

    3  time                                 1.000    1  T1
                                            2.000    2  T2
                                            3.000    3  T3
 ------------------------------------------------------------------------------


 GROUP STRUCTURE, COUNTING ALL CASES WITH POSITIVE USE-VALUE,
 AND IGNORING CASE WEIGHT AND FREQUENCY, IF ANY

  group     period    time      COUNT
  B         P1        T1            1
  B         P1        T2            1
  B         P1        T3            1
  B         P2        T1            1
  B         P2        T2            1
  B         P2        T3            1
  A         P1        T1            1
```

```
PAGE   4  5V leanne piller test data

  A          P1         T2                1
  A          P1         T3                1
  A          P2         T1                1
  A          P2         T2                1
  A          P2         T3                1

      DECODED FORMULA

 group + period + time + loc + group.period + group.time + period.time +
 group.loc + period.loc + time.loc

 INTERCEPT IS INCLUDED IN THE MODEL.


 ANALYSIS FOR  1ST DEPENDENT VARIABLE



 NUMBER OF CASES READ. . . . . . . . . . . . . . . . . . .         12
       CASES CONTRIBUTING DATA TO THE ANALYSIS . . . . .           12
    CASES WITH COVAR. OR DEP.VAR. MISSING OR BEYOND LIMITS          0
       COMPLETE CASES (CASES WITH NO MISSING DATA) . . .           12
    TOTAL NUMBER OF MEASUREMENTS . . . . . . . . . . . .          504

 ITER  STEP     LOG       CHG IN LOG       MAX CHG
   NO  HLVS  LIKELIHOOD  LIKELIHOOD        IN COV.PAR
 ---------------------------------------------------
    0   0      -2369.71
    1   0      -2294.83  0.74881E+02  0.75277E+03
    2   0      -2294.83  0.18190E-11  0.23511E-12

 MAXIMUM LOG LIKELIHOOD          =       -2294.826
 CHANGE SINCE LAST STEP          =     0.000000000

 APPROX. CONVERGENCE RATE        =     0.000000000
 MIN. TOL. FOR COV. MATRIX       =     0.996467897


      AKAIKE'S INFORMATION CRITERION(AIC):

   AIC MAY BE USED TO SELECT AN APPROPRIATE COVARIANCE
   STRUCTURE BY RUNNING 5V WITH DIFFERENT TYPES OF
   STRUCTURES AND SELECTING THE ONE WITH MAXIMUM AIC VALUE.

 AIC                             =       -2296.826
```

```
     ESTIMATES OF COVARIANCE PARAMETERS:

  WITHIN-SUBJECT COVARIANCE MATRIX IS A FUNCTION
  OF COVARIANCE PARAMETERS. 5V PROVIDES SEVERAL
  BUILT-IN STRUCTURES YOU CAN CHOOSE FROM BY
  SPECIFYING THE TYPE IN THE STRUCTURE PARAGRAPH


 COV. STRUCTURE TYPE=COMPOUND SYMMETRY
 UNDER THIS MODEL, THE RESPONSES HAVE A
      VARIANCE=COV PAR 1 + COV PAR 2
      COMMON COVARIANCE=COV PAR 2

 COV PAR      ESTIMATE   ASYMPTOTIC SE     Z-SCORE
 -------------------------------------------------
    1          522.871         33.3370    15.684
    2          5.90280         7.53414     0.783
```

```
PAGE   6  5V leanne piller test data


     MODEL:  WITHIN-SUBJECT COVARIANCE MATRIX


                     1            2            3            4            5            6
           1  528.77343
           2    5.90280    528.77343
           3    5.90280      5.90280    528.77343
           4    5.90280      5.90280      5.90280    528.77343
           5    5.90280      5.90280      5.90280      5.90280    528.77343
           6    5.90280      5.90280      5.90280      5.90280      5.90280    528.77343
           7    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
           8    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
           9    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          10    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          11    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          12    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          13    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          14    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          15    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          16    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          17    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          18    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          19    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          20    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          21    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          22    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          23    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          24    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          25    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          26    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          27    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          28    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          29    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          30    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          31    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          32    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          33    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          34    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          35    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          36    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          37    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          38    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          39    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          40    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          41    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
          42    5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
```

```
               7            8            9           10           11           12
   7   528.77343
   8     5.90280    528.77343
   9     5.90280      5.90280    528.77343
  10     5.90280      5.90280      5.90280    528.77343
  11     5.90280      5.90280      5.90280      5.90280    528.77343
  12     5.90280      5.90280      5.90280      5.90280      5.90280    528.77343
  13     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  14     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  15     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  16     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  17     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  18     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  19     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  20     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  21     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  22     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  23     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  24     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  25     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  26     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  27     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  28     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  29     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  30     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  31     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  32     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  33     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  34     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  35     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  36     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  37     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  38     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  39     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  40     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  41     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  42     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280


              13           14           15           16           17           18
  13   528.77343
  14     5.90280    528.77343
  15     5.90280      5.90280    528.77343
  16     5.90280      5.90280      5.90280    528.77343
  17     5.90280      5.90280      5.90280      5.90280    528.77343
  18     5.90280      5.90280      5.90280      5.90280      5.90280    528.77343
  19     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  20     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  21     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  22     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
  23     5.90280      5.90280      5.90280      5.90280      5.90280      5.90280
```

```
              13         14         15         16         17         18
 24      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 25      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 26      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 27      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 28      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 29      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 30      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 31      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 32      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 33      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 34      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 35      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 36      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 37      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 38      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 39      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 40      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 41      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 42      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280


              19         20         21         22         23         24
 19    528.77343
 20      5.90280  528.77343
 21      5.90280    5.90280  528.77343
 22      5.90280    5.90280    5.90280  528.77343
 23      5.90280    5.90280    5.90280    5.90280  528.77343
 24      5.90280    5.90280    5.90280    5.90280    5.90280  528.77343
 25      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 26      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 27      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 28      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 29      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 30      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 31      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 32      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 33      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 34      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 35      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 36      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 37      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 38      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 39      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 40      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 41      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
 42      5.90280    5.90280    5.90280    5.90280    5.90280    5.90280
```

```
             25          26          27          28          29          30
 25   528.77343
 26     5.90280   528.77343
 27     5.90280     5.90280   528.77343
 28     5.90280     5.90280     5.90280   528.77343
 29     5.90280     5.90280     5.90280     5.90280   528.77343
 30     5.90280     5.90280     5.90280     5.90280     5.90280   528.77343
 31     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 32     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 33     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 34     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 35     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 36     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 37     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 38     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 39     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 40     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 41     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 42     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280


             31          32          33          34          35          36
 31   528.77343
 32     5.90280   528.77343
 33     5.90280     5.90280   528.77343
 34     5.90280     5.90280     5.90280   528.77343
 35     5.90280     5.90280     5.90280     5.90280   528.77343
 36     5.90280     5.90280     5.90280     5.90280     5.90280   528.77343
 37     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 38     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 39     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 40     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 41     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280
 42     5.90280     5.90280     5.90280     5.90280     5.90280     5.90280


             37          38          39          40          41          42
 37   528.77343
 38     5.90280   528.77343
 39     5.90280     5.90280   528.77343
 40     5.90280     5.90280     5.90280   528.77343
 41     5.90280     5.90280     5.90280     5.90280   528.77343
 42     5.90280     5.90280     5.90280     5.90280     5.90280   528.77343
```

```
 ALL-PAIRS WITHIN-SUBJECT COVARIANCE MATRIX



                 1            2            3            4            5            6
    1     676.6063
    2    -131.9447     146.1043
    3      -6.0932     122.9666    1156.7509
    4     689.8237    -151.4641    -121.2676     864.2812
    5      30.9178      21.8592      51.1706      24.7238      41.0788
    6     -30.7160      61.9721      85.7380     -52.4164      26.3255      66.9778
    7     292.2792    -122.8025     152.3228     223.7804      10.0451     -15.9895
    8    -165.9824      59.4029      51.5033    -137.0316     -14.9821      -0.9287
    9     125.1291     123.4983     660.3273    -256.5424     141.6369     104.4453
   10     305.9880    -133.0329    -189.2680     398.0299      23.8217     -60.4396
   11      53.6906      19.4713      -9.2332      48.5998      44.5798      27.7174
   12    -111.3354      42.1176      40.9966    -121.7739     -18.2463      25.1679
   13     306.3520    -163.2575    -347.5300     283.6795     -28.4625     -80.3066
   14    -127.3637      20.2121     -28.3552    -174.6460      -3.3733     -74.5927
   15     109.9584      57.0945     437.1824     104.0260       7.8313      72.5872
   16     251.3300    -115.1602    -402.6076     427.7210     -61.1638    -110.3476
   17       4.3156      22.2054      71.7023     -17.1473      52.2594      32.5477
   18    -163.0930       2.1358      -3.6271    -154.3658     -41.2777       0.8478
   19     -74.1199     -25.3306    -208.8074    -122.7705     -88.1001     -36.3202
   20    -178.2714     131.5801     132.6160    -232.6013      13.3717      51.2019
   21      98.2127      49.4431    -157.7964     114.1057     151.9537    -110.8252
   22    -123.8499       0.3057    -329.6158       7.1681    -116.2018     -41.1228
   23      -8.0650     -90.2675     -33.6981      -7.9674      -9.6054     -51.3656
   24    -194.9978      68.5673      63.0862    -204.1853     -30.7132      40.6871
   25     346.0395     -67.6494     -32.0786     391.0992     -17.0022     -33.4108
   26    -144.5869      92.4690     202.6458    -150.6886      17.0414      57.3686
   27    -251.0796      14.7807    -332.4002      54.8878     -65.4270     -79.2633
   28      37.1755      13.4145    -440.2094      29.3483      -1.3162       4.4265
   29     -45.2998     -20.0925    -122.1522     -56.3450     -45.5386     -38.7433
   30      31.6781      23.7532      13.7869      52.3408      67.1423      44.2946
   31     308.7224     -28.2304       3.7928     287.1828      12.2740       6.3792
   32    -227.8147     141.4842      99.4239    -267.2925     -31.0228      42.0842
   33    -344.8382     122.8039     149.5445    -482.0583     -55.6667     -92.4297
   34     182.8105      19.9979      72.8521     232.3701      28.7929      17.7340
   35    -125.3858     -67.1636    -112.7173    -129.2048     -58.1008     -70.5436
   36    -128.0014      66.4188       8.6441    -121.1056     -11.9143      23.7430
   37     210.8480     -12.6315     120.9730     210.8839      25.1179      14.5406
   38    -151.5174     113.5117      99.2926    -163.5626      -3.5558      59.8696
   39     433.7322    -176.1604     202.0634     365.0508       6.3075       3.1973
   40     136.5767      65.9764     412.7185     159.7762       7.1147     -32.2111
   41      42.1354      23.0976      18.8872      18.7469      22.2121      27.0907
   42     -49.8546      -8.8381      -2.4055     -42.8625      -7.5115       7.2023
```

```
                7             8             9            10            11            12
  7      882.0355
  8     -149.5902      175.1182
  9      -35.3716      -94.0483     1914.6537
 10      472.4447     -107.6837     -453.8761      613.0285
 11       74.9013      -57.0367       52.3164       98.5310       82.7474
 12     -184.0256       52.2168      124.7873     -195.9637      -64.7711      121.4414
 13      246.5249     -162.4619     -161.8911      299.0939       37.7270     -105.1760
 14     -260.8881       98.5107      224.8432     -129.4648      -30.0112       -0.0306
 15      192.5411      -17.0354      -76.1578       85.6090       32.5942      -19.1542
 16      409.2033     -113.1443     -644.3824      440.0530       15.5455     -100.2885
 17       74.4429      -26.6359      109.0019       78.3673       80.0103      -59.2740
 18     -175.6165       62.1516       -3.0031     -191.8890      -90.2192      120.0380
 19     -178.0303      -16.6183      -78.2519     -126.8562     -105.8272      120.3938
 20     -190.5459      103.3787      211.0644     -233.6701       -6.3495       53.0141
 21     -278.9546     -189.4369     1342.5300     -226.3113      123.2166      -25.9832
 22       73.1901       31.5716     -484.4740      -38.9999     -134.8258      133.4364
 23      105.1456       14.3079      -50.7319      121.2139      -21.7711      -20.9374
 24     -229.1046       50.6665       83.0436     -280.3751      -72.8213      134.8773
 25     -151.1209      -42.7704     -108.1064       88.1802      -27.6460       -0.2802
 26     -255.9447       78.4343      177.0942     -270.7574      -15.3465       72.5141
 27     -230.8303      113.6507    -1056.9072      143.7208       -3.6641      -33.5047
 28       -3.0344      -39.1529      197.0158      -54.7363        3.0598       90.6524
 29     -200.5891       35.5662       11.6474     -124.7471      -77.7876       78.6849
 30      137.9880       -6.9810       59.2443      129.2344       87.1175      -64.8486
 31      240.0620      -46.1848     -117.3184      269.4305       51.2134      -99.2402
 32     -240.9225      130.3662       27.0390     -268.3613      -53.4940       94.3130
 33       73.5778      128.9239      495.8709     -251.8920      -79.9038       63.1623
 34      154.4338      -11.4863     -106.5060      225.3688       59.9189      -31.9568
 35       -8.0918       75.1618     -159.5844       43.4764      -91.5164       52.3847
 36      -90.0249       89.6847       -3.8152     -153.5454      -26.3557       48.0998
 37        0.4376      -11.8359        4.1119      135.2982       13.4740      -36.0788
 38     -326.2086      136.1436      244.4910     -377.5481      -72.1937      148.8484
 39      671.7316       -2.4571      153.7231      300.5505      -34.0963      -58.1274
 40      281.2834      -18.1744      168.2770      138.6082        3.2406      -30.5685
 41      -27.8206      -19.4103       67.1035      -10.1552       44.2131      -25.7311
 42      -35.7947       36.1778       35.7185      -55.4690      -39.6196       58.6425
```

```
               13            14            15            16            17            18
 13      425.3477
 14      -43.0932      375.9865
 15      -33.8117     -207.2272      387.3640
 16      380.9358     -207.8421       36.2694      954.6608
 17       -2.1480      -15.1104       47.1130      -50.2848       99.9399
 18      -93.1836       13.4876      -50.8612      -82.6304      -83.2221      150.8845
 19      114.7925       39.0838      -67.5059       58.9857     -139.9522      148.7195
 20     -192.5842      114.1879       -2.3393     -260.2974        9.8846       31.0323
 21      -28.4741      540.4546     -666.8648       88.4324       64.8187      -96.0236
 22       43.4226     -175.4595      -57.8222      565.3579     -196.8228      181.6778
 23       72.2214       40.5834      -52.2041       50.4784        1.7418       11.8645
```

```
               13          14          15          16          17          18
 24  -163.0051      1.0025    -15.6479   -165.0332    -76.7410    147.2238
 25   139.9519     16.0983     65.7230     -1.3112    -65.2710    -17.0378
 26  -216.4830     51.3268     31.6071   -290.4681      5.9709     61.6989
 27    50.6502    -16.6244     45.7813    584.2979    -16.5619     20.9549
 28   181.6147    -97.6840   -157.2491    426.6215    -21.4373     47.4771
 29    24.2366    113.0083   -105.6581    -41.0659    -90.7747    100.1535
 30   -35.4958    -64.7283     21.9695     -2.5904    103.9478    -92.0020
 31   163.8014    -81.3994    153.4277    100.0224     32.0884   -131.6644
 32  -181.8776     87.6754     39.3019   -183.7386    -47.2599     85.0812
 33   -57.1917    347.5654   -163.6906    222.1018    -59.8016     70.9553
 34   125.3330   -181.9340    223.8957    362.5599     76.4219    -93.3820
 35    55.7339     81.4372    -84.2233     82.9910    -73.6702     99.1866
 36  -104.9254     21.1874     -4.2567    -29.8701    -17.8587     48.9464
 37   -11.9063     20.1162     78.3579   -207.8598      0.5990    -54.6697
 38  -248.3303     57.7028    -40.9961   -272.8421    -59.2929    132.0333
 39   148.4621   -228.3155    155.9949    101.6276     -4.4108    -46.1678
 40   -35.1508    -16.5388    172.3455    307.2160     -6.5897    -71.3271
 41    22.4218     -0.1349     46.2146    -55.6406     45.7260    -45.9291
 42   -48.3619    -17.9029    -28.7230    -36.5437    -30.1226     69.1557


               19          20          21          22          23          24
 19   379.9872
 20   -19.9906    180.3893
 21  -211.6682     67.7592   3553.9063
 22   285.0558    -73.9148    -79.3258    848.0550
 23     5.5005    -74.4216    -55.0817    -18.8930    116.5437
 24   143.2314     92.2971    -38.3936    170.3584    -58.4877    195.5631
 25   116.5633    -77.0594   -201.6894    -99.9078    -18.4016    -31.5259
 26   -43.3061    139.3615     37.3723   -100.9188    -74.4186    117.0471
 27     7.5394    -60.7365   -216.0308    372.4563      3.7877    -28.4151
 28   127.5813    -41.0560    468.6639    409.2352    -19.6740     21.7410
 29   193.5157     16.9200     48.9642    113.8127     14.5272     87.7180
 30  -208.4260     -0.2670    106.5571   -138.1155      4.1178    -90.9961
 31   -43.1705    -61.7238   -415.9847   -127.4908     -1.8755   -142.0692
 32    99.8827    179.7101   -204.1829     82.6440    -85.7328    146.7628
 33   121.2808    177.5367    930.9139    360.8435     30.5479     75.8352
 34   -85.5338    -87.3060   -281.1912     38.5904      6.1018   -133.4515
 35   172.6797    -49.3177   -223.2676    167.2029    123.2150     22.5011
 36    -5.1056     95.6487    -28.7524    103.9381    -40.7721     71.4523
 37   -20.7948    -14.4582   -234.7211   -236.7897     -1.3649    -44.5745
 38    41.1800    174.4042     68.1025     76.1239    -88.7658    186.1315
 39  -135.7320   -147.5943   -615.4839      1.9526    148.1054   -144.9545
 40   -77.1842    -25.4109    397.6752    165.4965    -13.7432    -57.3966
 41   -44.0491     29.4435    -21.6631   -129.1787    -35.3055    -25.6147
 42    41.0412      1.1417    -49.4687     83.5145     24.7974     54.9950
```

```
              25          26          27          28          29          30
  25    398.6394
  26    -27.8749    180.7504
  27    -52.9817    -19.2067   1146.7820
  28   -131.4657    -84.8933    161.3627    752.4988
  29     90.3636     10.9230     -1.9164     45.7817    139.5940
  30   -100.3500     -7.0170    -25.0477     22.8504   -123.4265    162.7781
  31    177.2389   -104.7893   -116.1937    -94.7153    -56.4436     41.3567
  32    -41.5194    133.4323     57.9880    -18.1638     67.8588    -77.3847
  33   -366.1570     -5.0169    125.9768    340.6666    100.3439   -107.6307
  34     39.2526    -80.1433    291.2575    258.8539   -101.9426     86.4913
  35     -4.9724    -80.3148     83.6851     41.8385    106.9485    -90.1434
  36    -90.0295     79.7320     96.5594     85.1540     13.0170     -3.5235
  37    243.4479    -10.8570   -264.0968   -319.0976      4.1503      5.6014
  38    -26.8055    192.3764    -74.0599     79.8993     76.1591    -43.2660
  39     49.1635   -150.8979   -503.6711    -17.0576    -89.0153    102.6629
  40    -21.3979    -68.8315     47.0406      1.0933    -67.2041      3.4629
  41     21.2154     31.0298     -4.5437     -2.6264    -28.8220     29.6575
  42    -18.4660     16.0584    -38.4068     49.3137     33.1697    -11.3975


              31          32          33          34          35          36
  31    278.0051
  32    -63.6838    247.8642
  33   -233.7856    217.1779   1321.3382
  34    132.6696    -65.6638    -37.4386    482.5424
  35    -41.9463     11.7044    172.8621    -13.3857    239.7197
  36    -67.8228    117.7809    166.3098     -8.7885     -9.1166    103.0916
  37    185.9641    -35.7516   -370.1887    -73.8793    -30.3524    -95.4948
  38   -135.4698    197.1416    104.4632    -95.6840    -32.1620    135.7330
  39    270.3682   -197.1198   -192.1430     96.6705     65.5863    -40.7299
  40     54.1858    -16.4353    411.1778    184.8652    -12.9806    -19.9002
  41     40.6582     11.4657    -66.1168     40.2327    -73.4675      5.6010
  42    -49.3427     11.7740      1.3435    -22.2121     55.3695     19.0509


              37          38          39          40          41          42
  37    317.5064
  38    -47.1209    314.0024
  39    147.6317    -82.4177   1057.6259
  40     -1.8631    -82.1222     72.2036    554.4379
  41      9.5021      2.0993    -40.0592    -50.1955     52.8453
  42    -13.8480     62.5594     73.8871    -32.9072    -28.9963     49.0102
```

```
     MODEL:  WITHIN-SUBJECT CORRELATION MATRIX


                   1          2          3          4          5          6
        1    1.00000
        2    0.01116    1.00000
        3    0.01116    0.01116    1.00000
        4    0.01116    0.01116    0.01116    1.00000
        5    0.01116    0.01116    0.01116    0.01116    1.00000
        6    0.01116    0.01116    0.01116    0.01116    0.01116    1.00000
        7    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
        8    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
        9    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       10    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       11    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       12    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       13    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       14    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       15    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       16    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       17    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       18    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       19    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       20    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       21    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       22    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       23    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       24    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       25    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       26    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       27    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       28    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       29    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       30    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       31    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       32    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       33    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       34    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       35    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       36    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       37    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       38    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       39    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       40    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       41    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
       42    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
```

```
              7          8          9          10         11         12
     7    1.00000
     8    0.01116    1.00000
     9    0.01116    0.01116    1.00000
    10    0.01116    0.01116    0.01116    1.00000
    11    0.01116    0.01116    0.01116    0.01116    1.00000
    12    0.01116    0.01116    0.01116    0.01116    0.01116    1.00000
    13    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    14    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    15    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    16    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    17    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    18    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    19    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    20    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    21    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    22    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    23    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    24    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    25    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    26    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    27    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    28    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    29    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    30    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    31    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    32    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    33    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    34    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    35    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    36    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    37    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    38    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    39    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    40    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    41    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    42    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116


              13         14         15         16         17         18
    13    1.00000
    14    0.01116    1.00000
    15    0.01116    0.01116    1.00000
    16    0.01116    0.01116    0.01116    1.00000
    17    0.01116    0.01116    0.01116    0.01116    1.00000
    18    0.01116    0.01116    0.01116    0.01116    0.01116    1.00000
    19    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    20    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    21    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    22    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
    23    0.01116    0.01116    0.01116    0.01116    0.01116    0.01116
```

	13	14	15	16	17	18
24	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
25	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
26	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
27	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
28	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
29	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
30	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
31	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
32	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
33	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
34	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
35	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
36	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
37	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
38	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
39	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
40	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
41	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
42	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116

	19	20	21	22	23	24
19	1.00000					
20	0.01116	1.00000				
21	0.01116	0.01116	1.00000			
22	0.01116	0.01116	0.01116	1.00000		
23	0.01116	0.01116	0.01116	0.01116	1.00000	
24	0.01116	0.01116	0.01116	0.01116	0.01116	1.00000
25	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
26	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
27	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
28	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
29	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
30	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
31	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
32	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
33	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
34	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
35	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
36	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
37	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
38	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
39	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
40	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
41	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116
42	0.01116	0.01116	0.01116	0.01116	0.01116	0.01116

```
PAGE  17  5V leanne piller test data



              25          26          27          28          29          30
  25     1.00000
  26     0.01116     1.00000
  27     0.01116     0.01116     1.00000
  28     0.01116     0.01116     0.01116     1.00000
  29     0.01116     0.01116     0.01116     0.01116     1.00000
  30     0.01116     0.01116     0.01116     0.01116     0.01116     1.00000
  31     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  32     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  33     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  34     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  35     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  36     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  37     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  38     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  39     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  40     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  41     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  42     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116


              31          32          33          34          35          36
  31     1.00000
  32     0.01116     1.00000
  33     0.01116     0.01116     1.00000
  34     0.01116     0.01116     0.01116     1.00000
  35     0.01116     0.01116     0.01116     0.01116     1.00000
  36     0.01116     0.01116     0.01116     0.01116     0.01116     1.00000
  37     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  38     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  39     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  40     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  41     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116
  42     0.01116     0.01116     0.01116     0.01116     0.01116     0.01116


              37          38          39          40          41          42
  37     1.00000
  38     0.01116     1.00000
  39     0.01116     0.01116     1.00000
  40     0.01116     0.01116     0.01116     1.00000
  41     0.01116     0.01116     0.01116     0.01116     1.00000
  42     0.01116     0.01116     0.01116     0.01116     0.01116     1.00000
```

```
 ALL-PAIRS WITHIN-SUBJECT CORRELATION MATRIX


              1          2          3          4          5          6
   1     1.0000
   2    -0.4197     1.0000
   3    -0.0069     0.2991     1.0000
   4     0.9021    -0.4262    -0.1213     1.0000
   5     0.1855     0.2822     0.2347     0.1312     1.0000
   6    -0.1443     0.6265     0.3080    -0.2179     0.5019     1.0000
   7     0.3783    -0.3421     0.1508     0.2563     0.0528    -0.0658
   8    -0.4822     0.3714     0.1144    -0.3522    -0.1766    -0.0086
   9     0.1099     0.2335     0.4437    -0.1994     0.5050     0.2917
  10     0.4751    -0.4445    -0.2248     0.5468     0.1501    -0.2983
  11     0.2269     0.1771    -0.0298     0.1817     0.7646     0.3723
  12    -0.3884     0.3162     0.1094    -0.3759    -0.2583     0.2791
  13     0.5711    -0.6549    -0.4955     0.4679    -0.2153    -0.4758
  14    -0.2525     0.0862    -0.0430    -0.3064    -0.0271    -0.4701
  15     0.2148     0.2400     0.6531     0.1798     0.0621     0.4506
  16     0.3127    -0.3084    -0.3831     0.4709    -0.3089    -0.4364
  17     0.0166     0.1838     0.2109    -0.0583     0.8156     0.3978
  18    -0.5104     0.0144    -0.0087    -0.4275     0.5243     0.0084
  19    -0.1462    -0.1075    -0.3149    -0.2142    -0.7052    -0.2277
  20    -0.5103     0.8105     0.2903    -0.5891     0.1553     0.4658
  21     0.0633     0.0686    -0.0778     0.0651     0.3977    -0.2272
  22    -0.1635     0.0009    -0.3328     0.0084    -0.6226    -0.1725
  23    -0.0287    -0.6918    -0.0918    -0.0251    -0.1388    -0.5814
  24    -0.5361     0.4056     0.1326    -0.4967    -0.3427     0.3555
  25     0.6663    -0.2803    -0.0472     0.6663    -0.1329    -0.2045
  26    -0.4134     0.5690     0.4432    -0.3813     0.1978     0.5214
  27    -0.2850     0.0361    -0.2886     0.0551    -0.3014    -0.2860
  28     0.0521     0.0405    -0.4718     0.0364    -0.0075     0.0197
  29    -0.1474    -0.1407    -0.3040    -0.1622    -0.6014    -0.4007
  30     0.0955     0.1540     0.0318     0.1395     0.8211     0.4242
  31     0.7118    -0.1401     0.0067     0.5859     0.1149     0.0467
  32    -0.5563     0.7435     0.1857    -0.5775    -0.3074     0.3266
  33    -0.3647     0.2795     0.1210    -0.4511    -0.2389    -0.3107
  34     0.3199     0.0753     0.0975     0.3598     0.2045     0.0986
  35    -0.3113    -0.3589    -0.2141    -0.2839    -0.5855    -0.5567
  36    -0.4847     0.5412     0.0250    -0.4057    -0.1831     0.2857
  37     0.4549    -0.0586     0.1996     0.4026     0.2199     0.0997
  38    -0.3287     0.5300     0.1648    -0.3140    -0.0313     0.4128
  39     0.5127    -0.4481     0.1827     0.3818     0.0303     0.0120
  40     0.2230     0.2318     0.5154     0.2308     0.0471    -0.1672
  41     0.2228     0.2629     0.0764     0.0877     0.4767     0.4554
  42    -0.2738    -0.1044    -0.0101    -0.2083    -0.1674     0.1257
```

```
                7          8          9         10         11         12
   7       1.0000
   8      -0.3806     1.0000
   9      -0.0272    -0.1624     1.0000
  10       0.6425    -0.3287    -0.4189     1.0000
  11       0.2772    -0.4738     0.1314     0.4375     1.0000
  12      -0.5623     0.3581     0.2588    -0.7182    -0.6461     1.0000
  13       0.4025    -0.5953    -0.1794     0.5857     0.2011    -0.4628
  14      -0.4530     0.3839     0.2650    -0.2697    -0.1701    -0.0001
  15       0.3294    -0.0654    -0.0884     0.1757     0.1821    -0.0883
  16       0.4459    -0.2767    -0.4766     0.5752     0.0553    -0.2945
  17       0.2507    -0.2013     0.2492     0.3166     0.8798    -0.5380
  18      -0.4814     0.3824    -0.0056    -0.6309    -0.8074     0.8868
  19      -0.3075    -0.0644    -0.0917    -0.2628    -0.5968     0.5604
  20      -0.4777     0.5816     0.3591    -0.7027    -0.0520     0.3582
  21      -0.1576    -0.2401     0.5147    -0.1533     0.2272    -0.0396
  22       0.0846     0.0819    -0.3802    -0.0541    -0.5090     0.4158
  23       0.3279     0.1002    -0.1074     0.4535    -0.2217    -0.1760
  24      -0.5516     0.2738     0.1357    -0.8098    -0.5725     0.8752
  25      -0.2549    -0.1619    -0.1237     0.1784    -0.1522    -0.0013
  26      -0.6410     0.4409     0.3010    -0.8134    -0.1255     0.4894
  27      -0.2295     0.2536    -0.7133     0.1714    -0.0119    -0.0898
  28      -0.0037    -0.1079     0.1641    -0.0806     0.0123     0.2999
  29      -0.5717     0.2275     0.0225    -0.4264    -0.7238     0.6043
  30       0.3642    -0.0413     0.1061     0.4091     0.7506    -0.4612
  31       0.4848    -0.2093    -0.1608     0.6526     0.3377    -0.5401
  32      -0.5153     0.6257     0.0392    -0.6885    -0.3735     0.5436
  33       0.0682     0.2680     0.3118    -0.2799    -0.2416     0.1577
  34       0.2367    -0.0395    -0.1108     0.4144     0.2999    -0.1320
  35      -0.0176     0.3668    -0.2356     0.1134    -0.6498     0.3070
  36      -0.2985     0.6675    -0.0086    -0.6108    -0.2854     0.4299
  37       0.0008    -0.0502     0.0053     0.3067     0.0831    -0.1837
  38      -0.6198     0.5806     0.3153    -0.8605    -0.4479     0.7622
  39       0.6955    -0.0057     0.1080     0.3733    -0.1153    -0.1622
  40       0.4022    -0.0583     0.1633     0.2378     0.0151    -0.1178
  41      -0.1289    -0.2018     0.2110    -0.0564     0.6686    -0.3212
  42      -0.1722     0.3905     0.1166    -0.3200    -0.6221     0.7601


               13         14         15         16         17         18
  13       1.0000
  14      -0.1078     1.0000
  15      -0.0833    -0.5430     1.0000
  16       0.5978    -0.3469     0.0596     1.0000
  17      -0.0104    -0.0780     0.2394    -0.1628     1.0000
  18      -0.3678     0.0566    -0.2104    -0.2177    -0.6777     1.0000
  19       0.2855     0.1034    -0.1760     0.0979    -0.7182     0.6211
  20      -0.6953     0.4385    -0.0088    -0.6272     0.0736     0.1881
  21      -0.0232     0.4675    -0.5684     0.0480     0.1088    -0.1311
  22       0.0723    -0.3107    -0.1009     0.6283    -0.6761     0.5079
  23       0.3244     0.1939    -0.2457     0.1513     0.0161     0.0895
```

```
             13          14          15          16          17          18
 24     -0.5652      0.0037     -0.0569     -0.3819     -0.5489      0.8571
 25      0.3399      0.0416      0.1673     -0.0021     -0.3270     -0.0695
 26     -0.7808      0.1969      0.1194     -0.6993      0.0444      0.3736
 27      0.0725     -0.0253      0.0687      0.5584     -0.0489      0.0504
 28      0.3210     -0.1836     -0.2913      0.5033     -0.0782      0.1409
 29      0.0995      0.4933     -0.4544     -0.1125     -0.7685      0.6901
 30     -0.1349     -0.2616      0.0875     -0.0066      0.8150     -0.5871
 31      0.4763     -0.2518      0.4675      0.1942      0.1925     -0.6429
 32     -0.5601      0.2872      0.1268     -0.3777     -0.3003      0.4400
 33     -0.0763      0.4931     -0.2288      0.1978     -0.1646      0.1589
 34      0.2766     -0.4271      0.5179      0.5342      0.3480     -0.3461
 35      0.1745      0.2713     -0.2764      0.1735     -0.4760      0.5215
 36     -0.5011      0.1076     -0.0213     -0.0952     -0.1759      0.3925
 37     -0.0324      0.0582      0.2234     -0.3775      0.0034     -0.2498
 38     -0.6795      0.1679     -0.1175     -0.4983     -0.3347      0.6066
 39      0.2213     -0.3621      0.2437      0.1011     -0.0136     -0.1156
 40     -0.0724     -0.0362      0.3719      0.4223     -0.0280     -0.2466
 41      0.1496     -0.0010      0.3230     -0.2477      0.6292     -0.5144
 42     -0.3350     -0.1319     -0.2085     -0.1689     -0.4304      0.8042


             19          20          21          22          23          24
 19      1.0000
 20     -0.0764      1.0000
 21     -0.1821      0.0846      1.0000
 22      0.5021     -0.1890     -0.0457      1.0000
 23      0.0261     -0.5133     -0.0856     -0.0601      1.0000
 24      0.5254      0.4914     -0.0461      0.4183     -0.3874      1.0000
 25      0.2995     -0.2874     -0.1694     -0.1718     -0.0854     -0.1129
 26     -0.1652      0.7718      0.0466     -0.2578     -0.5127      0.6226
 27      0.0114     -0.1335     -0.1070      0.3777      0.0104     -0.0600
 28      0.2386     -0.1114      0.2866      0.5123     -0.0664      0.0567
 29      0.8402      0.1066      0.0695      0.3308      0.1139      0.5309
 30     -0.8380     -0.0016      0.1401     -0.3717      0.0299     -0.5100
 31     -0.1328     -0.2756     -0.4185     -0.2626     -0.0104     -0.6093
 32      0.3255      0.8499     -0.2176      0.1803     -0.5044      0.6666
 33      0.1712      0.3636      0.4296      0.3409      0.0778      0.1492
 34     -0.1997     -0.2959     -0.2147      0.0603      0.0257     -0.4344
 35      0.5721     -0.2372     -0.2419      0.3708      0.7372      0.1039
 36     -0.0258      0.7014     -0.0475      0.3515     -0.3720      0.5032
 37     -0.0599     -0.0604     -0.2210     -0.4563     -0.0071     -0.1789
 38      0.1192      0.7328      0.0645      0.1475     -0.4640      0.7511
 39     -0.2141     -0.3379     -0.3175      0.0021      0.4219     -0.3187
 40     -0.1682     -0.0804      0.2833      0.2414     -0.0541     -0.1743
 41     -0.3108      0.3016     -0.0500     -0.6102     -0.4499     -0.2520
 42      0.3007      0.0121     -0.1185      0.4096      0.3281      0.5617
```

```
            25         26         27         28         29         30
  25     1.0000
  26    -0.1038     1.0000
  27    -0.0784    -0.0422     1.0000
  28    -0.2400    -0.2302     0.1737     1.0000
  29     0.3831     0.0688    -0.0048     0.1413     1.0000
  30    -0.3939    -0.0409    -0.0580     0.0653    -0.8188     1.0000
  31     0.5324    -0.4675    -0.2058    -0.2071    -0.2865     0.1944
  32    -0.1321     0.6304     0.1088    -0.0421     0.3648    -0.3853
  33    -0.5045    -0.0103     0.1023     0.3416     0.2336    -0.2321
  34     0.0895    -0.2714     0.3915     0.4296    -0.3928     0.3086
  35    -0.0161    -0.3858     0.1596     0.0985     0.5846    -0.4563
  36    -0.4441     0.5841     0.2808     0.3057     0.1085    -0.0272
  37     0.6843    -0.0453    -0.4377    -0.6528     0.0197     0.0246
  38    -0.0758     0.8075    -0.1234     0.1644     0.3638    -0.1914
  39     0.0757    -0.3451    -0.4573    -0.0191    -0.2317     0.2474
  40    -0.0455    -0.2174     0.0590     0.0017    -0.2416     0.0115
  41     0.1462     0.3175    -0.0185    -0.0132    -0.3356     0.3198
  42    -0.1321     0.1706    -0.1620     0.2568     0.4010    -0.1276


            31         32         33         34         35         36
  31     1.0000
  32    -0.2426     1.0000
  33    -0.3857     0.3795     1.0000
  34     0.3622    -0.1899    -0.0469     1.0000
  35    -0.1625     0.0480     0.3071    -0.0394     1.0000
  36    -0.4006     0.7368     0.4506    -0.0394    -0.0580     1.0000
  37     0.6259    -0.1274    -0.5715    -0.1887    -0.1100    -0.5278
  38    -0.4585     0.7067     0.1622    -0.2458    -0.1172     0.7544
  39     0.4986    -0.3850    -0.1625     0.1353     0.1303    -0.1233
  40     0.1380    -0.0443     0.4804     0.3574    -0.0356    -0.0832
  41     0.3354     0.1002    -0.2502     0.2519    -0.6527     0.0759
  42    -0.4227     0.1068     0.0053    -0.1444     0.5108     0.2680


            37         38         39         40         41         42
  37     1.0000
  38    -0.1492     1.0000
  39     0.2548    -0.1430     1.0000
  40    -0.0044    -0.1968     0.0943     1.0000
  41     0.0734     0.0163    -0.1694    -0.2932     1.0000
  42    -0.1110     0.5043     0.3245    -0.1996    -0.5698     1.0000
```

```
    ESTIMATES OF REGRESSION PARAMETERS:

 IN THE TABLE BELOW EACH FIXED EFFECT PART OF THE MODEL IS
 DECOMPOSED INTO SINGLE DEGREE OF FREEDOM REGRESSION TERMS
 AND COVARIATES

                                                  Z-     TWO-SIDED
 PARAMETER          ESTIMATE   ASYMPTOTIC SE   SCORE     P-VALUE
 -------------------------------------------------------------------
   1  CONST.        38.08333        1.23667   30.795     0.0000
   2  group1        -1.40079        1.23667   -1.133     0.2573
   3  period1        1.39286        1.23667    1.126     0.2600
   4  time1          0.66071        1.74891    0.378     0.7056
   5  time2         -2.49405        1.74891   -1.426     0.1539
   6  loc1           2.32143        2.27754    1.019     0.3081
   7  loc2         -11.45238        2.27754   -5.028     0.0000
   8  loc3          29.00000        2.27754   12.733     0.0000
   9  loc4          28.01190        2.27754   12.299     0.0000
  10  loc5         -22.60714        2.27754   -9.926     0.0000
  11  G1.P1          1.99603        1.23667    1.614     0.1065
  12  G1.T1         -2.81944        1.74891   -1.612     0.1069
  13  G1.T2         -1.48611        1.74891   -0.850     0.3955
  14  P1.T1         -0.61310        1.74891   -0.351     0.7259
  15  P1.T2         -0.94643        1.74891   -0.541     0.5884
  16  G1.L1         11.71032        2.27754    5.142     0.0000
  17  G1.L2          8.72222        2.27754    3.830     0.0001
  18  G1.L3        -19.30159        2.27754   -8.475     0.0000
  19  G1.L4        -17.93254        2.27754   -7.874     0.0000
  20  G1.L5          7.51984        2.27754    3.302     0.0010
  21  P1.L1         -5.36905        2.27754   -2.357     0.0184
  22  P1.L2          8.09524        2.27754    3.554     0.0004
  23  P1.L3         -9.66667        2.27754   -4.244     0.0000
  24  P1.L4         -2.05952        2.27754   -0.904     0.3659
  25  P1.L5          3.36905        2.27754    1.479     0.1391
  26  T1.L1          4.82738        3.22093    1.499     0.1339
  27  T1.L2          4.24405        3.22093    1.318     0.1876
  28  T1.L3        -11.99405        3.22093   -3.724     0.0002
  29  T1.L4          0.42262        3.22093    0.131     0.8956
  30  T1.L5          1.07738        3.22093    0.334     0.7380
  31  T2.L1         -4.80357        3.22093   -1.491     0.1359
  32  T2.L2         -3.02976        3.22093   -0.941     0.3469
  33  T2.L3         10.62500        3.22093    3.299     0.0010
  34  T2.L4         -5.24405        3.22093   -1.628     0.1035
  35  T2.L5          2.62500        3.22093    0.815     0.4151
```

```
    WALD TESTS OF SIGNIFICANCE OF
    FIXED EFFECTS AND COVARIATES

 TEST        DF    CHI-SQUARE    P-VALUE
 ---------------------------------------
 group        1          1.28      0.257
 period       1          1.27      0.260
 time         2          2.18      0.336
 loc          5        467.83      0.000
 G.P          1          2.61      0.107
 G.T          2          6.25      0.044
 P.T          2          0.81      0.668
 G.L          5        168.69      0.000
 P.L          5         37.77      0.000
 T.L         10         21.95      0.015

 NUMBER OF INTEGER WORDS USED IN PRECEDING    PROBLEM  109422
 CPU TIME USED     10.033 SECONDS
```

Appendix P Animal Taxa Recorded at GSV Study Sites During Preliminary Monitoring.

Phylum	Class	Scientific Name
Annelida	Polychaeta	*Galeolaria caespitosa* (Savigny)
Cnidaria	Anthozoa	*Actinia tenebrosa* Farquhar
Crustacea	Cirripedia	*Catomerus polymerus* (Darwin)
Crustacea	Cirripedia	*Chamaeosipho tasmanica* Foster & Anderson
Crustacea	Cirripedia	*Chthamalus antennatus* (Darwin)
Crustacea	Cirripedia	*Tetraclitella purpurescens* Wood
Mollusca	Gastropoda	*Austrocochlea adelaidae*
Mollusca	Gastropoda	*Austrocochlea concamerata* Wood
Mollusca	Gastropoda	*Austrocochlea constricta* Lamarck
Mollusca	Gastropoda	*Austrocochlea odontis* (Wood 1828)
Mollusca	Gastropoda	*Bembicium nanum* (Lamarck)
Mollusca	Gastropoda	*Cellana tramoserica* (Sower)
Mollusca	Gastropoda	*Cominella lineolata* (Lamarck)
Mollusca	Gastropoda	*Haliotis* spp.
Mollusca	Gastropoda	*Lepsiella vinosa* (Lamarck)
Mollusca	Gastropoda	*Littorina praetermissa* May
Mollusca	Gastropoda	*Littorina unifasciata* Gray
Mollusca	Gastropoda	*Nerita atramentosa* Reeve
Mollusca	Gastropoda	*Notoacmea* spp.
Mollusca	Gastropoda	*Patelloida alticostata* (Angas)
Mollusca	Gastropoda	*Patelloida latistrigata* (Angas)
Mollusca	Gastropoda	*Siphonaria diemenensis* Quoy & Gaimard
Mollusca	Gastropoda	*Siphonaria zelandica* Quoy & Gaimard
Mollusca	Gastropoda	*Thais orbita* (Gmelin)
Mollusca	Gastropoda	*Turbo undulatus* Solander
Mollusca	Bivalvia	*Brachidontes erosus* (Lamarck)
Mollusca	Bivalvia	*Xenostrobus pulex* (Lamarck)

Appendix Q: Pearson Matrix with Bonferroni Corrections (Taxa vs SSH MDS Ordination Axes)

The Pearson correlation was performed in "SYSTAT", v 3.0, and values were determined to 3 significant figures (s.f.) but are presented here to 2 s.f. Problems associated with the use of this analysis have been mentioned in Chapter 4 (section 4.3.2).

Table Q.1 Pearson Matrix of Bonferroni Probabilities: MDS Axis 1, 2 & 3 *vs* Dominant Taxa. Bartlett's chi-squared statistic: 850.188 (df = 45), P=0.00 (Global test of whether the population correlation matrix is an identity i.e. if the set of correlations is insignificant). Bold numbers represent significant probabilities at the 0.05 level (based on 3 s.f.), negative values reveal a negative correlation, and positive values a positive correlation.

Char.	Axis 1	Axis 2	Axis 3	*Ner*	*A. cc.*	*A. cs.*	*B. n.*	*L. v.*	*C. tr.*	*S. di.*	*Noto.*	*X. p.*	*Br. e.*	*C. a.*
Axis 1	**0.00**													
Axis 2	0.20	**0.00**												
Axis 3	**-0.05**	**-0.00**	**0.00**											
Ner.	-1.00	**0.00**	**0.00**	**0.00**										
A. cc.	-1.00	**0.01**	0.10	**0.00**	**0.00**									
A. cs.	**0.00**	**-0.02**	-1.00	**-0.02**	-1.00	**0.00**								
B. n.	**0.00**	1.00	**-0.00**	-1.00	-1.00	**0.00**	**0.00**							
L. v.	**0.00**	-1.00	-1.00	-1.00	-1.00	**0.00**	**0.00**	**0.00**						
C. tr.	1.00	1.00	**0.00**	**0.00**	0.12	1.00	-1.00	1.00	**0.00**					
S. di.	**0.01**	-0.05	**0.00**	-1.00	-1.00	1.00	-1.00	-1.00	**0.00**	**0.00**				
Noto.	-1.00	1.00	**0.00**	**0.00**	**0.00**	1.00	-1.00	-1.00	0.05	-1.00	**0.00**			
X. p.	**0.04**	**-0.05**	**0.00**	1.00	1.00	1.00	-1.00	**0.00**	1.00	1.00	1.00	**0.00**		
Br. e.	0.07	1.00	**-0.02**	-1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	-1.00	**0.00**	
C. a.	**0.03**	-1.00	**0.00**	1.00	1.00	-1.00	1.00	-1.00	0.53	**0.00**	1.00	1.00	1.00	**0.00**

N.B. Species Abbreviations; *Ner. (Nerita atramentosa), A. cc. (Austrocochlea concamerata), A. cs. (Austrocochlea constricta), B. n. (Bembicium nanum), L. v. (Lepsiella vinosa), C. tr. (Cellana tramoserica), S. di. (Siphonaria diamenensis), Noto. (Notoacmea* spp.*), X. p. (Xenostrobus pulex), Br. e. (Brachiodontes erosus), C. a. (Chthamalus antennatus).*

The global test revealed that the population correlation matrix was an identity, with the set of correlations yielding a significant probability value of 0.00. MDS Axis 1 was significantly negatively correlated with *A. constricta, Lepsiella vinosa, S. diamenensis* and *Chthamalus antennatus*, and positively correlated with *B. nanum* and *X. pulex*. Axis 2 shared a significant positive relationship with *N. atramentosa* and *A. concamerata* and a significant negative relationship with *A. constricta* and *X. pulex*. The two *Austrocochlea* spp. and *L. vinosa* did not have a significant relationship with Axis 3, but *B. nanum* and *B. erosus* had negative correlations with this axis and the remaining species had significant positive correlations. Intercorrelations also existed between four of the taxa used to generate the MDS axes. For example, *N. atramentosa* had significant positive correlations with *A. concamerata*, *Cellana tramoserica* and *Notoacmea* spp., and a negative correlation with *A. constricta*. *B. nanum* had a positive correlation with *L. vinosa*, which in turn had a significant positive correlation with *X. pulex*.

Appendix R: Pearson Matrix with Bonferroni Corrections (Environmental Variables *vs* SSH MDS Ordination Axes)

The Pearson correlation was performed in "SYSTAT", v 3.0, and values were determined to 3 significant figures (s.f.) but are presented here to 2 s.f. Problems associated with the use of this analysis have been mentioned in Chapter 4 (section 4.3.2).

Table R.1 Pearson Matrix of Bonferroni Probabilities: MDS Axes *vs* Environmental Variables. Bartlett's chi-squared statistic: 1399.374 (df = 45), *P*=0.00 (Global test of whether the population correlation matrix is an identity i.e. if the set of correlations is insignificant). Bold numbers represent significant probabilities at the 0.05 level and negative signs reveal a negative correlation.

Char.	Axis 1	Axis 2	Axis 3	BR	B	C	P/G	S	RW	El	Ch	Ol
Axis 1	**0.00**											
Axis 2	0.20	**0.00**										
Axis 3	**-0.05**	**-0.00**	**0.00**									
BR	**0.00**	**0.00**	**0.00**	**0.00**								
B	**-0.01**	**0.01**	0.10	**-0.00**	**0.00**							
C	-0.98	**-0.02**	-1.00	**-0.00**	**0.03**	**0.00**						
P/G	-0.57	1.00	**-0.00**	**-0.00**	0.10	**0.00**	**0.00**					
S	-1.00	-1.00	-1.00	-1.00	-1.00	**0.04**	1.00	**0.00**				
RW	**-0.00**	1.00	**0.00**	**-0.00**	1.00	-1.00	-1.00	-1.00	**0.00**			
El	1.00	**-0.05**	**0.00**	0.38	-0.44	-1.00	1.00	-1.00	-1.00	**0.00**		
Ch	**-0.02**	1.00	**0.00**	**-0.00**	**0.00**	**0.00**	**0.00**	1.00	-1.00	-1.00	**0.00**	
Ol	-1.00	-1.00	**0.00**	-1.00	1.00	-1.00	-1.00	1.00	1.00	-1.00	1.00	**0.00**

N.B. Environmental Abbreviations; BR (Bedrock or reef-rock; stable substrata), B (Boulder), C (Cobble), P/G (Pebble or Gravel), S (Sand or Shellgrit), RW (Retained Water), El (Maximum elevation of substrata), Ch (Chain-to-Tape distance), Ol (Oil Score).

The Pearson Correlation revealed significant positive relationships between Axis 1 and stable substrata (bedrock and reef-rock), and significant negative correlations with boulder presence, retained water and the 'chain' measure of topographic complexity. Axis 2 had significant positive correlations with stable substrata, and boulder presence, and a significant negative correlation with cobble substrata and substrata elevation. As was found with the other axes, Axis 3 had a positive correlation with stable substrata, but significant negative correlations with pebble and gravel substrata, the percentage of retained water, elevation, topographic complexity and oil presence. Not surprisingly (because of the way the substrata scores were generated) the substrata parameters showed a high degree of intercorrelation. This could have been accomodated, but it was felt that the PCC analysis would be more appropriate in elucidating environmentally (physically) driven ordination patterns.

Appendix S: "The FLOWC Model"
(Bye and Ng 1994)

The FLOWC Model

John A.T. Bye
and
Sar C. Ng

School of Earth Sciences
Flinders University of South Australia
March, 1994

Table of Contents

1 INTRODUCTION

FLOWSPA is the name of the computer program developed by the School of Earth Sciences for thallasso-modelling. The fundamental mathematics in this program are the 'basic equations' and the 'transport equations' (see theory in next section). FLOWSPA was relatively simple to use and it contains a series of programs, hence it was very versatile. With minor modifications to the program and appropriate input, it can be tailored to suit many specific simulations. Since it was developed in 1970, many researchers have used FLOWSPA in assisting their works (Bye and Harbison, 1991).

In 1993, the code was updated and extended to include a dispersive advective model applicable to salinity, tracer concentration and temperature anomaly, the mathematical equations of this extension are based on the advection-diffusion scheme of Fiadeiro and Veronis (1977). The new program was named FLOWC.

The purpose of this handbook is to explain some basic equations used by the FLOWC program, and provide some examples on how to operate this program.

2 THEORY

2.1 The Equations

The Boussinesq Approximation states that the actual density of sea water (ρ) may be replaced by the density of a standard ocean (ρ_o) except in the gravitational acceleration term (eq. 2.1.3). The momentum equations under this approximation are :

$$\rho_o\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv\right)=-\frac{\partial p}{\partial x}+\rho_o X+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z} \quad \text{.......(2.1.1)}$$

$$\rho_o\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu\right)=-\frac{\partial p}{\partial y}+\rho_o Y+\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z} \quad \text{........(2.1.2)}$$

$$\rho_o\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}-\rho g+\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z} \quad \text{.............(2.1.3)}$$

Where the Ox, Oy, Oz axes are respectively towards the East, North and vertically upwards. The components of velocity along Ox, Oy, Oz are u, v and w (ms^{-1}). The body forces are the acceleration of gravity, g (ms^{-2}), and the horizontal forces X and Y that give rise to the tides. The density is ρ (kgm^{-3}) and ρ_o (kgm^{-3}) is the density of the standard ocean. p (Nm^{-2})is pressure, and f (s^{-1})is the Coriolis term, defined by $2\Omega\sin\varnothing$, in which Ω is the angular speed of rotation of the Earth, and $\varnothing$ is latitude. τ_{xx}, τ_{xy}, τ_{xz}, τ_{yx}, τ_{yy}, τ_{yz}, τ_{zx}, τ_{zy}, τ_{zz} (Nm^{-2}) are components of the viscous stress tensor.

To the same approximation, the fluid is incompressible, and obeys the continuity equation,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad \text{..(2.1.4)}$$

The transport momentum equations, derived from (2.1.1) to (2.1.4) for the components of mean transport velocity,

$$U = \overline{\int_{-H}^{\eta} u\,dz} \quad \text{(2.1.5)}$$

$$V = \overline{\int_{-H}^{\eta} v\,dz} \quad \text{(2.1.6)}$$

where H (m) is the depth at sea bottom and η is the elevation above sea surface (m), and the overbar denotes a spatial and/or temporal average.

$$\frac{\partial U}{\partial t} = fV - gH\frac{\partial}{\partial x}(\eta-\zeta) + \tfrac{1}{2}gH^2\rho_o\frac{\partial\delta}{\partial x} + \frac{\tau_{sx}}{\rho_o} - C|u_B|\left(\frac{U}{H} + \frac{1}{2}\frac{gH\rho_o}{f}\frac{\partial\delta}{\partial y}\right) \quad \text{(2.1.7)}$$

$$\frac{\partial V}{\partial t} = -fU - gH\frac{\partial}{\partial y}(\eta-\zeta) + \tfrac{1}{2}gH^2\rho_o\frac{\partial\delta}{\partial y} + \frac{\tau_{sy}}{\rho_o} - C|u_B|\left(\frac{V}{H} - \frac{1}{2}\frac{gH\rho_o}{f}\frac{\partial\delta}{\partial x}\right) \quad \text{(2.1.8)}$$

where
$$|u_B| = \left[\left(\frac{U}{H} - \frac{1}{2}\frac{gH\rho_o}{f}\frac{\partial\delta}{\partial y}\right)^2 + \left(\frac{V}{H} + \frac{1}{2}\frac{gH\rho_o}{f}\frac{\partial\delta}{\partial x}\right)^2\right]^{\frac{1}{2}}$$

$$\delta = \frac{1}{\rho} - \frac{1}{\rho_o}$$

τ_{sx}, τ_{sy} are the x and y component surface shear stress.

In (2.1.7) and (2.1.8) η is the surface elevation, and ζ is the equilibrium surface elevation, due to tidal forces and atmospheric pressure, (p_a),

$$\zeta = -\frac{\Omega}{g} - \frac{p_a}{g\rho_o} + \text{const.}$$

in which Ω is the tidal potential, and $\underline{u}_B = \frac{\underline{U}}{H}$ is the bottom current, and C is the bottom drag coefficient, and lateral stresses and inertial accelerations have been omitted.

The velocities at any level are,

$$u = \frac{U}{H} - \frac{g\rho_o}{f}\left(z + \frac{H}{2}\right)\frac{\partial\delta}{\partial y} \qquad \text{(2.1.9)}$$

$$v = \frac{V}{H} + \frac{g\rho_o}{f}\left(z + \frac{H}{2}\right)\frac{\partial\delta}{\partial x} \qquad \text{(2.1.10)}$$

The transport continuity equation derived from (1.4) is,

$$\frac{\partial\eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = R - E + \frac{Q}{A_p} \qquad \text{(2.1.11)}$$

where R is the rainfall (ms^{-1}) and E is the evaporation (ms^{-1}) over the sea surface, and Q is the discharge (m^3s^{-1}) over a specific area, A_p (m^2).

This system of equations is applicable to vertically well mixed water columns, such as often approximately occur in coastal, tidally active seas.

The dispersion equation for a solute, also to the Boussinesq approximation is,

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = -\frac{\partial F_x}{\partial x} - \frac{\partial F_y}{\partial y} - \frac{\partial F_z}{\partial z} - \lambda C \qquad \text{(2.1.12)}$$

where C is the concentration of the solute, λ is the exponential decay constant, and F_x, F_y and F_z are the components of diffusive flux.

On integration over the water column, we obtain,

$$\frac{\partial}{\partial t}HC + \frac{\partial}{\partial x}UC + \frac{\partial}{\partial y}VC + \frac{\partial}{\partial x}F_xH + \frac{\partial}{\partial y}F_yH = \frac{P}{\rho_o A_p} - \lambda HC \qquad \text{(2.1.13)}$$

Where $F_x = -K\frac{\partial C}{\partial x}$, $F_y = -K\frac{\partial C}{\partial y}$ are the component of lateral diffusive flux, in which K is a diffusion coefficient. The terms on the right hand side of (2.1.13) take account of possible non conservative behaviour of the solute, and a pollution flux.

An alternate form of (2.1.13) obtained by substituting the diffusive fluxes, and using (2.1.11) is

$$H\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}+V\frac{\partial C}{\partial y}-\frac{\partial}{\partial x}\left(KH\frac{\partial C}{\partial x}\right)-\frac{\partial}{\partial y}\left(KH\frac{\partial C}{\partial y}\right)=(E-R)C-\frac{QC}{A_p}+\frac{P}{\rho_o A_p}-\lambda HC \quad \text{(2.1.14)}$$

in which, for a source of undissolved solute $Q = 0$, and for a source of dissolved solute

$$P = \rho_o C_p Q \quad \text{(2.1.15)}$$

where C_p is the concentration of the inflowing dissolved solute.
Equation (2.2.14) is also applicable to heat by setting $P = Q = \lambda = 0$, and the net rainfall (R - E) to be equal to the Newtonian piston velocity, μ (ms^{-1}), ie.

$$E - R = -\mu \quad \text{(2.1.16)}$$

such that C is the sea temperature anomaly relative to a constant zero air temperature.

We note that the anomaly (δ) is specified so that the momentum equations are not coupled with the solute equations, but the solute equations are (of course) coupled with the momentum equations.

2.2 The method of solution

The set of equations (2.1.7), (2.1.8), (2.1.11) and (2.1.14) is solved by finite-difference algorithms. The momentum and continuity equations ((2.1.11) and (2.1.7), (2.1.8)) are solved by an explicit staggered forward-difference scheme as described in Bye (1988), which has the Courant limit on the time step,

$$\Delta t_m \le \frac{\sqrt{2}\Delta s}{\sqrt{gH_{max}}} \quad \text{(2.2.1)}$$

where Δs is the grid interval of the staggered mesh, and H_{max} is the maximum depth.

The solute equation (2.1.14) is represented using the advective-diffusive scheme of Fiadeiro and Veronis (1977) for the spatial derivative and the solutes forecast is made using the implicit difference scheme of Johnson and Kowalik (1986), which is unconditionally stable, so that the time step Δt_c is arbitrary.

In practice, it is often sufficient for solution accuracy that

$$\Delta t_c = \alpha \, \Delta t_m$$

where $\alpha >>1$.

In many applications in which a steady solution is sought, eg. due to constant wind stress driving, the (uncoupled) momentum solution will achieve steady-state much more rapidly than the solute solution, so that for computation speed the solution can be obtained in two phases. In the first phase both the momentum and solute equations are iterated with their respective time steps Δt_m and Δt_c, and in the second phase, a constant momentum field is assumed, while the solute field continues to evolve to a steady state with the time step (Δt_c).

2.3 Integral properties

In order to monitor the evolving properties of the solutions, a series of integral properties of the mass and solute fields are calculated. These are of three types, firstly line fluxes of the mass and solute across specified sections often along the open boundaries of the simulation, secondly area fluxes of the mass and solute across the sea surface and for the specified discharges, and thirdly volume integrals of mass, energy and solute.

In the steady state pleasing balances occur between this appropriate fluxes indicating the conservative properties of the simulation.

In the steady-state the integral balances are :

Mass

$$\int_s U_n ds = \int_A (R-E)dA + \sum_i Q_i \qquad (2.3.1)$$

where n is normal (inwards) and s is tangential to the sea boundary, and $\int_s$ denotes an integral along the sea boundary and U_n is the normal component of transport, $\int_A$ denotes an areal integral, and $\sum_i$ is a summation over all the discharges, Q_i. All the terms in (2.3.1) are directly represented in the finite-difference simulation.

Solute

$$\int_s \left(U_n C - KH \frac{\partial C}{\partial n} \right) ds = \sum_i \frac{P_i}{\rho_o} - \int_A \lambda HCdA \qquad (2.3.2)$$

where $\frac{\partial C}{\partial n}$ is the normal gradient of solute, and P_i is the pollution source (i). All the terms in (2.3.2) are also directly represented in the finite difference simulation.

The mass of water and of solute are respectively

$$M = \rho_o \int_A HdA, \qquad (2.3.3)$$

and

$$G = \rho_o \int_A HCdA \qquad (2.3.4)$$

2.4 Exchange, Flushing and Renewal times

These expressions enable, exchange (τ), flushing (τ_F) and renewal (τ_R) times to be defined, where exchange refers to the mass balance, flushing refers to the solute balance where the mean concentration in the simulated region is greater than in the adjacent open sea, and renewal refers to the solute balance where the mean concentration in the simulated region is less than in the adjacent open sea.

For mass, the exchange time,

$$\tau = \frac{M}{\rho_o I} \qquad (2.4.1)$$

where

$$I = \int U_n^- ds, \qquad \bar{C} > C_o$$

$$I = \int U_n^+ ds, \qquad \bar{C} < C_o$$

in which $^+$ and $^-$ denote respectively +ve and -ve transport, ie. the total inflow; and the total outflow, into the simulated region, and $\bar{C}$ and C_o are respectively the mean concentration of solute in the simulated region, and in the adjacent open sea.

Similarly for solute, the flushing time,

$$\tau_F = \frac{G}{\rho_o I_F} \qquad (2.4.2)$$

where $I_F = \int_s \left(U_n C - K \frac{\partial C}{\partial n} \right)^- ds$, $\bar{C} > C_o$,

and the renewal time,

$$\tau_R = \frac{G}{\rho_o I_R} \qquad (2.4.3)$$

where $I_R = \int_s \left(U_n C - K\frac{\partial C}{\partial n}\right)^+ ds, \ \bar{C} < C_o,$

in which $^+$ and $^-$ denote respectively total influx and total outflux of solute.

These expressions are generally applicable in semi-enclosed regions in which net imbalances of mass and solute exist, and which are of most interest in coastal applications. In enclosed regions steady-state balances would only exist when the sources and sinks are in balanced, in which case the flushing and renewal times become the residence time.

2.5 The Strutton time constant

Accurate field evaluation of τ_F and τ_R however is a very demanding task, and accordingly a much simpler time constant (τ_S) which can be used to estimate τ_F or τ_R, and is easily computed from field data, is also calculated, by application of a method developed by Strutton (1992).

The Strutton time constant is determined by considering the mass and solute balances in a well mixed region, subject to evaporation, rainfall and pollution, in the presence of advective/diffusive exchange across the open sea boundary. In this idealised situation the time variation of the solute concentration would be controlled by the equation

$$\frac{dC}{dt} = -\frac{C}{\tau_s} + f(t) \quad \cdots\cdots\cdots (2.5.1)$$

in which f(t) is an arbitrary forcing function, and τ_s is a constant if the advective/diffusive exchange across the boundary is a steady process. The transient solution of (2.5.1) then has the form $e^{-\frac{t}{\tau_s}}$ where τ_s is the Strutton time constant, which can be expressed exactly in terms of the mean concentration ($\bar{C}$) due to steady forcing as follows,

$$\tau_s = \frac{M\left(\bar{C} - C_o\right)}{C_o\left(\rho_o \int_A (E - R)dA - \lambda M\right) + \sum_i \left(P_i - \rho_o Q_i C_o\right)} \quad \cdots\cdots\cdots (2.5.2)$$

τ_s is the ratio of the excess solute $\left(M\left(\overline{C}-C_o\right)\right)$ in the region, divided by the net source of solute, integrated over the region, due to pollution and exchange with the open sea, cf., the terms on the right hand side of (2.1.14)

For salinity, (2.5.2) reduces to the simple expression

$$\tau_s = \frac{\bar{h}\left(\overline{C}-C_o\right)}{\left(\overline{E-R}\right)C_o} \qquad (2.5.3)$$

where $\bar{h}$ is the mean depth, and $\overline{E\text{-}R}$ is the mean net evaporation which can be readily evaluated from field data, and is equal to the corresponding flushing time (τ_F)/renewal time (τ_R) by advection, with an outflow concentration equal to the mean concentration, and an inflow concentration equal to the open sea concentration (Ng, 1993).

In a simulation of Gulf St. Vincent and Investigator Strait (Ng, 1993) it was found that τ_s (2.5.3) was representative of the flushing time (τ_F) for a conservative tracer with a source well within the region.

Two interesting limiting results are :

(i) For an undissolved conservative pollution source (Q = 0) discharging into a pure ocean, the flushing times and the Strutton time constant are equal,

$$\tau_F = \tau_s = \frac{G}{P} \qquad (2.5.4)$$

(ii) For salinity variations with small gradients, the flushing, renewal and exchange times are equal,

$$\tau_F = \tau_R = \tau = \frac{M}{\rho_o I} \qquad (2.5.5)$$

3 INPUT DATA FOR FLOWC

Data Set 1 :

```
1         1 1       2 1  2 6  3 1
   FLOWSPA  1993        0       21   25
```

Position	Data	Format
1	Name.	2A10
21	Indicator : 0 if data to follow, 1 if no data.	I1
26	Maximum dimension to East (ie. allowable no. of columns). Dimension = 75, if not set.	I5
31	Maximum dimension to North (ie. allowable no. of rows). Dimension = 75, if not set.	I5

Data Set 2 :

```
1    6    1 1       2 1       3 1
 35.0  0.0    .00025    .0512     .005
4 1       5 1       6 1  6 6  7 1
     -12.0       0.0       5.0      20.
```

Position	Data	Format
1	Latitude (+ve if °S). [Degrees]	F5.0
6	Latitude (+ve if 'S). [Minutes]	F5.0
11	Coefficient of bottom stress (If -ve, inclusion of σ_T).	F10.5
21	X-component of wind stress. [Nm^2] (North)	F10.5
31	Y-component of wind stress. [Nm^2] (East)	F10.5
41	Boundary slope along OX (A_B)^3.	8PF10.5
51	Boundary slope along OY (B_B)^3.	8PF10.5
66	Current fluctuation. [cms^{-1}][1]	F5.1
71	Minimum depth. [m] (any depth less than the minimum depth are set internally to the standard depth)	F5.0

---

[1] The current fluctuation is a constant current speed which is added to the bottom current u_B to take account of unresolved currents, eg. if the tide is not explicitly calculated it would be a root mean square tidal current.

Data Set 3 :

```
1    6    11        21        31
   81   99      90.0    2000.0   43200.0
41        51        61   66
       0.0    2                60.0   11
```

Position	Data	Format
1	Dimension to East (ie. no. of columns, M).	I5
6	Dimension to North (ie. no. of rows, N).	I5
11	Time step $(\Delta t)^2$. [s]	F10.5
21	Grid interval. [m]	F10.5
31	Period of changes $(T)^3$. [s]	F10.5
41	Amplitude of tide $(C_B)^4$. [m]	F10.5
51	Number of doublings of time step.	I5
66	Standard depth. [m] (any depth greater than the standard depth will be internally set equal to the standard depth)	F10.5
78	Maximum elevation/current speed indicator. if 1, maximum elevation if 2, maximum current speed (with direction) are output.[5]	I1
79	Expanded resolution indicator. if 0, $M^* = 2(M/2)+1$, $N^* = 2(N/2)+1$ if 1, $M^* = 2M+1$, $N^* = 2N+1$ Dimension of internal model grid to East $=M^*$ Dimension of internal model grid to North $= N^*$ M^*, N^* may vary from M and N due to the staggered grid.	I1
80	Bathymetry indicator. if 0, depths in fathoms (I3.0) and feet (I1.0) if 1, depths in m (I4.0) if 2, depths in cm. (I4.0)	I1

---

[2] $$\Delta t \le \Delta t_m = \frac{\sqrt{2}\Delta s}{\sqrt{gH}}$$

where, Δt_m is maximum time step, Δs is grid interval, g is gravitational acceleration and H is the maximum depth.

[3] $$\left(\frac{\partial\zeta}{\partial x}\right)_{i,j} = -A\sin\frac{2\pi t}{T}, \left(\frac{\partial\zeta}{\partial y}\right)_{i,j} = -B\cos\frac{2\pi t}{T} \qquad (T \ne 0)$$
$$= A \qquad\qquad = B \qquad\qquad (T = 0)$$

[4] $$\eta_{iB,jB}(t) = C_B\cos\frac{2\pi t}{T} - \left((i_B - i_o)A_B\sin\frac{2\pi t}{T} + (j_B - j_o)B_B\cos\frac{2\pi t}{T}\right)\Delta s \quad (T \ne 0)$$
$$= C_B + \left((i_B - i_o)A_B + (j_B - j_o)B_B\right)\Delta s \qquad (T = 0)$$

(For more detail refer to Bye (1988) - page 43,49.)

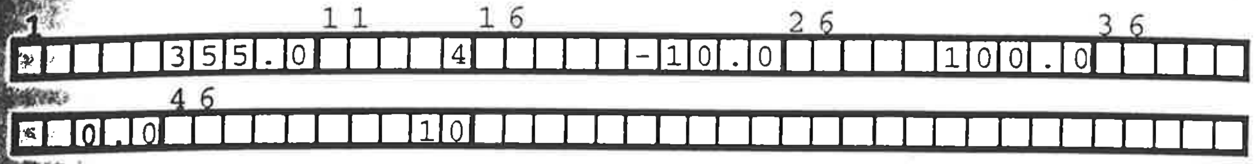
[5] Facility can be used with utility program to obtain cophase and cotidal charts.

Data Set 4:

```
1         11    17   22  26   31
    175200 43800 1680   1  0.0
41        51        61        71
       0.0       0.0    -43800      1440
```

Position	Data	Format
1	Number of time steps (how long the model is run for).	I10
11	Number of time steps between displays of model sea.	I6
17	Number of time steps between recordings of instruments in model sea.	I5
22	Initial conditions indicator. 0 if initially U=V=η=0 1 if initially U=V=0, and η for the standard ocean, applied at all elevation points.	I4
26	Time of start of experiment. [s]	F5.1
31		I5
36		I5
41	Gradient of static level along OX $(A)^3$.	8PF10.5
51	Gradient of static level along OY $(B)^3$.	8PF10.5
61	Time at which first display of model sea occurs. If -ve a steady circulation is assumed to occur after this time, cf. Section 2.2.	I10
71	Time steps between displays of designated sections (displays of cumulative transports and mass fluxes). If -ve, no section data is output. The utility output file is output with the same time step, and this facility can be used when the information is required at frequent intervals, cf. Section 4.2.	I10

Data Set 5 :

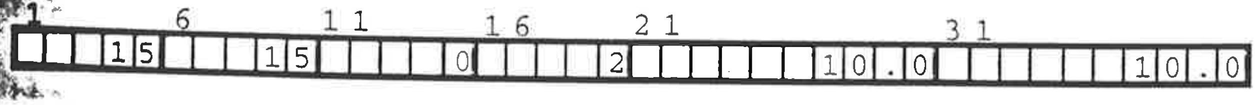


Position	Data	Format
1	Background Concentration (C_o). Scaled units.	F10.5
11	Scaling of background concentration[6]. ie. for a background concentration of 355 with scaling of 4, background concentration = 355E-4, = 35.5 ppt.	I5
16	Rainfall [mm/month] (-ve if evaporation greater than rainfall).	F10.5
26	Diffusion coefficient. [m^2s^{-1}]	F10.5
36	Time constant for tracer (λ^{-1}). [days]	F10.5
46	Time steps between calculation of concentration. [α in 2.2, if $0, \alpha = 1$] Later put in waves	

Data Set 6 :

Bathymetry data according to Data Set 3, Position 80, by rows starting from bottom of model sea. Format code in data set 3 can be amended by user.

Data Set 7 (Data Set I) :



Position	Data		Format
1	Location of instrument (column)		I5
6	Location of instrument (row)		I5
11			I5
16			I5
21	Volume flux (Q) [m^3s^{-1}]		F10.5
31	Concentration of input (C_p).	($Q \neq 0$)	F10.5
	Pollution flux (P). [kgs^{-1}]	($Q \neq 0$)	

Data Set 8 :

Set points/sections indicator. I5

if 0, → Data Set 10,
if 1, time series input,[7]
if 2, time series input and sections,
if, -1, sections. (Data Set 9).

---

[6] FLOWC uses internally c.g.s. units and scaled concentrations.

[7] For information on time series input refer to Bye (1988) - page 56-8.

Data Set 9 :

Each section specified by sets of coordinate pairs based on the grid after doubling or expanded resolution has been implemented. Format 2I3. Maximum of 12 pairs, eg.

Section 1 :

```
1  4  7  10 13 16 19 22
  2  3  2  5  2  7  2  9
```

Section 2 :

```
1  4  7  10 13 16 19 22
 15  2 17  2 19  2-20  3
```

The grids (i,j) of section 1 are (2,3), (2,5), (2,7) & (2,9).
The grids of section 2 are (15,2), (17,2), (19,2) & (20,3).

If i is even and j is odd, section is in the Y-direction (to North),
If i is odd and j is even, section is in the X-direction (to East),
If i is +ve, +ve flow is into model,
If i is -ve, +ve flow is out of model.
A blank line terminates the data set.

Data Set 10 :

An array of σ_T [kgm^{-3}] of the model sea (cf. Data Set 2, position 11). σ_T x 100 values are entered on i odd, j odd nodes only by rows starting from the bottom of the model sea. Array dimensions : $M = \frac{(M^*-1)}{2}$, $N = \frac{(N^*-1)}{2}$ are those used in the simulation after doubling or expanded resolution has been implemented. Not valid with maximum indicator set unless amended by user. Format I4.

Data Set 11 :

See Data Set 1.

4 SAMPLE SIMULATION - tracer distribution in Gulf St. Vincent and Investigator Strait

The accompanying sample listing consist of three parts.

4.1 Data Input

(UNIT = 10, FILE = 'F13PA.DAT')

(The bold numbers in bracket are the Data Set number)

```
(1)     FLOWC  1993       0     81     99
(2)     35. 0.    -0.0025  .0512      .0058          -12.0 0.0
       20.0 20.0
(3)     81  99    90.0      2000.0    0.0       0.        2
       60.0         1
(4)    175200    43800 1680 1    0.0  0    0    0.0        0.0
       -43800     14400
(5)     0.0      6      -100.0   100.0    0.0       10
(6)     (81 columns x 99 rows of grids not shown)
(7)     69  65         2    10.0      100000.0
(8)     -1
(9)      2  3  2  5  2  7  2  9
        15  2 17  2 19  2-20  3
       0
(10)   000 000 000 000 000 000 000 2566256625632561
       258425782572000 2575257725832586256625632561
       25862579257225752571257725892589260926080000
       26552613257225752578258826012601260226070000
       26222572257225782584257925922592259826190000
       25892512258525832580257525882598259926150000
       000 000 260125862571259026032618263126310000
       000 000 000 000 000 2590261626332644263100 0
       000 000 000 000 000 000 2641265126552619000
       000 000 000 000 000 000 2631264826912655000
       000 000 000 000 000 000 266926792735000 000
       000 000 000 000 000 000 000 27912791000 000
       000 000 000 000 000 000 000 000 000 000 000

                               1
```

4.2 Utility Output File

(UNIT = 13, FILE = 'BIOLPA.RES') for input into programs in which total inflow (I) into the model sea is required.

Line 1 : Volume of model sea. [m^3] F20.3
Time step. [hours] (Data Set 4, Position 71) F12.3

Line 2 : Inflow (I). [m^{3}s^{-1}] F20.5

```
317760012287.99998    1440.000
        106592.45313
        106592.41406
        106592.42969
        106592.43750
        106592.43750
        106592.43750
        106592.43750
        106592.43750
        106592.43750
        106592.43750
        106592.43750
        106592.43750
```

4.3 Output file of Results

(UNIT = 11, FILE = 'F13PA.RES')

```
  FLOWC  1993

DENSITY QUOTIENT =    .0000E+00
MAX. DEPTH =  60.   (METRES)
MIN. DEPTH =  20.   (METRES)
1  LAYER DYNAMICS


STEADY CIRCULATION AFTER    4380.00(HOURS)


net rainfall =   -100.00  (mm/mth)
decay =   .00  (days)
diffusion =  100.00  (m^2/s)
background conc. =   .000E+00

SECTION   1 :    2   3    2   5    2   7    2   9
SECTION   2 :   15   2   17   2   19   2  -20   3

INSTRUMENT LOCATION =   19   17    0  (x  y  z)
flow rate =      10.00  (m^3/s)
mass flux =    1000.00  (kg/s)


TOTAL FLOW RATE =      10.00  (M^3/SEC)
TOTAL MASS FLUX =    1000.00  (KG/SEC)
```

```
SIGMA-T

    .0     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
    .0     .0     .0     .0     .0     .0     .0   27.9   27.9     .0     .0
    .0     .0     .0     .0     .0     .0   26.7   26.8   27.3     .0     .0
    .0     .0     .0     .0     .0     .0   26.3   26.5   26.9   26.5     .0
    .0     .0     .0     .0     .0     .0   26.4   26.5   26.5   26.2     .0
    .0     .0     .0     .0     .0   25.9   26.2   26.3   26.4   26.3     .0
    .0     .0   26.0   25.9   25.7   25.9   26.0   26.2   26.3   26.3     .0
  25.9   25.1   25.8   25.8   25.8   25.8   25.9   26.0   26.0   26.1     .0
  26.2   25.7   25.7   25.8   25.8   25.8   25.9   25.9   26.0   26.2     .0
  26.5   26.1   25.7   25.8   25.8   25.9   26.0   26.0   26.0   26.1     .0
  25.9   25.8   25.7   25.8   25.7   25.8   25.9   25.9   26.1   26.1     .0
  25.8   25.8   25.7     .0   25.8   25.8   25.8   25.9   25.7   25.6   25.6
    .0     .0     .0     .0     .0     .0     .0   25.7   25.7   25.6   25.6


PERIOD =      .00  HRS        TIME STEP =     6.00  MINS
GRID = 8000.00  M             CORIOLIS =  -.8365E-04  /SEC


diffusion time step =    60.00  mins


CENTRE OF MODEL (  14.66, 12.53 )
MEAN DEPTH =    19.39   (M)
AREA =  .164E+11   (M^2)


BOTTOM QUAD FRIC =    .0025
CURRENT FLUCTUATION = 20.0000  CM/SEC

SECTIONS - CUMULATIVE TRANSPORT (M^3/S) AND MASS FLUX (KG/S)
AT TIME =    1440.00   (HOURS)

  1        1523.    -6213.    53690.    36197.
       -.104E-05 -.165E-04  .587E-04 -.497E-04
  2       26027.    -2074.    17066.   -35584.
        .724E+01 -.106E+02 -.753E+01 -.322E+02

FLUX =      .10000E+04  (KG/S)
FLUSHING/RENEWAL TIME =          .00  (DAYS)

X-,Y- WIND STRESS(N/MSQX1000),ELEVATION(MMX10),
SPEED(MMX10/SEC), DIRECTION(DEGX100)  concentration(x.10E-07)

TIME =  168.00   HOURS       INTERVAL =  168.00   HOURS


            51      51      51      51      51      51      51      51
             5       5       5       5       5       5       5       5
elevatn    464     464     464     464     464     464     464     464
Speed      103     103     103     103     103     103     103     103
directn   -115    -115    -115    -115    -115    -115    -115    -115
[ ]      16449   24807   29764   33151   35722   37810   39572   41093
```

```
SECTIONS - CUMULATIVE TRANSPORT (M^3/S) AND MASS FLUX (KG/S)
AT TIME =   2880.00   (HOURS)

  1         1523.    -6213.    53690.    36197.
        -.382E-04 -.416E-03  .994E-03 -.195E-02
  2        26027.    -2074.    17066.   -35584.
         .561E+02 -.910E+02 -.644E+02 -.279E+03

FLUX =      .10000E+04 (KG/S)
FLUSHING/RENEWAL TIME =          .00 (DAYS)

SECTIONS - CUMULATIVE TRANSPORT (M^3/S) AND MASS FLUX (KG/S)
AT TIME =   4320.00   (HOURS)

  1         1523.    -6213.    53690.    36196.
        -.999E-04 -.995E-03  .216E-02 -.502E-02
  2        26027.    -2074.    17066.   -35584.
         .104E+03 -.172E+03 -.121E+03 -.528E+03

FLUX =      .10000E+04 (KG/S)
FLUSHING/RENEWAL TIME =          .00 (DAYS)


TIME =     182.50   (DAYS)
MEAN ELEVATION =       .0340   (M)
MEAN ENERGY =   .305E+01   (J)
TOTAL SOLUTE MASS =   .163E+11   (KG)
DECAY FLUX =   .000E+00   (KG/S)
EVAPORATION FLUX =   .361E+02   (KG/S)
STRUTTON EXCHANGE CONSTANT =     188.64   (DAYS)
AVERAGE CON. =   .513E-04


X- COMPT. OF STATIC SLOPE =        .000E+00
Y- COMPT. OF STATIC SLOPE =        .000E+00
X- COMPT. OF WIND STRESS =           .051  (N/MSQ)
Y- COMPT. OF WIND STRESS =          .006  (N/MSQ)
X- COMPT. OF BOUNDARY SLOPE =     -.120E-06
Y- COMPT. OF  BOUNDARY SLOPE =      .000E+00
```

```
TOP LAYER


ELEVATION (CMS)

999  999  999  999  999  999  999  999  999  999  999

999  999  999  999  999  999  999    2    3  999  999

999  999  999  999  999  999    3    3    3  999  999

999  999  999  999  999  999    3    3    3    4  999

999  999  999  999  999  999    3    3    3    4  999

999  999  999  999  999  999    3    3    3    4  999

999  999  999  999  999    3    3    3    3    4  999

999  999    3    3    3    3    3    4    4    4  999

  1    3    3    3    3    3    3    4    4    4  999

  1    2    2    2    3    3    3    4    4    4  999

  1    2    2    2    2    3    3    4    4  999  999

  1    2    2  999    1    2    2    1    1    0    0

999  999  999  999  999  999  999    0    0    0 ****
```

```
SPEED(CMS/SEC), DIRECTION(DEGREES)

 999    999    999    999    999    999      3      3    999
 999    999    999    999    999    999     44    134    999

 999    999    999    999    999      3      0      1    999
 999    999    999    999    999     44     58   -147    999

 999    999    999    999    999      1      0      0      1
 999    999    999    999    999    -24   -151   -171    -44

 999    999    999    999    999      2      1      1      1
 999    999    999    999    999     30     86    159     -1

 999    999    999    999    999      3      0      2      0
 999    999    999    999    999     11     88    164     49

 999    999    999    999      5      3      0      1      0
 999    999    999    999     44     33    155   -169    -47

 999      6      5      5      3      0      1      1      0
 999     44     81     87     62     38   -153    178     85

   6      3      2      2      1      1      1      1      1
 -34     31     70     85    121   -140   -120   -106    -63

   6      3      1      0      1      2      1      0      3
  98     36     87    156   -156   -156   -133      0     45

   3      4      5      4      4      3      3      5    999
 175     40     95    113    129    133    122     45    999

   3      7    999      5      8     15     16     15     18
 128     45    999    135    114    104     77    106     77
```

```
concentration(x .10E-05)

999   999   999   999   999   999   999   999   999   999   999

999   999   999   999   999   999   999    59    58   999   999

999   999   999   999   999   999    50    60    80   999   999

999   999   999   999   999   999    51    89   246   478   999

999   999   999   999   999   999    19    54   219   526   999

999   999   999   999   999   999    16    57   172   205   999

999   999   999   999   999     2    13    63   143   137   999

999   999     0     0     0     2    29    75   117   105   999

  0     0     0     0     1    11    46    66    67    54   999

  0     0     0     0     6    22    42    44    35    34   999

  0     0     0     0     1     9    22    29    28   999   999

  0     0     0   999     1     5     9    10     9     7     7

999   999   999   999   999   999   999     0     9     0  ****

X-,Y- WIND STRESS(N/MSQX1000),ELEVATION(MMX10),
SPEED(MMX10/SEC), DIRECTION(DEGX100) concentration(x.10E-07)

TIME =10920.00   HOURS      INTERVAL =  168.00  HOURS


          51     51     51     51     51     51     51     51
           5      5      5      5      5      5      5      5
[illegible]  464    464    464    464    464    464    464    464  [illegible]
speed    103    103    103    103    103    103    103    103
direc   -115   -115   -115   -115   -115   -115   -115   -115
C      56410  56430  56448  56465  56480  56495  56509  56522
```

0464   0464 mm x 10

[illegible]

```
SECTIONS - CUMULATIVE TRANSPORT (M^3/S) AND MASS FLUX (KG/S)
AT TIME =  14400.00   (HOURS)

  1          1523.    -6213.    53690.    36197.
          -.207E-03 -.196E-02  .403E-02 -.103E-01
  2         26027.    -2074.    17066.   -35584.
           .176E+03 -.295E+03 -.208E+03 -.908E+03

FLUX =        .10000E+04 (KG/S)
FLUSHING/RENEWAL TIME =      243.99 (DAYS)

SECTIONS - CUMULATIVE TRANSPORT (M^3/S) AND MASS FLUX (KG/S)
AT TIME =  15840.00   (HOURS)

  1          1523.    -6213.    53690.    36197.
          -.208E-03 -.197E-02  .404E-02 -.103E-01
  2         26027.    -2074.    17066.   -35584.
           .177E+03 -.296E+03 -.209E+03 -.912E+03

FLUX =        .10000E+04 (KG/S)
FLUSHING/RENEWAL TIME =      243.99 (DAYS)

TIME =13608.00   HOURS        INTERVAL =  168.00   HOURS


    51       51       51       51       51       51       51       51
     5        5        5        5        5        5        5        5
   464      464      464      464      464      464      464      464
   103      103      103      103      103      103      103      103
  -115     -115     -115     -115     -115     -115     -115     -115
 56608    56615    56621    56627    56632    56637    56642    56647


SECTIONS - CUMULATIVE TRANSPORT (M^3/S) AND MASS FLUX (KG/S)
AT TIME =  17280.00   (HOURS)

  1          1523.    -6213.    53690.    36197.
          -.209E-03 -.198E-02  .405E-02 -.103E-01
  2         26027.    -2074.    17066.   -35584.
           .177E+03 -.297E+03 -.210E+03 -.914E+03

FLUX =        .10000E+04 (KG/S)
FLUSHING/RENEWAL TIME =      243.99 (DAYS)


TIME =      730.00   (DAYS)
MEAN ELEVATION =          .0340   (M)
MEAN ENERGY =    .305E+01   (J)
TOTAL SOLUTE MASS =   .212E+11   (KG)
DECAY FLUX=   .000E+00   (KG/S)
EVAPORATION FLUX =   .456E+02   (KG/S)
STRUTTON EXCHANGE CONSTANT =      245.50   (DAYS)
AVERAGE CON. =   .668E-04
```

```
concentration(x .10E-05)
  999  999  999  999  999  999  999  999  999  999  999

  999  999  999  999  999  999  999   84   85  999  999

  999  999  999  999  999  999   69   84  110  999  999

  999  999  999  999  999  999   68  114  283  524  999

  999  999  999  999  999  999   27   70  249  566  999

  999  999  999  999  999  999   23   73  200  243  999

  999  999  999  999  999    3   18   81  175  177  999

  999  999    0    0    0    3   41  100  151  143  999

    0    0    0    0    2   17   68   96  100   86  999

    0    0    0    1   11   36   67   72   59   60  999

    0    0    0    0    2   16   36   49   49  999  999

    0    0    0  999    2    8   15   16   16   13   13

  999  999  999  999  999  999  999    0   16    0 ****
```

In the event that the user wishes to adapt FLOWC for her/his own needs, it is strongly recommended that a reference original FLOWC is archived.

5 REFERENCES

Bye, J.A.T. (1988). The flow series of thallasso - Models. School of Earth Sciences, The Flinders University of South Australia.

Bye, J.A.T. and Harbison, P. (1991). Transfer of inland salts to the marine environment at the head of Spencer Gulf, South Australia. Palaeoecology, 84 : 357-368.

Fiadeiro, M.E. and Veronis, G. (1977). On weighted-mean schemes for the finite-difference approximation to the advection-diffusion equation. Tellus 29 : 512-522.

Johhnson, W.R. and Kowalik, Z. (1986). Modelling of Storm Surge in the Bering Sea and Norton Sound. Journal of Geophycal Research, 91(C4) : 5199-5128.

Ng, S.C. (1993). Numerical modelling of Gulf St. Vincent and Investigator Strait, and spectral analysis of their chlorophyll a. Honours Thesis, The Flinders University of South Australia.

Strutton, P. (1992). Hydrodynamical and biological Aspects of Coffin Bay, and their application to aquaculture. Honours Thesis, The Flinders University of South Australia.

Appendix T: "The FLOWM Model"

THE FLOWM MODEL

(supplement to Flow c Model).

Supplement to the FLOWC MODEL incorporating the generation of circulation by wind waves and swell through longshore processes, tidal progression, and buoyant solute dispersion, and also time series input and initial field input specification.

Table of Contents

6. Longshore circulation

6.1 The transport momentum equations

The transport momentum equations (30) and (31) in Bye (1988) include the terms, respectively,

$$-\frac{\partial}{\partial x} S_{xx} - \frac{\partial}{\partial y} S_{xy}$$

and

$$-\frac{\partial}{\partial x} S_{yx} - \frac{\partial}{\partial y} S_{yy}$$

on the right hand side which are due to the surface wave field, where

$$S_{xx} = \int_{-H}^{\eta} \left(\overline{u'^2} - \overline{w'^2} \right) dz + \frac{1}{2} g \overline{\eta'^2}$$

$$S_{xy} = S_{yx} = \int_{-H}^{\eta} \overline{u'v'} dz$$

$$S_{yy} = \int_{-H}^{\eta} (\overline{v'^2} - \overline{w'^2}) dz + \frac{1}{2} g \overline{\eta'^2}$$

are the radiation stresses due to the orbital motion of the wave (u', v',w') and the wave elevation (η'). The bottom stress also is influenced by the wave orbital motions ($\underline{u}'_{BW}$), where $\underline{u}'_{BW}$, = (u'_{BW}, v'_{BW}).

The radiation stress terms give rise to setups and setdowns, and also may generate a circulation.

The aim of the FLOWM model is to provide an algorithm which generates the circulation for a prescribed wind forcing (which generates local wind waves) and external forcing due to swell.

A simplified representation is incorporated in which the effects of the radiation stresses are confined to forcing the longshore transports immediately adjacent to the coast, and it is further assumed that the wave refraction can be represented simply as a function of the angle of approach of the wave train relative to the coastal boundary.

It is well known that the normal components of radiation stress (S_{xx} for a meridional coast, and S_{yy} for a zonal coast) are mainly responsible for the setup and setdown, whereas the tangential component (S_{xy}) mainly generates the longshore circulation (Longuet-Higgins, 1970), and in FLOWM, S_{xy} only, is computed at the depth node adjacent to the coast, from which $\frac{\partial}{\partial y}S_{xy}$ is calculated for a zonal coast, and $\frac{\partial}{\partial x}S_{xy}$ is calculated for a meridional coast, by assuming that $S_{xy}=0$ at the coast. The root mean square bottom velocity ($|\overline{u}'_{BW}|$) is also calculated at the same depth node.

6.2 The tangential radiation stress (S_{xy})

The tangential radiation stress for a deep water wave of amplitude (a) propagating at an angle (ϕ) to the zonal direction (x - axes) is

$$S_{xy}=\frac{1}{4}ga^2 \ \sin\phi\cos\phi$$

On approaching the surf zone this wave is refracted towards the coast, and we represent this process by assuming that at the edge of surf zone the angle of incidence at breaking is proportional to ϕ, such that along the Eastern meridional coast (Fig 1),

$$S_{xy} = \frac{1}{4}ga^2\alpha\phi \ / \ (\frac{\pi}{2}) \qquad o\leq\phi\leq\frac{\pi}{2}$$

where α is a refraction coefficient, and along the Western meridional coast,

$$S_{xy} = -\frac{1}{4}ga^2\alpha\phi \;/\; (\frac{\pi}{2}) \qquad o \leq \phi \leq \frac{\pi}{2}$$

This heuristic formulation drives a longshore transport which is proportional to α, and also the square of the wave amplitude, Similar formulae apply for waves approaching the Western meridional coast, and for Northern and Southern Zonal coasts.

The wave amplitude is determined by two methods.

(i) Swell Swell is assumed to propagate into the model sea from the boundary without change of property, i.e.

$$a = \frac{1}{2}H_s, \quad T = T_s, \quad \phi = \phi_o$$

where H_s is the swell height, T_s is the period of the swell, and ϕ_o is its angle of propagation relative to the zonal direction.

(ii) Wind waves Wind waves are assumed to propagate in the direction of the wind stress; and their significant height (H_s) and period (T_s) are determined by the formulae (Toba, 1978)

$$H^* = 0.05 \left(\frac{gF}{u_*^2}\right)^{½}$$

$$T^* = 6.4\; H^{*⅔}$$

where $H^* = gH_s \;/\; u_*^2$ and $T^* = \dfrac{gT_s}{u_*}$
in which u_* is the air friction velocity, and F is the fetch.

The root mean square bottom velocity is given by the relation,

$$|\underline{u}'_{BW}| = \frac{\beta}{\sqrt{2}}\left(\frac{\pi H_s}{T_s}\right)$$

where β is a parameter ($0 \leq \beta \leq 1$).

6.3 Implementation

The fetch is determined by backtracking upwind from the coast until either another coast, or the boundary of the model sea, is encountered. In the latter situation a specified external fetch is added to the internal fetch to obtain the total fetch (Fig 1).

For convenience, fetches are only computed along eight directions (SW, W, NW, N, NW, SE and S), and the fetch to be applied is found by linear interpolation.

Two types of simulation can be made, using

(i) Specified external fetches option 1

in which the applied wind stress field acting along the total fetch (internal and external) generates the longshore circulation, in addition to the wind driven circulation, or

(ii) Specified external wavefield

in which:

(a) in the absence of wind, the specification is assumed to be swell, which propagates into the model sea, and in the absence of other forcing simulates a pure wave driven circulation; and

(b) with wind forcing, the specified external wave forcing propagates into the model sea along the wind direction, and locally wind forced wavefields are also generated by internal fetches.

The intensity of the longshore forcing is determined by the parameter (α) which typically has a value of 0.1. In FLOWM, β = 0, such that the bottom friction is unmodified by the breaking wavefield.

6.4 Input data for FLOWM

An extra data set is included after Data Set 5.

Data Set W:

1					6					11					16					21					26					31				
				1			0	•	1				3	•			1	0	•			3	4	•			2	2	•			3	3	•

36					41					46					51					56					61					
	1	0	0	•		2	5	0	•			2	2	•			1	0	•			4	6	•		1	2	0	•	

Position	Data			Format
1	Wave parameter	=0 if no wave data		I 5
		=1 if wave data		
6	Wave parameter (α)			F 5.2
11	Significant wave/swell height (m)			F 5.2
	= 0 if specified external fetches			
	≠ 0 if specified external wavefield			
16	Significant wave/swell period (s)			F 5.2
21	Swell direction (from °)			F 5.2
26	Fetch (km) from	SW	110 km	F 5.2
31		W	65 km	F 5.2
36		NW	80	F 5.2
41		N	0	F 5.2
46		NE	0	F 5.2
51		E	0	F 5.2
56		SE	0	F 5.2
61		S	0	F 5.2

6.5 References

Longuet-Higgins, M.S., (1970) Longshore currents developed by obliquely incident sea-waves 1, *J. Geophys.Res* **75** : 6778-89.

Toba, Y., (1978). Stochastic form of the growth of wind waves in a single-parameter representation with physical implications, *J.Phys.Oceanogr.* **8** 494-507.

7. Limited buoyant discharges

The facility implemented in Data Set 5, allows the effects of continuous discharges of fluid and solute from specified sources to be tracked on the assumption that total mixing of the solute in the water column occurs.

This facility has been extended to incorporate point releases of material, which may also be limited by its buoyancy to disperse in the surface layer of the water column, where it would be influenced by drift currents associated with the wave boundary layer.

7.1 Point releases

This facility assumes that all discharges occur only in a specified time interval.

Data Set 5

Position

61	Starting time for discharge (hours)	F5.2
66	Finishing time for discharge (hours)	F5.2

If both starting and finishing times are zero, a continuous discharge is assumed.

7.2 Buoyant plumes

Oil and other organic solutes, and also certain organisms, are buoyant, and disperse in a surface layer. The thickness of this layer depends on the buoyancy of the solute, and also the degree to which it is degraded through wave action.

The surface layer of solute also is advected by the Lagrangian wave drift, in addition to the non-wave induced currents due to the general and tidal circulation. These effects are represented through two parameters which are assumed to be constant throughout the model sea.

The thickness (h) of the surface layer, e.g. 0.1m, which contains the solute. The concentration of the solute is inversely proportional to h, since in (2.1.4), the water depth (H) is replaced by h, where $h << H$.

The effect of the wave-induced drift which is represented by the addition of a drift velocity,

$$\underline{u}_s = \gamma \underline{w}_* \qquad (7.1)$$

where w_* is the water friction velocity, defined by,

$$\underline{\tau}_s = \rho|\underline{w}_*|\underline{w}_*$$

in which $\underline{\tau}_s$ is the surface shearing stress, ρ is the water density, and γ is a constant. For a solute uniformly distributed vertically within a logarithmic wave boundary layer,

$$\gamma = 1/k \qquad (7.2)$$

where k is Von Karman's constant ($k \sim 0.4$). This situation would possibly correspond to a mature slick, whereas before the wave action on the solute has been completed, $\gamma > 1/k$. The estimate (7.2) of γ is used as a 'default option', however any value may be specified.

In the amended equation (2.1.4), we have

$(\underline{U} + \underline{u}_s H)$ in place of $\underline{U}$.

Data Set 5

Position

51 The depth of the surface layer (h) [m] F5.2

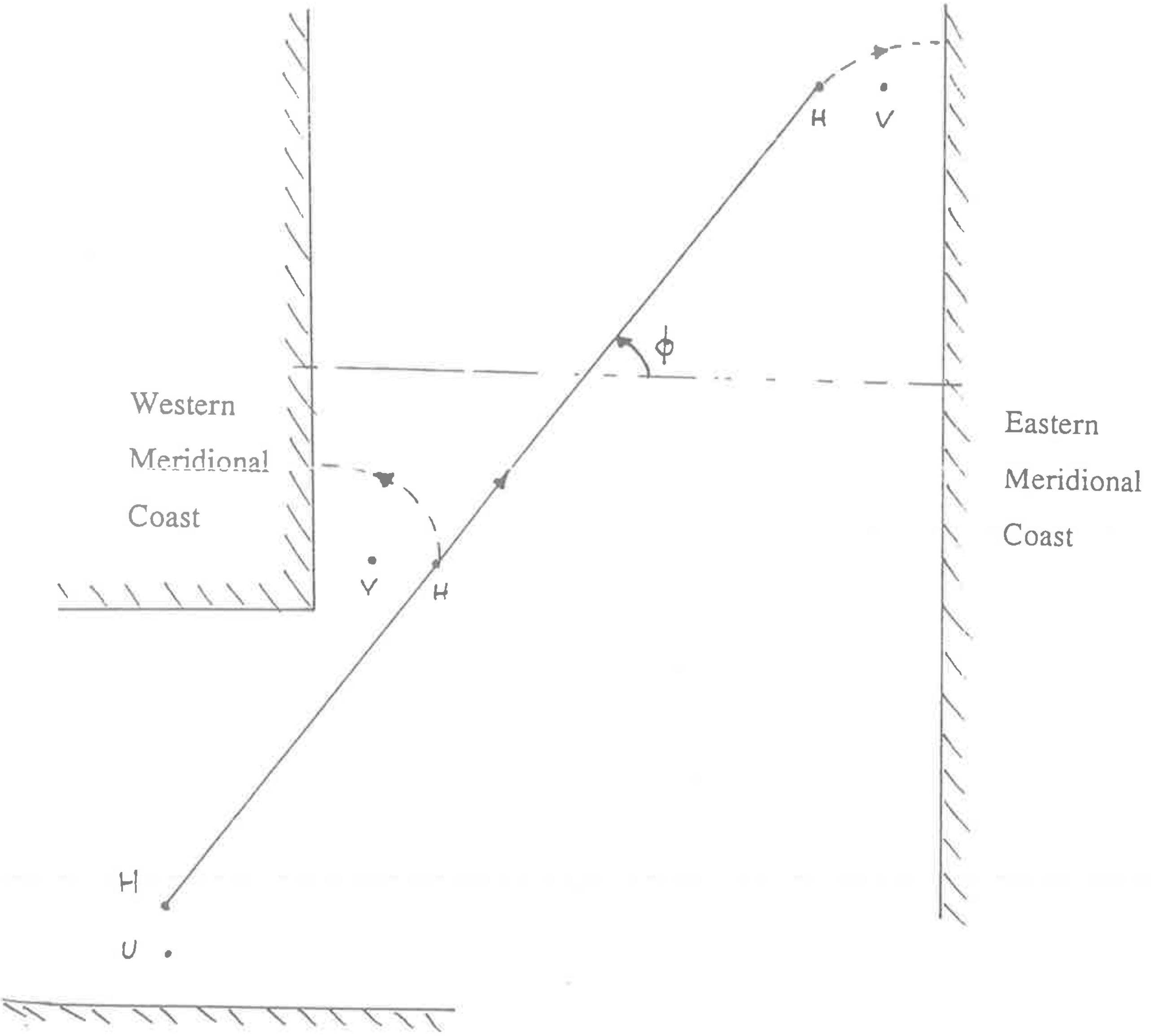
If h = o, the solute is assumed to be vertically well mixed.
If h < Minimum depth (Data Set 2, Position 71) h = Minimum depth

56 The wave drift parameter (γ). F5.2

If γ = o, γ = 1/k.

Note For a point release, e.g. an oil spill, the starting and finishing times may be set in Positions 61 and 66.

Fig.1 Method of computing fetches



8. Time series input

In the original FLOWSPA model provision was made for time series input. This facility has been adapted and extended in FLOWM.

There are three types of time series input, (i) Wind stress components, (ii) Background concentration and evaporation, and (iii) Boundary elevation.

The time series specification (Data Sets S1 and S2) follow Data Set 8.

The time series specification (Data Set S3) follows Data Set 12.

The time series (Data Sets D1, D2 and D3) follow Data Set S3.

Data Set S1:

1						6																									
				1	0					1																					

Position	Format
1 Time series indicator	I5

if -1 wind/wind stress components are specified

if -2 wind/wind stress components and background concentration and evaporation are specified

if X wind/wind stress components and background concentration and evaporation and boundary elevations are specified. Number of set points on boundary = X ($X \leq 25$)

6 Wind/wind stress indicator

if 0 wind stress components ($Nm^{-2} \times 10^3$)

if 1 wind components (ms^{-1})

if 2 wind speed (kn) and direction from (°)

Data Set S2:

1										11										21											
							3	•	0								6	•	0		L	A	R	V	A	L		D	I	S	T

Position		Format
1	Time of start of data (hours)	F10.2
11	Interval of time series data (hours) if 0 constant forcing required at set points, in this case only the first entry of the time-series is to be specified.	F10.2
21	Title of data	2A10

Data Set S3:

1					6															21		23									
			1	7				2	5													6	0		3	0	1	0			

Position		Format
1	Column of set point	I5
6	Row of set point both the row and column should be odd numbers, and set points for all boundary points should be given. Expanded resolution should not be used with time-series input.	I5
21	Percentages of corresponding data source points A linear combination of up to 3 time series entries, each corresponding to a data source point may be applied to any set point. The percentages to be taken from each data source point, with -1 for 100% are entered. Number of data source points = X (Data Set S1).	25I2

Data Set S4:

0 Set points terminator card.

Data Set D1:

1					6					11								
		2	7	1		-	5	2	9		-	4	6	2				

1					6					11								
		2	0	6			7	1	4			7	1	2				

Position		Format
1, 6, 11,	Wind/wind stress data	16F5.0
1, 6, 11,	as specified in Data Sets S1 and S2	16F5.0

Data Set D2:

1					6					11								
	3	6	.	2		3	7	.	1									

1					6					11								
		9	5	.			7	2	.									

Position		Format
1, 6, 11,	Background concentration (C_o) Scaled units	16F5.0
1, 6, 11,	Net rainfall [mm/month] (-ve if net evaporation) as specified in Data Sets S1 and S2	16F5.0

Data Sets D3:

1					6					11								
			2	5				7	9									

Position		Format
1, 6, 11,	Elevation in mm One time series input is required for each of the X set points, as specified in Data Sets S1, S2 and S3.	16F5.0

Note

The time series information is submitted in sets, i.e. Data Sets D1, D2, D3 - in batches of 16 entries.

9. Initial field input [illegible]

9.1 Initial concentration fields

It is sometimes useful to initiate the dispersion from an initial known field at a specified time. This facility uses Data Set 4 and a new Data Set 11 and Data Set 12.

Data Set 4

Position		Format
22	Initial concentration indicator if 0 initial concentration is set as C_o (Data Set 5). if 1 initial concentration field as specified in Data Sets 11 and 12 is expected.	I1

Note. This facility replaces the original initial conditions option. A standard ocean is now always assumed.

Data Set 11:

Position		Format
1	Start time for dispersion from the initial field (hrs)	F6.1

Data Set 12:

An array of C_o {scaled units} of the model sea. C_o values are entered on i odd j odd nodes only by rows starting from the bottom of the model sea.

Array dimensions : $M = \frac{M^*-1}{2}$, $N = \frac{N^*-1}{2}$ are those used in the simulation after doubling or expanded resolution has been implemented.

Format F5.0

9.2 Sigma -T field

The specification is amended and extended as follows:

Data Set 2:

Delete provision in Position 11

Data Set 3:

Position		Format
81	Baroclinic forcing indicator	I1
	if 0 no σ_T forcing	
	if 1 σ_T forcing	
	if 2 σ_T forcing, baroclinic on boundaries	

The specification of σ_T forcing is given in Data Set 10.

10 Preprocessing and graphical output

A preprocessing routine has been added to the FLOWM code which enables the data to be input interactively. Output files are also produced according to the specifications which are suitable for graphical outputs. A parameter has been included to specify the type of graphical output.

Data Set 3:

Position		Format
82	Graphical output indicator	I1
	if 0 GMT	
	if 1 Spyglass	

In the preprocessing routine the bathymetry data (Data Set 6) and also the σ_T data (Data Set 10) are imported as specified files.

11. Other input changes

11.1 Minor changes

These changes may be entered in the FLOWC booklet

Data Set 3:

Position

31

Add: if -ve the flushing/renewal time and Strutton exchange constant are computed using a rate of change of concentration averaged over the tidal period.

Note:

The term $\left(-M\frac{\partial \bar{c}}{\partial t}\right)$ has been added to the denominator of (2.5.2), to take account of storage.

Data Set 4:

Position	Format
1	I 7
8	I 7
15	I 7
22	I 1
23	F 8.3

4.2 Utility Output File

Line 2: Turnover rate

$\frac{M}{\rho_o \tau_F}$ or $\frac{-M}{\rho_o \tau_R}$ $[m^3 s^{-1}]$ F20F

Flushing (τ_F) or Renewal (τ_F) time

[days] F12.3

Time [days] F12.3

Note: The turnover rate is +ve for flushing and -ve for renewal, and is the effective discharge for the exchange of solute with the model sea.

Data Set 1:

Delete indicator in Position 21.

Delete specifications in Positions 26 and 31.

Dimensions are preset at (100, 100). This allocation can be changed in FLOWM by user.

Data Set 2:

Position 66 Format F 5·O

Data Set 3:

Position 76 Format I3

Data Set 4:

Timestep at which ..... Position 61

Data Set 5:

Position 46 Format I5

Data Set 7:

Pollution flux (P) $[kg s^{-1}]$ (Q = O) Position 31

Data Set 11 (Section 9.1)

11.2 Tidal progression

An alternate specification for the tidal forcing has been incorporated, in which it is assumed that the tidal wave is propagating across the boundaries of the model sea from a specified direction (θ°), and during its progression, its amplitude and phase are modulated, by the respective rates, α^* (cm/km), and β^* (°/km).

On the assumption that these rates are small, the appropriate boundary forcing that is applied on the boundary points is,

$$\eta = C_o\cos\frac{2\pi t}{T} + (j_B - j_o)\Delta S[\alpha\sin\gamma_a\cos\frac{2\pi t}{T} + C_o\beta\sin\gamma_g\sin\frac{2\pi t}{T}]$$
$$-(i_B - i_o)\Delta S[\alpha\cos\gamma_a\cos\frac{2\pi t}{T} + C_o\beta\cos\gamma_g\sin\frac{2\pi t}{T}]$$

in which $\gamma_a = 270-\theta_a$, $\gamma_g = 270-\theta_g$ and $\alpha = 10^{-5}\alpha^*$, $\beta = 10^{-5}\beta^*(\pi/180)$, and C_o is the amplitude of the tide at the centre of the model. This equation replaces the FLOWC input specification.

The procedure is implemented in Data Set 2.

Position

41	The rate of modulation of tidal amplitude (α^*)[cm/km]	F7.3
48	The rate of modulation of tidal phase (β^*)[°/km]	F7.3
55	The directions (θ°_a and θ^0_g) from which the tide (amplitude and phase) is progressing (if $\theta_a = 0°$,	
60	the new procedure is not implemented, and 41 and 48 are as	F5.1
	specified in the FLOWC input specification)	F5.1

Appendix U: Amendments to "The FLOWM Model"

7. Limited buoyant discharges

The facility implemented in Data Set 5, allows the effects of continuous discharges of fluid and solute from specified sources to be tracked on the assumption that total mixing of the solute in the water column occurs.

This facility has been extended to incorporate point releases of material, which may also be limited by its buoyancy to disperse in the surface layer of the water column, where it would be influenced by drift currents associated with the wave boundary layer.

7.1 Point releases

This facility assumes that all discharges occur only in a specified time interval.

Data Set 5

Position		
61	Starting time for discharge (hours)	F5.2
66	Finishing time for discharge (hours)	F5.2

If both starting and finishing times are zero, a continuous discharge is assumed.

7.2 Buoyant plumes

Oil and other organic solutes, and also certain organisms, are buoyant, and disperse in a surface layer of thickness (h). The dispersion in this layer is simulated by assuming that the concentration is well mixed vertically within the layer, and that it is zero beneath. If locally $h > H$ the surface layer model transforms into the standard model in which the concentration is uniform throughout the water column.

The thickness (h) can be specified, based on considerations of the buoyancy of the solute, and also the depth of the wave boundary layer (h_w), which acts to mix the solute downwards. The wave boundary layer depth (Bye 1988) is

$$h_w = g/_2 \left(\frac{T_s}{2\pi} \right)^2 \qquad (7.2.1)$$

where T_s is the significant wave period e.g., for $T_s = 3\text{s}$, $h_w = 1.1\text{m}$. It would be expected that this ratio (h/h_w) is controlled by the buoyancy of the solute. A very buoyant solute would be mixed down only a small fraction of h_w, and an almost neutrally buoyant solute would be mixed down over a depth greater than h.

The second important factor is the advection of the solute by the Lagrangian wave drift, which is additional to the non-wave induced currents due to the general and tidal circulation. The wave drift adds a surface water transport which is directed along the local wind direction. The total transport in the surface layer is,

$$\underline{U}_o = \left(\frac{\underline{U}}{H} + \gamma \underline{w}_*\right) h \qquad (7.2.2)$$

where $$\gamma = \frac{1}{\kappa}\left(1 - \ln h / h_w\right) \qquad (7.2.3)$$

in which the drift profile has been assumed to be logarithmic (Bye, 1988), and w_* is the water friction velocity, defined by,

$$\underline{\tau}_s = \rho \left|\underline{w}_*\right| \underline{w}_*$$

in which $\underline{\tau}_s$ is the surface shearing stress, ρ is the water density, and k is von Karman's constant ($k \sim 0.4$). The drift current parameter (γ) can be estimated using (7.2.3). In the natural environment, it is observed that the maximum value of γ is $25\left(\frac{h}{h_w} \sim 10^{-4}\right)$, which is the surface drift speed of small marker particles or dye patches. The minimum value of γ is 0 ($h = 10h_w$) at which the effect of the local drift vanishes. $\gamma = 2.5(1/k)$ corresponds to a solute uniformly distributed in the wave boundary layer.

If a greater value of γ than specified by (7.2.3) for the ambient thicknesses h and h_w is used, this simulates a concentration profile increasing towards the sea surface, whereas a lesser value corresponds with a concentration profile increasing towards the bottom of the surface layer.

The surface layer solute transport equation which replaces (2.1.14) is

$$h\frac{\partial C}{\partial t} + U_o\frac{\partial C}{\partial x} + V_o\frac{\partial C}{\partial y} - \frac{\partial}{\partial x}\left(Kh\frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial y}\left(Kh\frac{\partial C}{\partial y}\right) = -w_e C + \frac{P}{\rho_o A_p} - \lambda h C \qquad (7.2.4)$$

where

$$w_e = \frac{\partial U_o}{\partial x} + \frac{\partial V_o}{\partial y}$$

is the upwelling velocity from beneath the surface layer (in which C = O), and it has been assumed that h is a constant thickness, i.e. the surface layer floats on the deeper water.

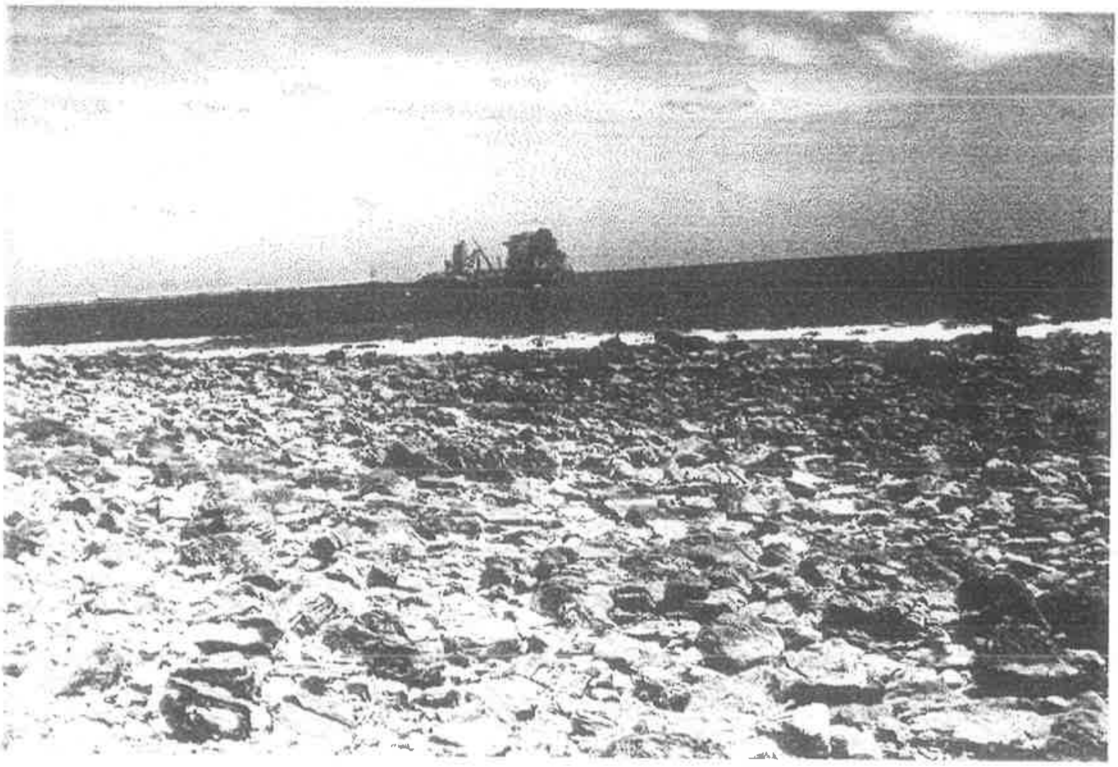
When the surface model is applied, i.e. $h \neq O$, it also assumed that loss of solute with the specified time constant (Data Set 5, Position 26) only occurs at concentration grid points adjacent to the coast. This simulates, for example the grounding of oil or the recruitment of larvae, or possibly the destruction of organisms in the surf zone. In the open water, the solute transport is conservative. The mass (M) of solute removed at a coastal grid point can be computed from the record of an instrument. In each recording time step,

$$M = L\, C^*$$

where C* is the scaled output concentration, L is the loss factor for the instrument, and M is in kg. In the surface layer simulation, the time constant of coastal decay $(\tau = 1/\lambda^*)$, where $\lambda^* = \lambda / b$ in which b is the number of doublings (Data Set 3, Position 51) and b = 2 for expanded resolution (Data Set 3, Position 79), is set proportional to the grid interval. This ensures that the flux/unit length of coastline lost from the solute field is independent of the resolution at the same concentration, i.e. it is independent of b.

Appendix V: Final Report to Mobil.

Recommendations for an Intertidal Monitoring Program at Port Stanvac.



Report for: Mobil's Port Stanvac Oil Refinery
Report by: Leanne Piller
Department of Zoology
University of Adelaide
January 1997

Table of Contents

Acknowledgments

I would like to thank Mobil Oil Australia Pty. Ltd. for financial support for this project which was conducted as part of a Masters Degree in Science at the Department of Zoology, University of Adelaide. I would also like to thank Port Stanvac Oil Refinery personnel for provision of materials and assistance throughout the time I have been working on the "Monitoring Project". I would particularly like to thank Michael Cove for his assistance during the last two years.

I would also like to thank my Academic Supervisors, Alan Butler, Fran Sheldon and Russ Baudinette for their guidance and support. Peter Pfennig, Peter Petrusevics, John Bye, Wendy March and the EPA have also made valued contributions to this report and my thesis. Special thanks to Phil Leppard (Statistics Department, University of Adelaide), for his valued statistical advice.

List of Tables

List of Figures & Plates

Figures

Plates

Appendices

Appendix 1	Map 152 - Kingston Park Study Site
Appendix 2	Map 164 - Marino Rocks Study Site
Appendix 3	Map 176 - Oil Refinery & Hallett Cove Study Sites
Appendix 4	Map 186 - Port Noarlunga South Study Sites
Appendix 5	Map 195 - Robinson Point Study Sites
Appendix 6	Raw abundances of *B. nanum* used for the Beyond-BACI analysis of the sand perturbation.
Appendix 7	Instructions for running GMAV5
Appendix 8	Data sheet for the Port Stanvac Monitoring Program

Attachments

Attachment A	Literature Review of Monitoring Design
Attachment B	Flow chart indicating stages involved in intertidal monitoring for an Oil-Spill Impact

1. Background and Aims

1.1 Background

Mobil's Port Stanvac Oil Refinery receives crude oil for refinement within its plant and exports refined oil and other products. One of the potential problems associated with refinery operation is accidental release of oil into the marine environment. The primary points where accidental spillage can occur are at the "Deep Ocean Point", otherwise known as the buoy, and the "Wharf Point" (refer to Fig. 1). Two cargoes of 100,000 tonnes and one cargo of 150,000 tonnes of crude oil are imported monthly via the "Deep Ocean Point", while 25,000 tonnes of refined fuel oil is exported from this point twice a week. Wharf operation sees exports of 50,000 tonnes of refined fuel oil and 15,000 tonnes of lube oil per month, while twice a year 35,000 tonnes of light oils and other substances are sent from the refinery. Accidental operational spillage of oil could occur from the "Deep Ocean Point", the "Wharf Point", or via the pipeline that feeds into the refinery. In the event of oil entering the ocean as a result of routine loading and unloading of oil product it is likely that it will impact on the rocky intertidal region as it is swept ashore by the action of wave, wind, tides and water currents (both tidal and non-tidal).

The health of the Port Stanvac shoreline and adjacent shores in Gulf St Vincent has not been well documented, and very few ecological studies have been conducted in the region. This is despite the fact that a number of factors (besides an oil spill) potentially impact the Port Stanvac coastline. These include dredging (currently being investigated by the University of Adelaide), the Mitsubishi storm water outfall which gives an intermittent, seasonal discharge of water runoff at close proximity to the northern boundary of the refinery and the E&WS secondary treated sewage discharge from Christies Beach. Mobil also discharges treated refinery effluent towards its northern boundary which is another potential source of pollution to the marine environment requiring consideration. In addition to these potential pollutants, Christies Creek and the Onkaparinga River flow into the coastal waters to the south of Port Stanvac, and northward sand drift in winter and spring can impact on the coastline. The final factor that potentially influences the health of the Port Stanvac coastline arises from the private ownership of the area which partially protects the intertidal animals from the trampling and collection pressure in similar, but publicly accessed, areas.

Mobil is aware that a potential risk of their operation is release of oil into the marine environment. To this end they want a monitoring program in place that will enable an objective assessment of injury (if any) to the coast following an oil spill and its recovery following such an event. In addition, a suitable monitoring program will allow Mobil to have discussions with the EPA concerning the consequences of an oil spill, mount a defence in response to any charges that may arise, and minimise the cost impact of such charges. On a broader level Mobil want to be environmentally aware of the effect of their activities.

1.2 Aims

This project aims to establish the existing (or baseline) condition of the intertidal area at Port Stanvac, and use this as the basis for designing an ongoing monitoring program using suitable biological indicator organisms. The monitoring program must be able to partition variation due to the other pollution sources mentioned above from those attributable to an oil spill. To achieve this aim it is necessary to investigate the temporal and spatial trends seen at various sites within Gulf St Vincent (GSV).

The specific aims of this project are to:

1. Establish the baseline (existing) condition of the intertidal area at Port Stanvac with respect to a suitable indicator organism(s).
2. Design an ongoing monitoring program capable of detecting an oil spill impact and differentiating this from effects associated with confounding factors.
3. Investigate the impact of trampling and collection pressure on animals whose characteristics and ecology suggest a propensity for being affected by such pressures.

The impact of recreational visitation, trampling and collection pressure on animals is a factor which is likely to influence community structure at sites in GSV. However, this will not be discussed in this report.

1.3 The Best Monitoring Design for Port Stanvac

A literature review of monitoring programs used to detect environmental impact (Attachment A) recommended the use of a Beyond-BACI design for the Port Stanvac preliminary monitoring program as well as for the ongoing monitoring program (Underwood 1991, 1992 & 1993). This design involves using at least a single 'impact' site and multiple 'control' sites that are sampled many times before and after an impact occurs. The purpose of this design is to detect whether there are changes at the 'impact' site that are greater than would be expected on average at the 'control' sites. Data collected during the sampling is analysed using an Analysis of Variance (ANOVA) to statistically partition the variance due to such factors as sampling times, locations, and 'before vs after' impact. The Beyond-BACI design will be explained along with a worked example in Section 4 of this report, and a flow chart is provided to indicate the stages that need to be worked through in using a Beyond-BACI design (Attachment B).

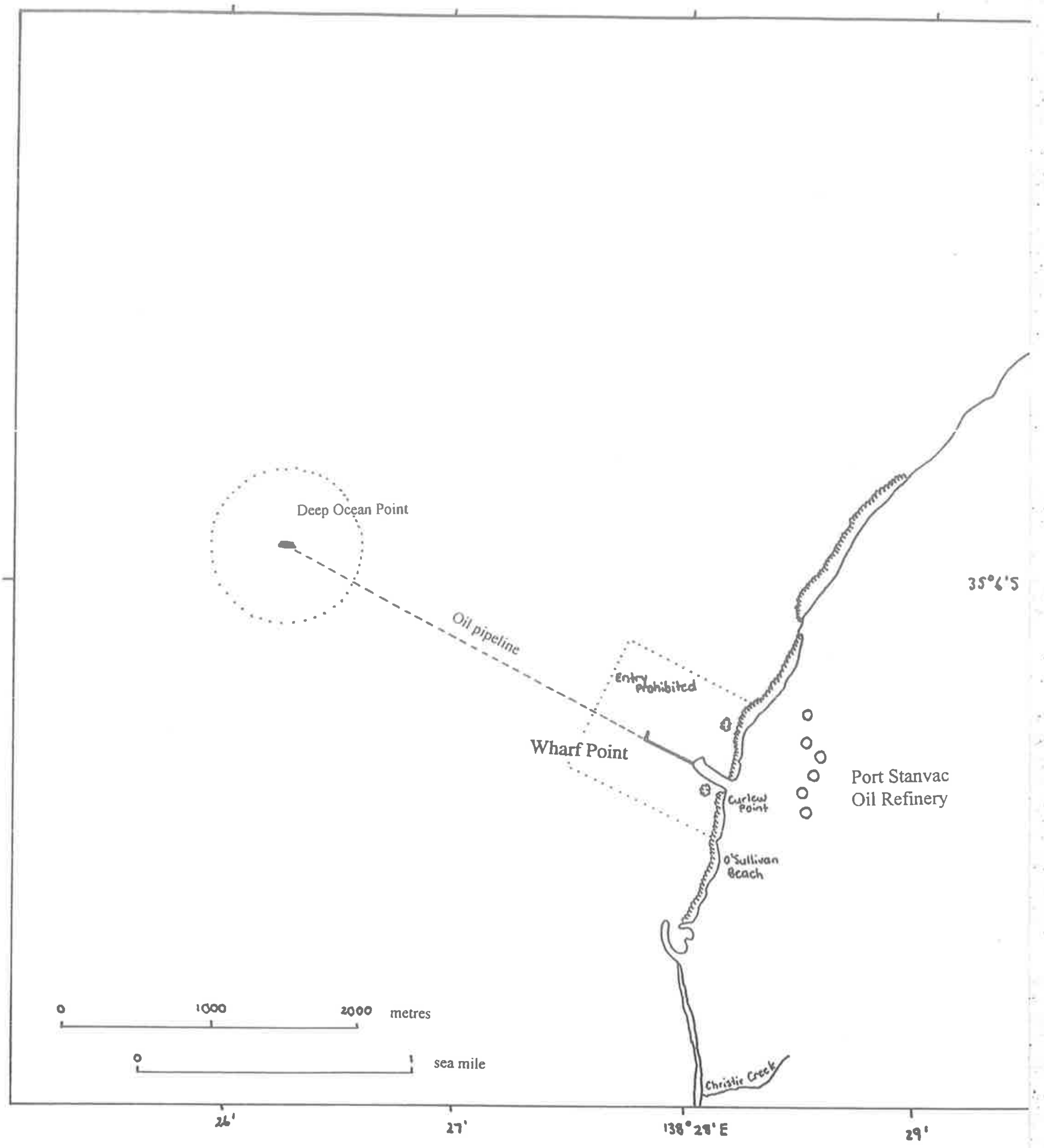


Fig. 1 The Port Stanvac Oil Refinery, indicating the position of the 'Wharf Point' and the 'Deep Ocean Point' where oil is handled, and the submarine pipeline.

2. Preliminary Monitoring of GSV Sites

A number of rocky intertidal sites were visited during the design phase of the ongoing monitoring program to select those suitable for preliminary monitoring and to choose the most appropriate sampling protocols. Nine sites which had similar suites of animals and ease of access, were chosen for ongoing monitoring during 1995 and 1996 (Fig. 2). The preliminary study sites extend from Kingston Park (to the north of Port Stanvac) to Robinson Point (to the south). The history of small (past) oil spills and patterns of circulation within GSV allowed prediction of three potential impact sites within the boundaries of Port Stanvac (designated PS1, PS2 & PS3). Although these sites are potentially impacted by some of the confounding factors mentioned previously, any could serve as an 'impact' site if a perturbation intervened during the preliminary sampling.

All animals and plants visible within quadrats, which were randomly assigned within a site, were censused along with physical parameters such as the presence of oil (subjectively scored on a scale of 0 to 4), substrate composition, topographic complexity, substrate elevation and percentage of retained water. The preliminary study allowed a determination of optimal sampling strategies and natural perturbations (such as the northward sand drift) which can be faced by rocky intertidal animals and which need to be considered in a monitoring program.

At the end of the preliminary monitoring the sites were redefined and where necessary, for example if the original site appeared to be especially susceptible to natural substrate perturbations, new, more stable sites, was selected. The final study sites are described in the next section (Section 3).

The Beyond-BACI design was used for the preliminary monitoring to ensure that in the event of an oil spill or other impact occurring, the effect of the perturbation could be statistically investigated. The preliminary monitoring involved using two specific time scales; 'Periods' which are two to three months apart, within which 'Times', two to three weeks apart, were nested. *Bembicium nanum* was used as the indicator animal for the Beyond-BACI analysis of the sand influx which occurred during the preliminary sampling, for reasons given in Section 5 of this report.

3. Study Sites

Of the nine preliminary study sites, Witton Bluff did not have a suitable suite of animals and was excluded from the final choice of study sites. PS2, PS3, Marino Rocks and Hallett Cove were all redefined due to the potential for repeated sand influx at the latter site, and mobilisation of adjacent boulder and cobble substrate at the other sites. The new sites are believed to be more stable than the sites they replaced and are dominated by the gastropod mollusc *Bembicium nanum* (Fig. 3). One 'zone', ie. one level within the intertidal zone, is to be sampled within each of the designated study sites, and except where otherwise specified, the substrate of interest is predominantly flat bedrock. Where an area is sampled in two directions, random numbers are used to assign the quadrat position by moving the required distance in the first direction, followed by the required distance in the second direction.

Kingston Park (Fig. 2, Plates 1 & 2)

This site is situated at the end of a Service Road which is turned into from Esplanade Road (Appendix 1; Map 152, Ref. E14.5). At the end of the Service Road is a seawall with a cemented lower section. The site to be sampled commences 24m from the start of this seawall and extends a further 11m from this point, and the area is worked towards the south and the west.

The sampled area is located to the south of a small boat ramp and the substrate is predominantly flat bedrock with very little elevation, interspersed by areas of rounded cobble, boulder and pebble that overlie some of the bedrock, and which dominates close to the low tide mark.

Marino (Fig. 2, Plates 3, 4 & 5)

The new Marino site is located to the south of Kingston Park, and is further north than the original Marino Rocks study site. It is accessed from a carpark at the end of Jervois Road (Appendix 2, Map 164, Ref. D0.5). A large square rock formation in the cliff landward of the sampled area is located 41.9m from the start of the concrete section of the boat ramp on the beach. From this rock a distance of 21.8m is measured to locate the start of the sampled area, which extends a further 4.8m west. The area is worked to the west and the south and sampling is in the lower, flatter bedrock interspersed between the more upthrust grey and slightly eroded rocks.

Hallett Cove (Fig. 2, Plates 6 & 7)

This site was redefined following the preliminary study. It is situated past the Surf Life Saving Club at Herron Way, adjacent to the car park that is entered from Grand Central Ave. (Appendix 3, Map 175, Ref. Q1). Sampling can commence 33m from the base of the ramp that allows entry to the beach, and can continue for a further 16m from this point. The sampled area is predominantly a cobble and boulder field with entrapped sand, and is directly to the south of the original Hallett Cove site. The area is worked to the west and south of the starting position.

Port Stanvac Study Sites (Figs 1 & 2)

The refinery is entered via Refinery Road (Appendix 3, Map 175, Ref. N15). All Port Stanvac sites are accessed by car via the coastal track within the refinery. A compulsory Safety Test needs to be done prior to working at the refinery, and a permit obtained to allow vehicle entry into the plant.

The beach within the boundary of the Port Stanvac Oil Refinery is predominantly rocky, with flat bedrock interspersed by heavily upthrust bedrock and in some areas being overlain by large amounts of mobile substrate. Topographically this substrate is the most complex and varied of all the substrate seen at study sites.

PS1 (Fig. 2, Plates 8, 9 & 10)

This site is reached at the end of the coastal refinery road and is the most northerly site. The actual area to be sampled begins at a point 30m to the south of the join on the effluent discharge pipe, and 7m to the west . The sampled area extends a further 15m west of this point and is worked in a west and south direction. The substrate is predominantly flat bedrock with occasional upthrust sections and interspersed areas of cobble and boulder.

PS2 (Fig. 2, Plates 11, 12 & 13)

This site is accessed from the coastal refinery road and is reached before PS1. To locate the site a distance of 48m to the west of survey peg no. 302 (the second blue surveyor's peg to the north of a large rock column) is measured, and an area of obvious upthrust rock located. The sampled area is situated 7m to the west of this point and consists of flatter bedrock strata which extends for approximately 30m. Another region of flat bedrock strata is found to the west, but the most easterly strata is the one which is worked on, with sampling remaining within this substrate and continuing in a southerly direction.

PS3 (Fig. 2, Plates 14 & 15)

This site is situated to the south of the Port Stanvac wharf. It begins 71m south of the rocks at the base of the southern side of the wharf, in line with the third light pole. It is also approximately 56m west of a large grey man-made boulder situated at the edge of the sand. The substrate is a flat bedrock strata which runs from north to south and is wider in its southern dimension. The area is worked to the west and south along the strata.

Port Noarlunga South (Fig. 2, Plates 16, 17 & 18)

This site is some distance from the Port Stanvac sites (see Appendix 4) and is entered from Esplanade Road beyond the Onkaparinga River. It is on the southern side of Onkaparinga Head, to the north of a Trig Point which is located in a car park (Appendix 5, Map 195, Ref. E12). The site is reached via a path from the car park, and the reef to be sampled is the last one north of the path immediately adjacent to deep water.

Sampling begins 24m to the west of an eroded hole in the centre of a small cliff landward of the intertidal reef and extends a further 18m from this point. The centre of the reef is worked in a west and south direction. This site consists of stable substrate which has large eroded holes which tend to retain water and form small rock pools.

Robinson Point (Fig. 2, Plates 19 & 20)

This site is further south of the previous one and is reached from Esplanade Road. The car park adjacent to bus stop 84 is entered, and the site accessed via stairs to the beach (Appendix 5, Map 195). The reef being sampled is the first to the south of the stairs. Sampling begins 68.5m from the base of the cliff, extending a further 26m from this point. Robinson Point consists of a relatively homogeneous substrate of embedded boulder and cobble stabilised in sand. As such it is a relatively stable substrate, made even more so by the sheltered aspect of the reef. For these reasons it is considered to be equivalent to sites with cemented bedrock substrate in terms of its substrate. It is low-lying and is difficult to access at times.

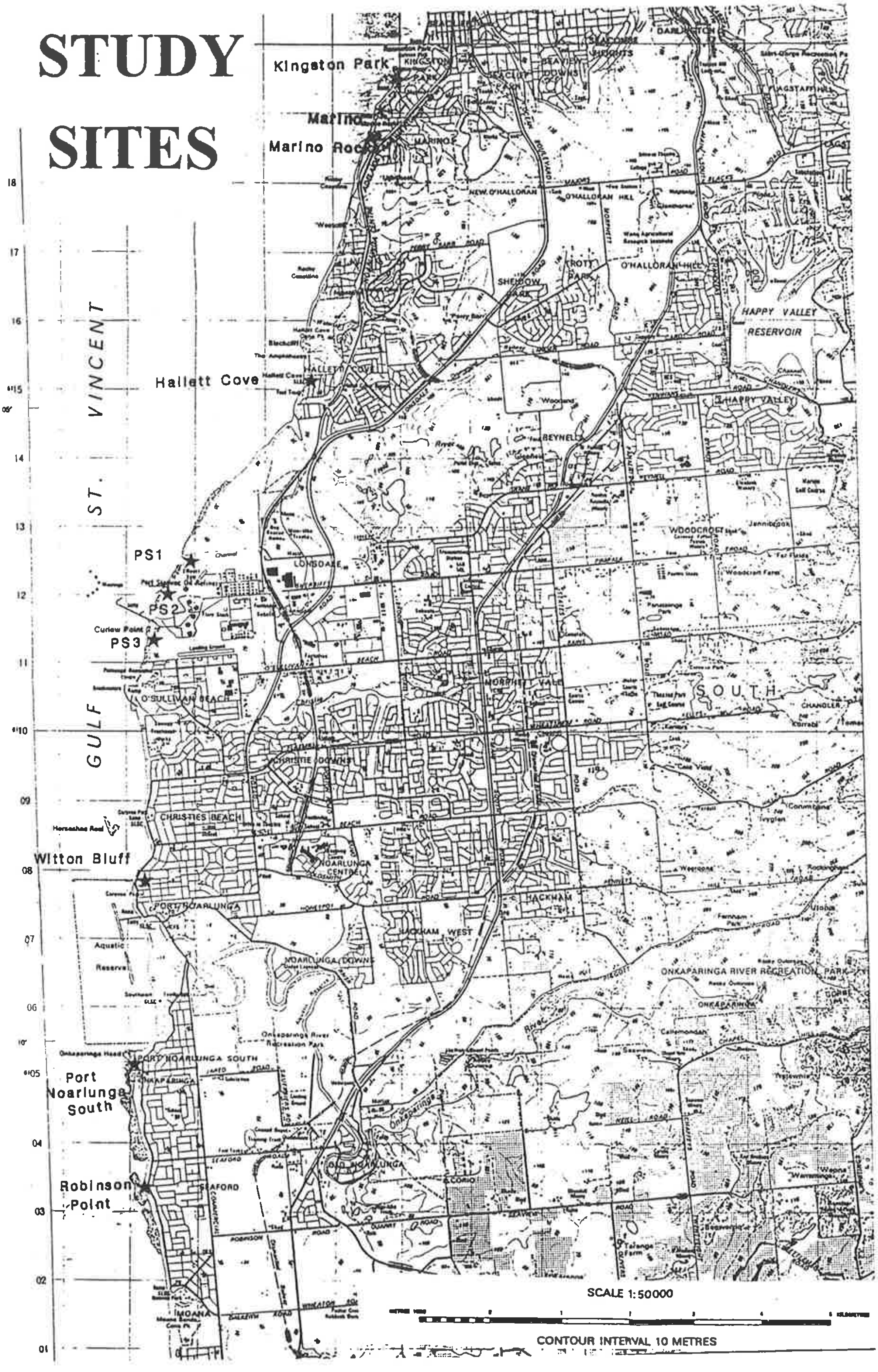


Fig. 2 The position of study sites along the eastern coast of Gulf St Vincent.

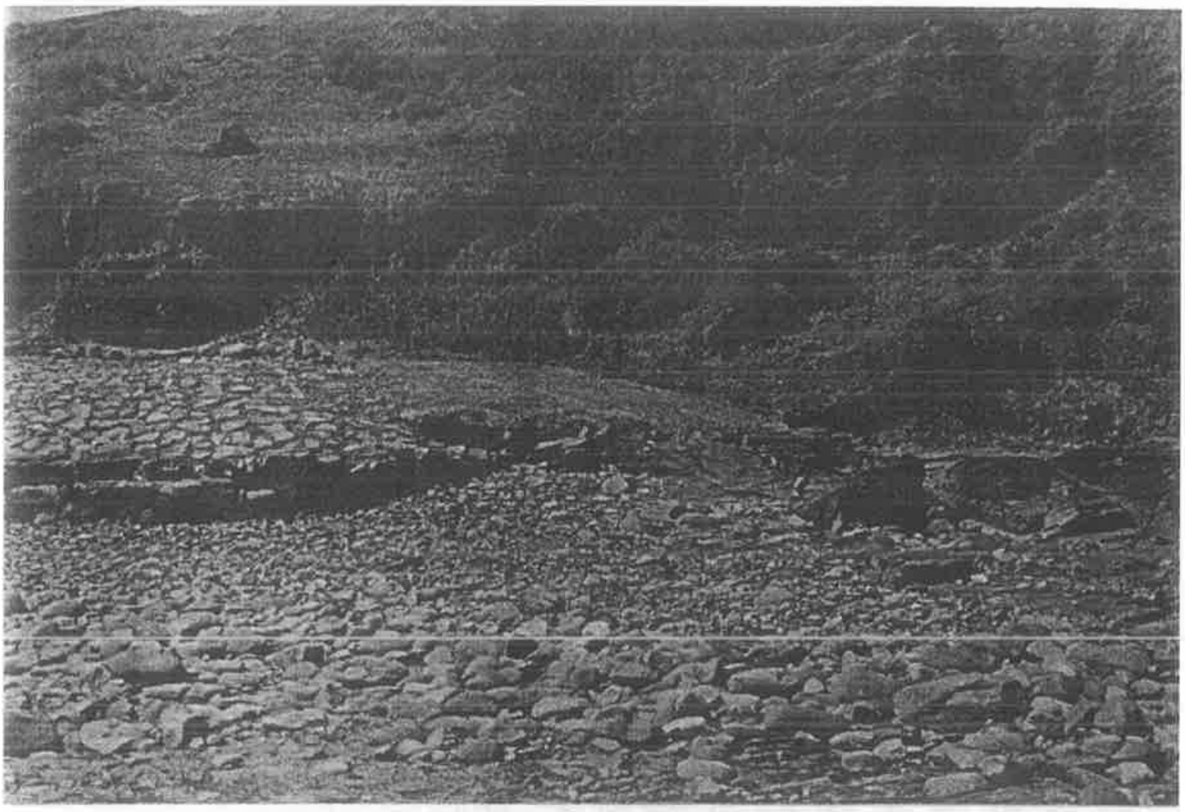


Plate 1. The Kingston Park study site is reached from a Service Road. At the base of the ramp is the man-made seawall used to locate the area to be sampled.

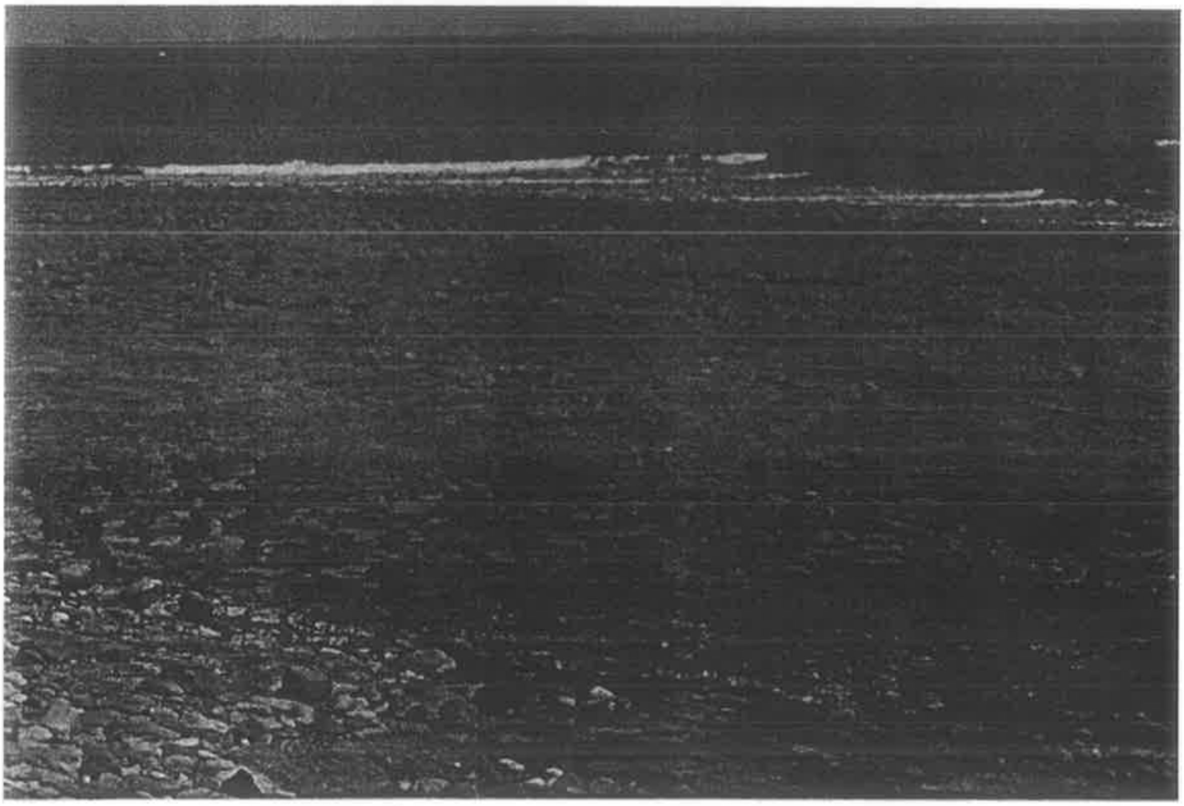


Plate 2. The area sampled at the Kingston Park study site. The study region extends from just beyond the darker bedrock in the foreground and stops before the cobble is reached.

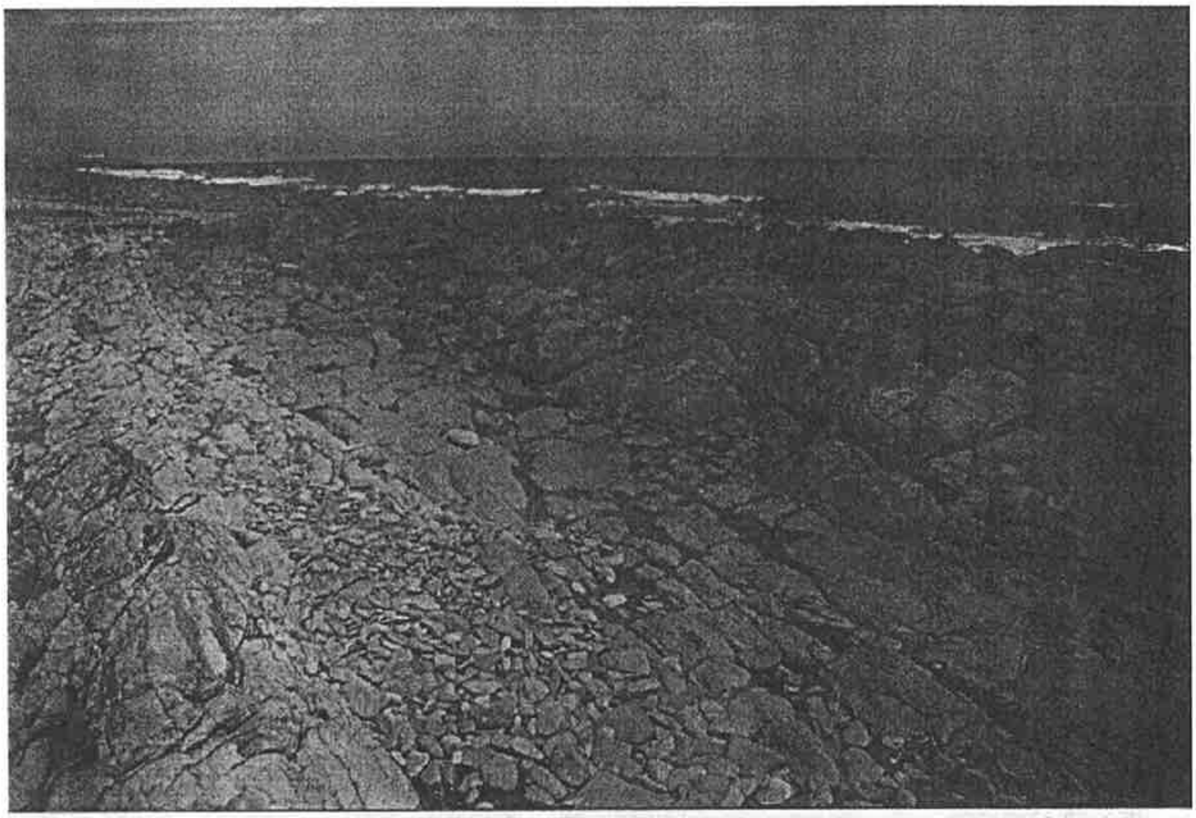


Plate 3. The Marino study site is located to the north of the boat ramp from which this photo was taken.

Plate 4. The sampled substrate at Marino begins where the person is standing.

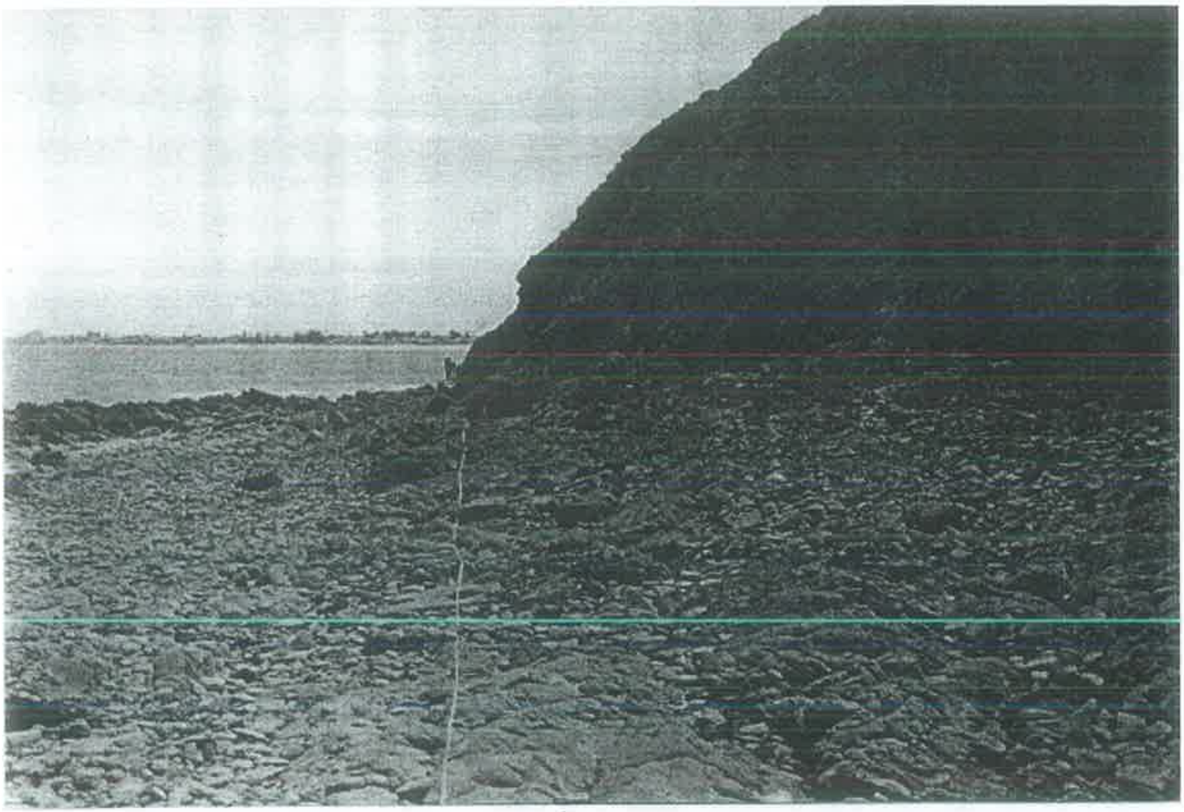


Plate 5. At Marino the substrate sampled is the flatter regions of bedrock occurring amongst more elevated bedrock. The sampled substrate lies to the seaward side of the paler strata.

Plate 6. The Hallett Cove site is located in the cobble and boulder field directly in front of the base of the ramp shown in the background.

Plate 7. The tape marks the beginning of the sampled region in the cobble and boulder field at Hallett Cove. The original study site used in the preliminary sampling is shown to the right of the new site and was prone to sand influx. This original site served as the 'impact' site in the Beyond-BACI analysis of the sand perturbation during preliminary sampling.

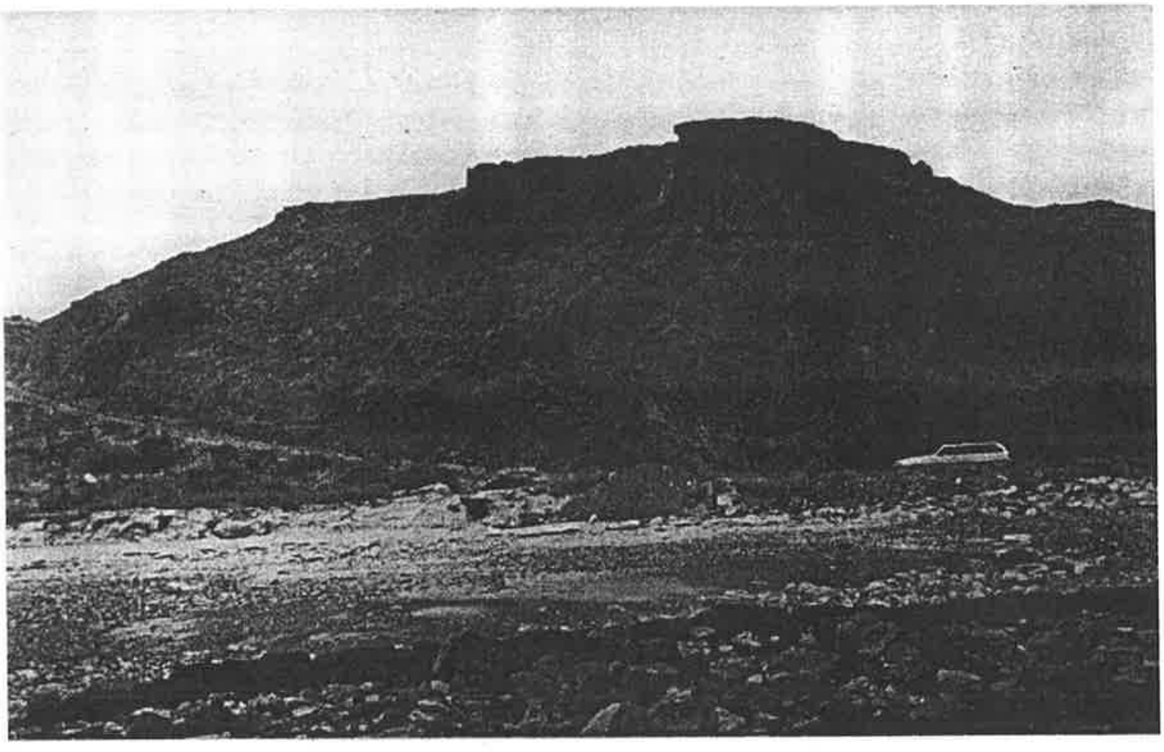


Plate 8. Location of the PS1 site is via the coastal track at the refinery. The car is parked at the southern end of the track, adjacent to PS1.

Plate 9. The refinery effluent pipe runs across the intertidal region south of PS1. The pipe join from which measurements are made to locate the start of this site is just in front of the cement box. The large pipe on the cliff in the background discharges runoff from the Mitsubishi Manufacturing Plant.

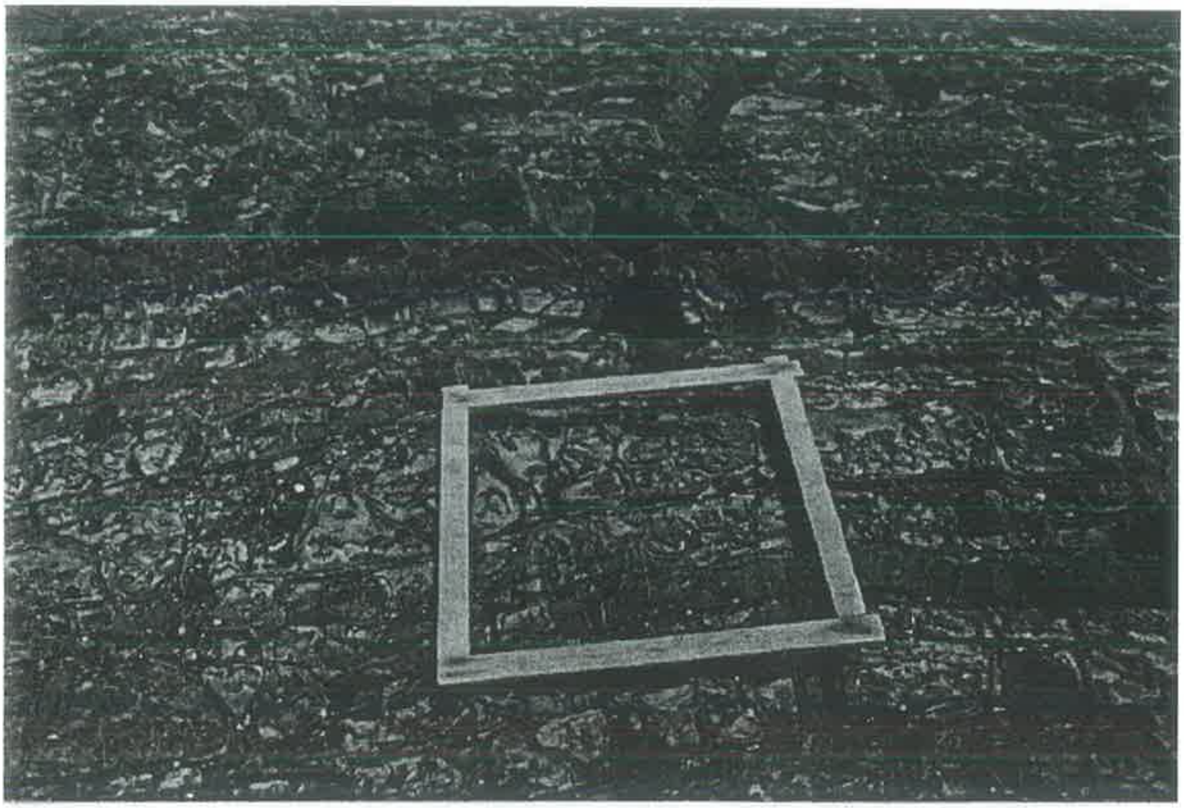


Plate 10. The wooden 0.25m^2 quadrat in position at the PS1 site. The substrate is predominantly stable bedrock with fissures and small eroded holes. The small molluscs present as brown specks on the rock are mainly *Bembicium nanum*.

Plate 11. This photo was taken facing east from PS2, the central study site within the refinery. This site is located using a surveyor's peg which is to the right of the boulder positioned at almost road level to the left of the car.

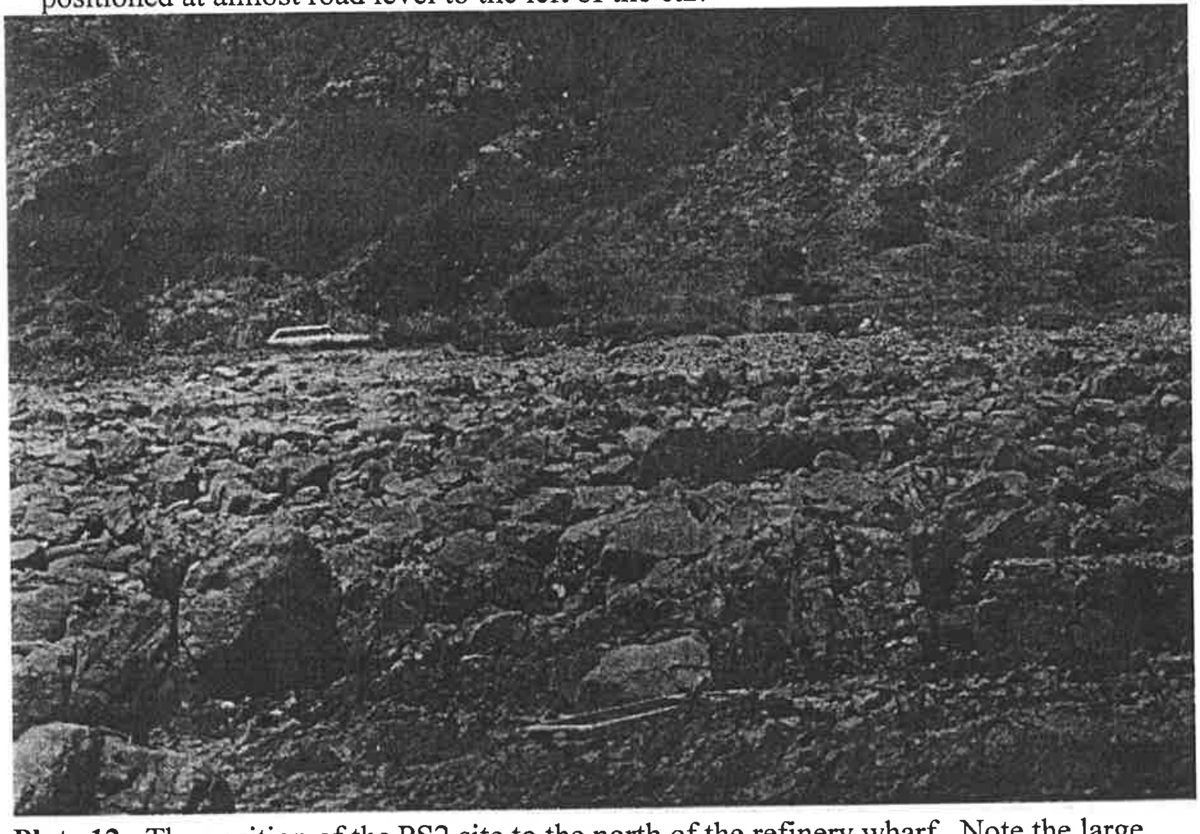


Plate 12. The position of the PS2 site to the north of the refinery wharf. Note the large amount of mobile boulder and cobble substrate close to the sampling area.

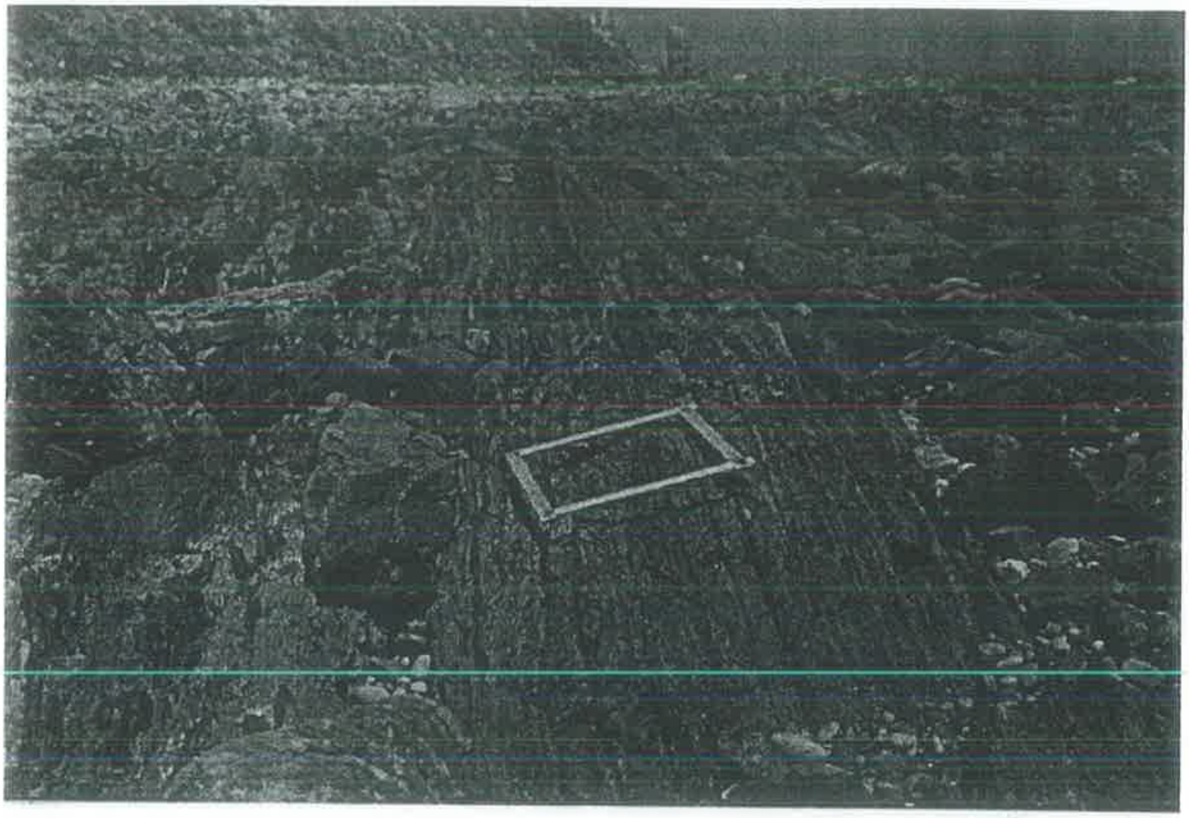


Plate 13. This photo was taken facing south along the bedrock strata that is sampled at PS2. Sampling at this site proceeds within the confines of the strata and is not carried out on adjacent mobile rock.

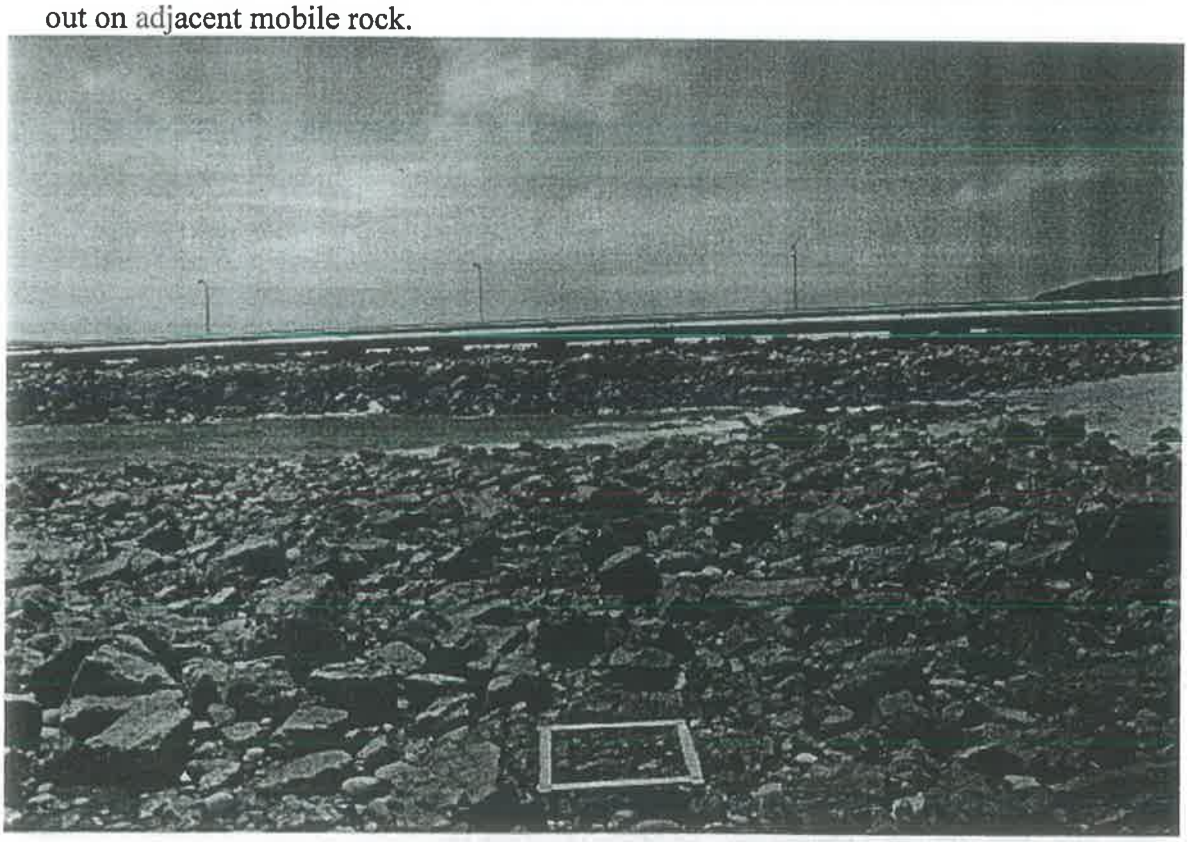


Plate 14. The PS3 site lies to the south of the refinery wharf and ship-to-shore pipeline. The quadrat in the foreground of this plate is positioned on the bedrock strata which is sampled at this site.

Plate 15. This plate again shows the PS3 study site with the quadrat in position. This time the area is viewed from the shore facing the sea (west).

Plate 16. The landward natural seawall used to locate the area to be sampled at the Port Noarlunga South site.

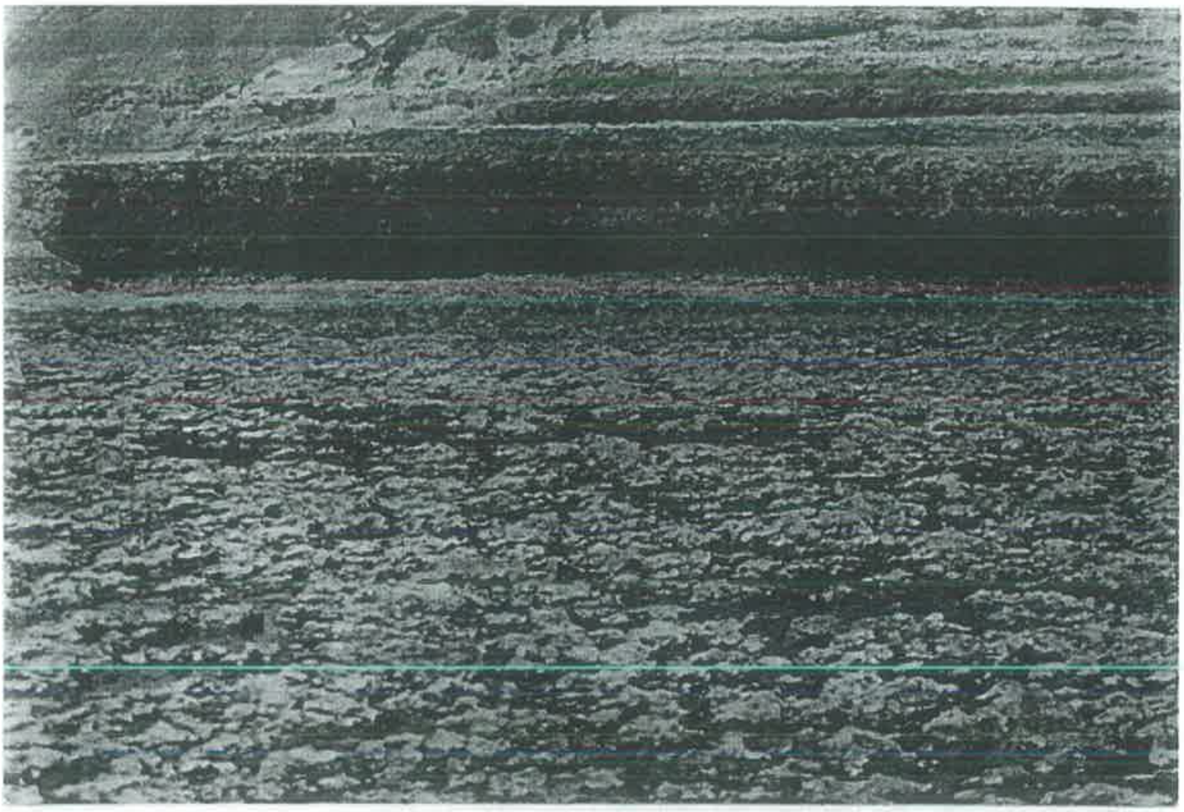


Plate 17. A distant view of the seawall that lies to the east of the Port Noarlunga South site. The area that is sampled at this site is shown in the foreground.

Plate 18. The Port Noarlunga South site is a low-lying reef which has formed from bedrock which has been eroded by constant wave action to form some quite deep holes.

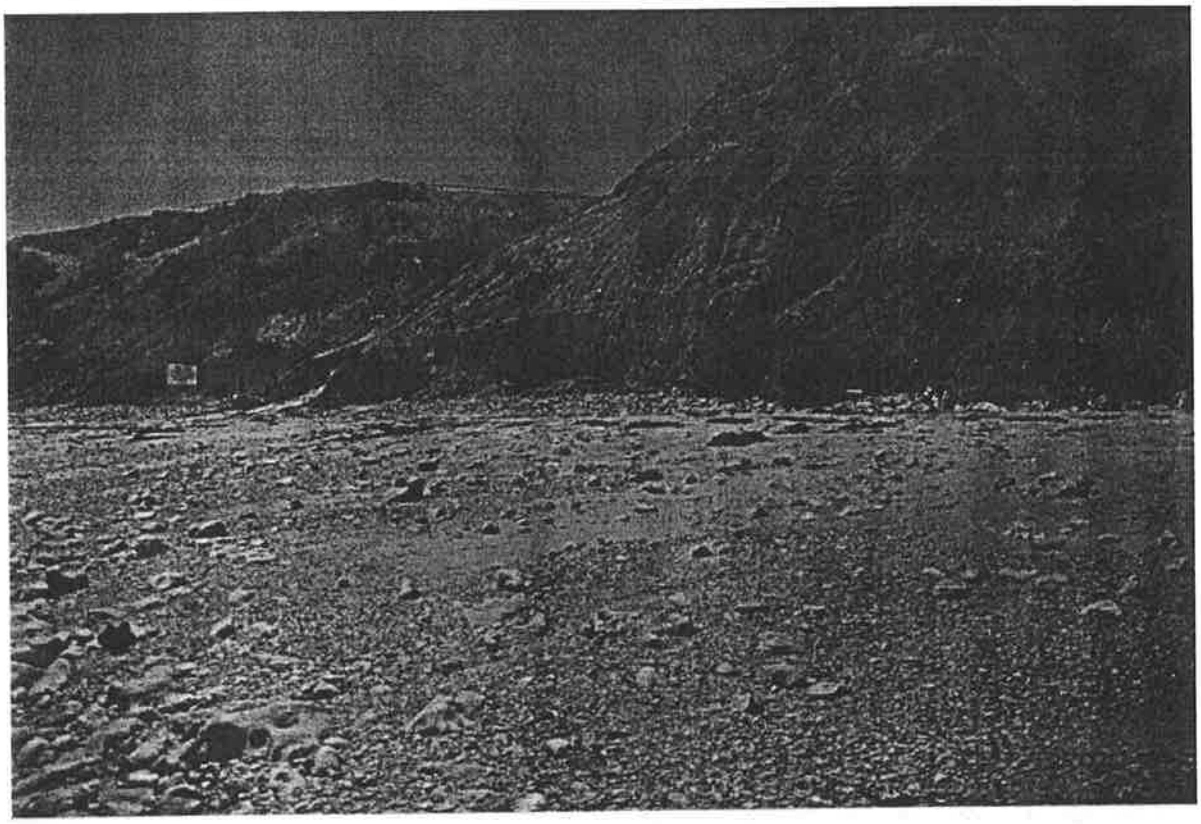


Plate 19. The access path to the Robinson Point site is shown. The area to be sampled is a reef that lies to the south of the stairs. A stormwater outfall discharges runoff to the north of this site under high rainfall conditions.

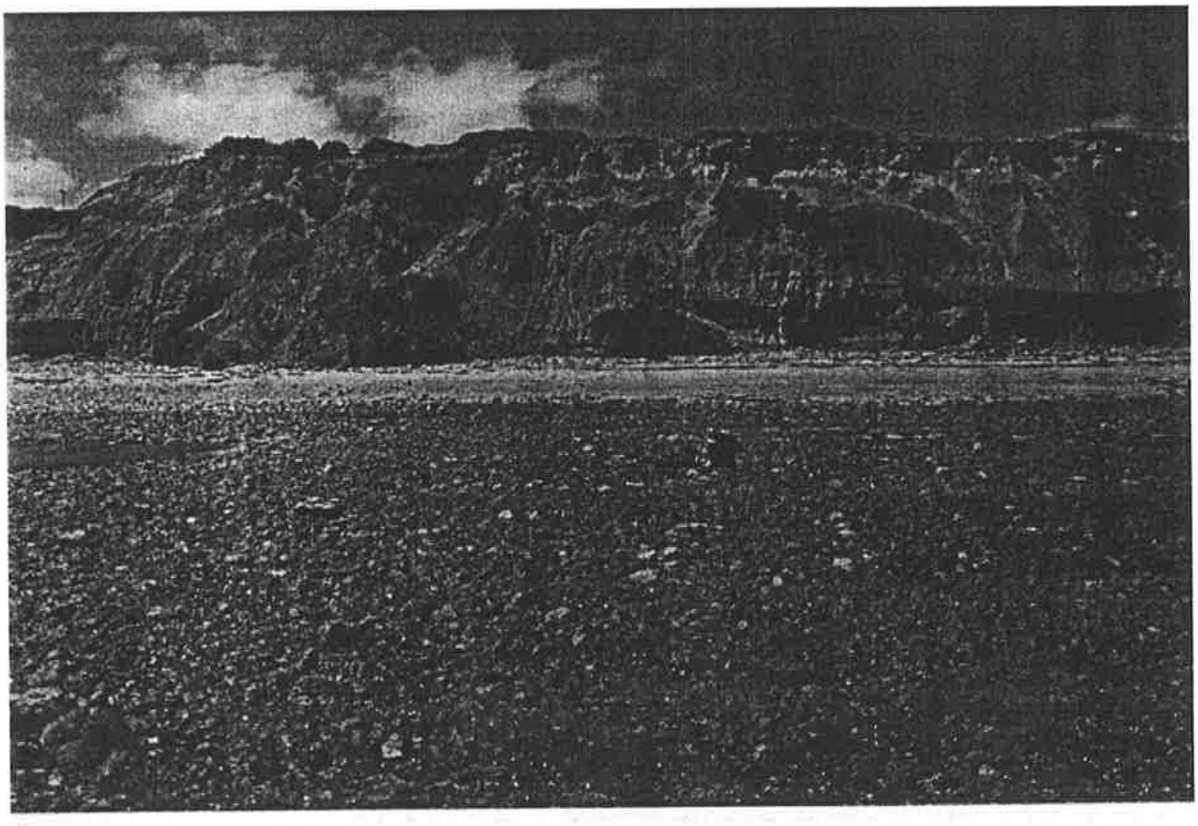


Plate 20. The sampled area at the Robinson Point site is predominantly embedded cobble secured by sand and mussels which affords relative stability.

4. Beyond-BACI

4.1 Beyond-BACI Design

A Beyond-BACI monitoring design involves the use of multiple control sites which can be compared to one or more impact sites over time (as a temporal sampling series). All sites are monitored for some time before and after an impact occurs. Although biological variables fluctuate at all sites all the time, it is expected that an impact will cause a temporal change in the disturbed location that will be different from the average change expected in the unimpacted control locations. The analysis involves using a series of statistical tests to determine whether an unusual pattern of temporal change is specific to the impact site(s) and coincident with the onset of the disturbance.

The two temporal scales of interest in the preliminary sampling program were weeks and months. The two temporal scales allow a determination of shorter-term and more persistent longer term changes at an impact site subsequent to a perturbation. In addition, change can be investigated at the scale of 'Before/After'.

The sampling protocol adopted two main temporal scales; 'Times' two to three weeks apart nested in sampling 'Periods' which were two to three months apart. Within each of these temporal scales actual sampling times were randomly chosen from the days when tidal conditions allowed site access, and all sites at each time were sampled as close as possible to the same day. Sampling continued according to this regime for 15 months, but when a disturbance occurred the post-impact sampling commenced immediately, with sampling continuing at the same intervals as the pre-impact sampling. The sampling protocol is illustrated in Table 1.

Table 1. The sampling schedule used in the preliminary sampling. In this instance two sampling periods were completed before the sand perturbation intervened. Periods are 2 to 3 months apart and times are 2 to 3 weeks apart.

Before Impact				**After Impact**			
Period 1		Period 2		Period 3		Period 4	
Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2

During the preliminary sampling the northward sand drift affected the Hallett Cove site but did not appear to affect other control sites. Therefore, a Beyond-BACI analysis was performed using Hallett Cove as an 'impact' site and five other sites as 'controls' (see Appendix 6). The general design used for the Beyond-BACI sand perturbation and the main factors involved are shown in Table 2.

Table 2. Main Factors and levels used in the Beyond-BACI Design for the 'sand-impact' analysis.

Factor	General Design	"Sand-Impact" Number of levels
1	**Before vs After (B)** orthogonal and fixed	2
2	**Periods (P)** nested in B, random	2
3	**Times (T)** nested in B and P, random	2
4	**Locations (L)** orthogonal and fixed	6

4.2 Beyond-BACI Analysis

The only animal present in sufficient numbers at the majority of study sites and suitable for use as a biological variable for the preliminary Beyond-BACI analysis was *Bembicium nanum* (Fig. 3). The total abundance of this animal at relevant study sites for the two periods before the sand influx and the two post-impact periods was used in the Beyond-BACI analysis of the 'sand' perturbation (Appendix 6).

Data were entered in the GMAV5 Program produced by Underwood (see Appendix 7). GMAV5 is a five factor analysis of variance program capable of dealing with complex models comprised of orthogonal or nested, fixed or random factors. It also tests heterogeneity of variances using Cochran's test and compares means using Student-Newman-Keuls tests (see Zar 1984). The GMAV5 package was used to analyse the sand perturbation data as described by Underwood (1993).

To calculate the appropriate ANOVA terms, four separate analyses are performed (see Table 3). The data are first analysed with all the locations considered as a set with no division of control and impact sites (Analysis a). Data are then reanalysed without the 'impact' site (Analysis b). Next, in order to manage the nested factor of 'Times' within 'Before and After', only the data from 'Before' are analysed (Analysis c). The final analysis uses the 'Before' data, but this time omits the 'impact' site from the analysis (Analysis d). From these four analyses the final variances can be obtained using subtractions and additions of the variance components generated (Table 3) as described in Underwood (1993) and shown in Table 4.

Bembicium nanum

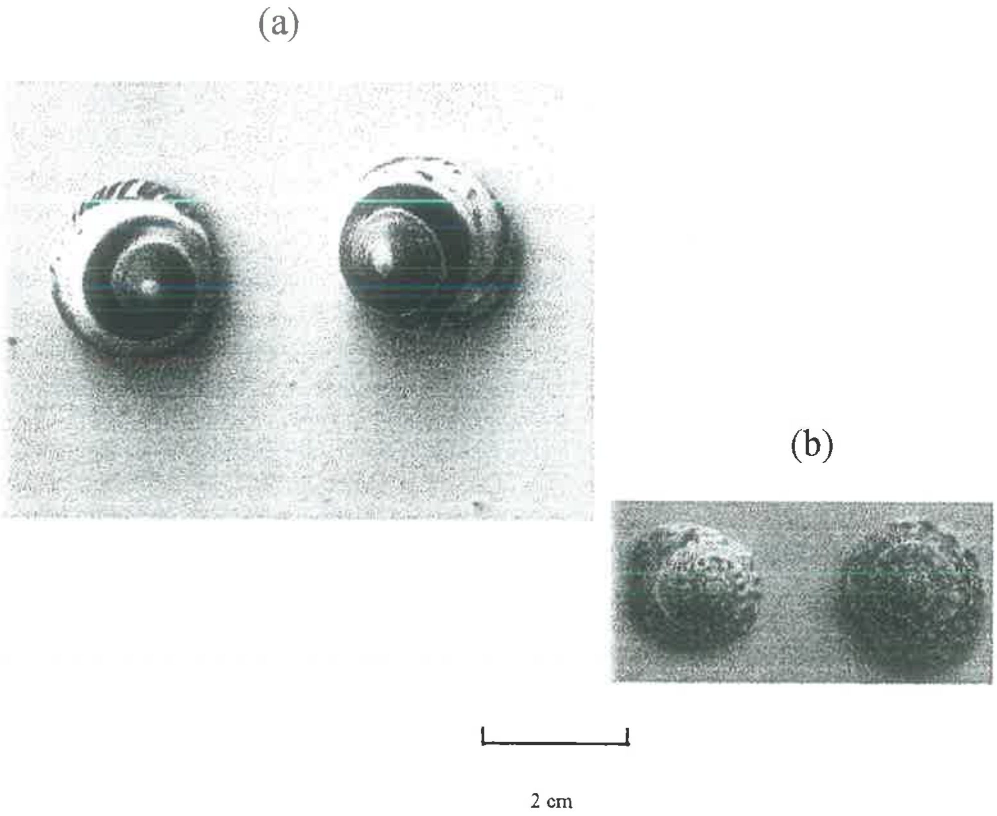


Fig. 3 The gastropod chosen as an indicator of change for the long-term intertidal monitoring program. (a) Shows large specimens with bright colouration. (b) Shows the duller appearance more typical of this animal at the majority of study sites.

Table 3. Calculation of analyses of impact in a Beyond-BACI design (After Underwood 1993). SS= sum of squares, df= degrees of freedom.

Analysis	**a (all data)**	**b (controls)**	**c (before)**	**d (before controls)**
Source of Variation	SS & df	SS & df	SS & df	SS & df
Before *vs* After = B			-	-
Periods = P(B)				
Times = T(P*B)				
Locations = L	a1	b1		
B x L	a2	b2	-	-
P(B) x L	a3	b3	c1	d1
T(P*B) x L	a4	b4	c2	d2
Residual				
Residual	a			
Total				

Table 4. Calculation of final variances in a Beyond-BACI design following an impact. Final values are calculated using preliminary analyses shown in Table 3 (After Underwood 1993). SS=sum of squares, df= degrees of freedom.

Source of variation	**SS**	**df**	**MS**	**Calculated from**
Before *vs* After = B				a
Periods (P) = P(B)				a
Times (B) = T(B)				a
Locations = L				a1
Impact *vs* Controls = I				a1-b1
Among Controls = C				b1
B x L				a2
B x I				a2-b2
B x C				b2
P(B) x L				a3
P(Bef) x L				c1
P(Bef) x I				c1-d1
P(Bef) x C				d1
P(Aft) x L				a3-c1
P(aft) x I				a3-c1-b3+d1
P(Aft) x C				b3-d1
T(B*P) x L				a4
T(Bef) x L				c2
T(Bef) x I				c2-d2
T(Bef) x C				d2
T(Aft) x L				a4-c2
T(Aft) x I				a4-c2-b4+d2
T(Aft) x C				b4-d2
Residual				a
Total				a

The final variances obtained are then subjected to statistical tests (Table 5) to see if there are significant differences between the impact and control sites at different temporal scales, and if these differences are coincident with the impact in question (as described fully in Underwood 1993).

Table 5. The sequence of statistical tests used in a Beyond-BACI analysis to test for significant environmental impacts at a range of temporal scales (After Underwood 1993).

---

1. Test for interaction among times (T) of sampling that differ between Impacted vs Control locations.

1a	No short term interaction among controls; T(aft)xC/Res is not significant, T(aft)xC is eliminated, go to 1b1. Short-term temporal interaction among controls; T(aft)xC/Res is significant, go to 1b2.
1b	**1.** T(aft)xI/Res not significant: no short-term interaction, go to 2. T(aft)xI/Res significant: go to 1c. **2.** T(aft)xI/T(aft)xC not significant: no short-term interaction: NO IMPACT DETECTED; END. T(aft)xI/T(aft)xC significant: go to 1c.
1c.	Two-tailed tests: T(Aft)xI/T(Bef)xC is significant and T(Aft)xC/T(Bef)xC is not. Therefore effect is specific to impact site and coincident with start of perturbation. IMPACT DETECTED. Two-tailed tests: either T(Aft)xI/T(Bef)xC is not significant or T(Aft)xC/T(Bef)xC is significant. Effect non-specific. NO IMPACT DETECTED; END.

2. Test for interaction among periods (P) of sampling that differ between Impacted vs Control locations.

2a	No medium-term temporal interaction among controls: P(aft)xC/Res is not significant, P(aft)xC is eliminated go to 2b1. Medium-term temporal interaction among controls; P(aft)xC/Res is significant, go to 2b2.
2b	**1.** P(aft)xI/Res not significant: no medium-term interaction, go to 3. P(aft)xI/Res significant: go to 2c.
2b	**2.** P(aft)xI/P(aft)xC not significant: no medium-term interaction: NO IMPACT DETECTED; END. P(aft)xI/P(aft)xC significant: go to 2c.
2c	Two-tailed tests: P(Aft)xI/P(Bef)xC is significant and P(Aft)xC/ P(Bef)xC is not. Therefore effect is specific to impact site and coincident with start of perturbation. IMPACT DETECTED. Two-tailed tests: either P(Aft)xI/P(Bef)xC is not significant or P(Aft)xC/P(Bef)xC is significant. Effect non-specific. NO IMPACT DETECTED; END.

3. Test for longer-term interactions that differ between Impacted vs Control locations.

3a	No Before/After interaction that differs between I and C locations; BxC/Res not significant and is eliminated, go to 3a1. Before/After interaction among controls; BxC/Res is significant, go to 3a2.
3a	**1.** BxI/Res is significant: IMPACT DETECTED. BxI/Res is not significant: NO IMPACT DETECTED.
3a	**2.** BxI/BxC is significant: IMPACT DETECTED. BxI/BxC is not significant: NO IMPACT DETECTED.

4.3 The 'Sand' Impact, a Worked Example

The abundance of *B. nanum* for two periods i) before and ii) after the sand influx at Hallett Cove was used as the variable of interest in a Beyond-BACI analysis (Appendix 6). A comparison of the substrate composition at control sites and the Hallett Cove site during this time, clearly shows an increase in sand at the impacted site of more than 95% immediately post-impact, at P3T1 (Fig. 4).

A preliminary analysis (using GMAV5) revealed that variances were heterogeneous even after a number of transformations were tried (Cochran's C= 0.0991 $P<0.05$). In general the data were normally distributed (tested using the Anderson-Darling statistic and the Student-Newman-Keuls test). After transformation, however, all groupings were not normally distributed, 6 data sets remained above the Anderson-Darling critical level (at $P=0.05$) of 0.652. Despite the fact that two assumptions of ANOVA were violated the analysis was undertaken using $\log_{10}(n+1)$ transformed data as sample sizes were equal, and extreme heterogeneity of variances was not displayed. Data were initially entered into Microsoft Excel and then saved as a *.csv (comma-separated-value) file for input into GMAV5 (refer to Appendix 7).

The analyses were conducted as described by Underwood (1993), using Tables 3 and 4 above. The raw results of the four analyses produced using GMAV5 (Table 6) were used to generate the final ANOVA table (Table 7).

Table 6. Calculation of analyses of impact in an asymmetrical Beyond-BACI design using the 'sand-impact' data set (After Underwood 1993). SS= sum of squares, df= degrees of freedom.

Analysis	**a (all data)**		**b (controls)**		**c (before)**		**d (before controls)**	
Source of Variation	SS	df	SS	df	SS	df	SS	df
Before *vs* After = B	40.53	1	0.73	1	-	-	-	-
Periods = P(B)	7.41	2	7.10	2	6.19	1	7.09	1
Times = T(P*B)	4.01	4	3.96	4	2.03	2	2.76	2
Locations = L	166.30	5	153.71	4	62.65	3	25.76	4
B x L	178.76	5	31.44	4	-	-	-	-
P(B) x L	16.87	10	14.23	8	11.00	5	10.58	4
T(P*B) x L	36.88	20	20.78	16	14.12	10	10.64	8
Residual	97.14	288	73.24	240	44.41	144	37.45	120
Total	547.89	335	305.18	279	141.11	167	94.28	139

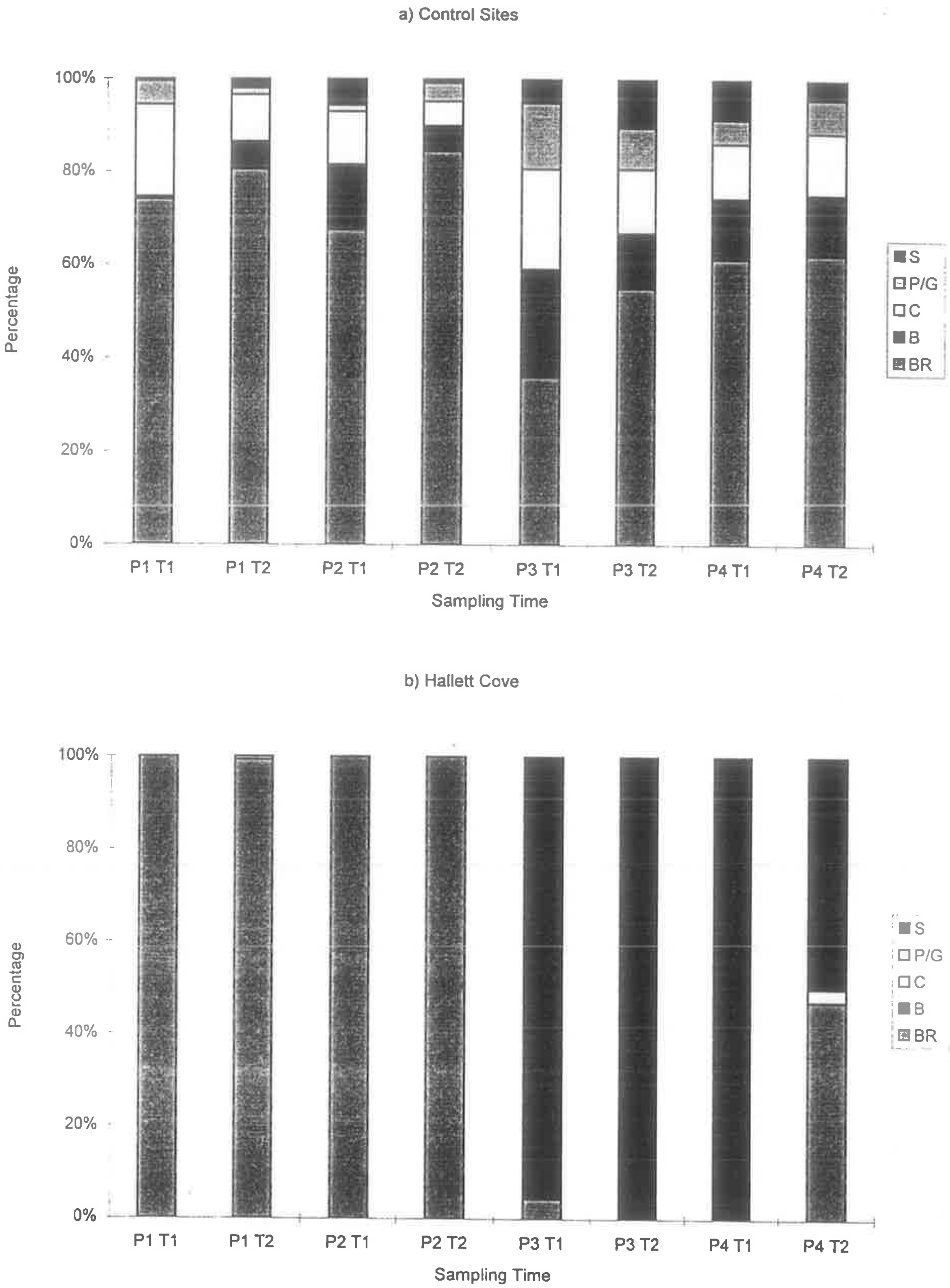


Fig. 4 Comparison of substrate composition between control sites (averaged) and Hallett Cove during 1995. BR=bed rock or reef rock, B=boulder, C=cobble, P/G= pebble or gravel, S=sand.

Table 7. Calculation of final variances in a Beyond-BACI design following the sand perturbation at Hallett Cove. Final values are calculated using preliminary analyses shown in Table 6 (After Underwood 1993). SS= sum of squares, df= degrees of freedom

Source of variation	SS	df	MS	Calculated from
Before *vs* After = B	40.53	1	40.53	a
Periods (P) = P(B)	7.41	2	3.71	a
Times (B) = T(B)	4.01	4	1.00	a
Locations = L	166.30	5	33.26	a1
Impact *vs* Controls = I	12.59	1	12.59	a1-b1
Among Controls = C	153.71	4	38.43	b1
B x L	178.76	5	35.75	a2
B x I	147.32	1	147.32	a2-b2
B x C	31.44	4	7.86	b2
P(B) x L	16.87	10	1.69	a3
P(Bef) x L	11.00	5	2.20	c1
P(Bef) x I	0.42	1	0.42	c1-d1
P(Bef) x C	10.58	4	2.65	d1
P(Aft) x L	5.88	5	1.18	a3-c1
P(aft) x I	2.23	1	2.23	a3-c1-b3+d1
P(Aft) x C	3.65	4	0.91	b3-d1
T(B*P) x L	36.88	20	1.84	a4
T(Bef) x L	14.11	10	1.41	c2
T(Bef) x I	3.47	2	1.74	c2-d2
T(Bef) x C	10.64	8	1.33	d2
T(Aft) x L	22.77	10	2.28	a4-c2
T(Aft) x I	12.63	2	6.32	a4-c2-b4+d2
T(Aft) x C	10.14	8	1.27	b4-d2
Residual	97.14	288	0.34	a
Total	547.89	335		a

The variances in Table 7 were then used to calculate the significance of the treatments of interest as described in Underwood (1993) and shown in Table 5;

1. Test for an interaction among 'Times' that differs between impact and control locations:

T(Aft) x C / Res = 3.76, $F_{crit(1)0.05,8,288} = 1.97$ ($P<0.005$). Significant short term temporal interaction between controls.

T(Aft) x I / T(Aft)x C = 4.98, $F_{crit(1)0.05,2,8} = 4.46$ ($0.025<P<0.05$). Significant short term interaction.

T(Aft) x I / T(Bef) x I = 3.64, $F_{crit(2)0.05,2,2} = 39$, ($0.20<P<0.50$). Non-significant effect, so effect is not specific to the "impact" location. <u>No impact detected at the temporal scale of 'Times'</u>.

2. Test for an interaction among 'Periods' that differs between impact and control locations:

> P(Aft) x C / Res = 2.70, $F_{crit(1)0.05,4,288}$ = 2.40 (0.025<*P*<0.05). Significant effect detected, indicating a medium-term temporal interaction among control sites.
>
> P(Aft) x I / P(Aft) x C = 2.44, $F_{crit(1)0.05,1,4}$ = 7.71 (0.10<*P*<0.25). Non-significant difference. No medium-term impact detected at the temporal scale of 'Periods'.

3. Test for a longer term interaction that differs in control and impact locations:

> B x C / Res = 23.30, $F_{crit(1)0.05,4,288}$ = 2.40 (*P*<<<0.0005). Significant impact detected, indicating a 'Before/After' interaction among controls.
>
> B x I / B x C = 18.74, $F_{crit(1)0.05,1,4}$ = 7.71 (0.025<*P*< 0.01). Significant effect detected, indicating detection of a "sand-impact" at the temporal scale of "Before/After". Impact detected at the temporal scale of 'Before/After'.

Therefore, there was no impact detected at the temporal scale of 'Times' or 'Periods', but an impact was detected at the temporal scale of 'Before/After'.

However, it is necessary to determine the confidence, or predictive power which the analysis had at the two temporal scales where an impact was not detected. Therefore, a power analysis was performed as described in Underwood (1993) using the formula;

F_{crit} / (1+n∅), where 1+n∅ =MS T(Aft) x I / MS Res (or MS P(Aft) x I / MS Res).

The value obtained is converted to 'Power' using an F distribution table (Zar 1984) or the equivalent F distribution function in Microsoft Excel. For further discussion of the theory behind the calculation of power refer to Underwood (1993). Calculations are shown below;

The power of the analysis to detect an impact at the temporal scale of 'Times';

> $F_{crit(1)0.05,2,288}$ / (T(Aft) x I / Res) = 3.03/18.73 = 0.16, $Fdist_{(0.16,2,288)}$ = *P* = 0.85.

The power of the analysis to detect an impact at the temporal scale of 'Periods';

> $F_{crit(1)0.05,1,288}$ / (P(Aft) x I / Res) = 3.87/6.61 = 0.59, $Fdist_{(0.59,1,288)}$ = *P* = 0.44.

The power analysis revealed that the probability of the ANOVA detecting the impact at the temporal scale of 'Times' was 0.85, and the equivalent test at the temporal scale of 'Periods' yielded a very low power of 0.44. The low power to detect an impact at the temporal scale of 'Periods' is a result of the early intervention of the 'sand' perturbation. If the sand-influx had occurred later in the sampling program the power to detect any effects would have been greater. The failure of the tests to reveal a significant effect at the temporal scale of 'Times' and 'Periods' is likely to be due to the instability of many of the control sites. The less stable control sites were subjected to boulder and cobble mobilisation under storm conditions (Fig. 4), a situation which was coincident with the sand influx and thus confounded the analysis.

The data used for the Beyond-BACI analysis, involving the sand perturbation, were potentially serially correlated, meaning that samples were not independent over time. To further explore this problem the data were taken to Phil Leppard at the Statistics Department, University of Adelaide, and independently analysed. The analysis was performed using an unbalanced repeated measures model with structured covariance matrices in the BMDP Statistical Software V5 Package (1990). Results were generated as a within subject correlation matrix. This analysis revealed that serial correlation was only present at low levels (0.01), suggesting that the results obtained using GMAV5 and Underwood's Beyond-BACI analysis were informative.

5. *Bembicium nanum* (Lamarck)

The small prosobranch gastropod *Bembicium nanum* was the only species of animal present in sufficient numbers at the majority of study sites to be useful in a statistical analysis of environmental impact. It is just one of a number of herbivorous molluscs that occurred throughout the majority of study sites, but is able to live higher on the shore than the majority of other gastropods (except *Littorina* spp.). It is quite a small animal, generally only attaining a maximum width of about 2cm (Quinn *et al.* 1992). Longevity of individuals has been estimated at between 4-8 years, and reproductive maturity in some populations in New South Wales has been estimated to occur at an average shell width of 11mm, 10-12 months after settlement on the shore (Underwood 1975). Females spawn yellow egg masses in spring from which larvae hatch and enter the plankton where they are believed to spend a long time, possibly up to a year (Underwood 1975). The longevity of this species means that individuals are likely to survive in a local population through several consecutive years of sparse larval recruitment. The long planktonic stage means that dispersal is likely to be over wide distances with adult local population dynamics having no influence on the number of new recruits arriving to an area (Underwood 1975).

Two experiments exposing *Bembicium nanum* to crude oil and refined product (petrol) for short periods, revealed that it was not killed when exposed to low concentrations of either product but did show behavioural changes. The primary response noted was closure of the operculum, and subsequent dislodgment in response to crude oil exposure. This would suggest that a significant crude oil spill could result in an initial decrease in *Bembicium* numbers due to dislodgment and in severe cases smothering of the animals.

Bembicium nanum would be an appropriate indicator of oil-induced change for a number of reasons. It is abundant at study sites, the adults do not appear to travel as far as other animals and so are unlikely to be able to avoid oil exposure, it shows some response to oil contamination but is not extremely sensitive, and it is herbivorous like the majority of other (non-sessile) gastropods. This last point means that it is likely to ingest and contact oil in a similar manner to other less numerous herbivorous gastropods.

Taxonomically, *Bembicium nanum* belongs to;

Phylum- Mollusca,
Class- Gastropoda,
Sub-Class- Prosobranchia,
Order- Mesogastropoda,
Superfamily- Littorinacea,
Genus- *Bembicium* Philippi,
Species- *nanum* (Lamarck).

6. Recommendations for the Ongoing Monitoring Program

Based on the outcomes of the preliminary monitoring of study sites in GSV during 1995 and 1996 and a literature review of relevant material, the following recommendations for the ongoing monitoring program at Port Stanvac have been made.

- A Beyond-BACI design is recommended. This uses many control sites sampled many times before and after an impact occurs.
- 8 rocky sites situated within GSV from Kingston Park (north of PS) to Robinson Point (south of PS), including three sites within the boundaries of the Port Stanvac Oil Refinery (refer to Section 3 for full site descriptions), are suitable for ongoing monitoring.
- The designated areas at each study site should be sampled using a randomly located $0.25m^2$ quadrat, which is deployed 7 times.
- In the event of an oil spill the affected site(s) should serve as impact site(s) while the remaining sites would act as controls.
- All sites should be sampled on the same day at low tide for each sampling time.
- The animal to be sampled is *Bembicium nanum* and the number in each of four size classes should be recorded. The smallest of these size classes will represent newly settled animals which will not be used in the final analysis, but their numbers through time may give an indication of the healthy dynamics of the system. The suggested size classes are; newly recruited- 2mm or smaller in width, small- greater than 2mm and up to 0.67cm wide, medium- greater than 0.67cm and up to 1.33cm wide, and large- greater than a width of 1.33cm.
- The presence of oil should be subjectively assessed (on a scale of 0-4). The suggested oil categories are; 0- no oil, 1- old weathered oil present as 'tar', 2- fresh oil present as a taint or sheen, 3- fresh oil present as an obvious thin film or small globules, 4- fresh oil present in large amounts as a thick oil film. General changes in substrate composition (in particular increased amounts of sand) for each site at each sampling time should also be scored. The data should be entered on field data sheets (e.g. Appendix 8) and then entered in the Microsoft Access Version 2.0 database.
- Sampling should be stratified to cover two temporal scales;
  1. 'Times'- suggested to be two-three weeks apart (randomly assigned) and nested in sampling periods, and
  2. 'Periods'- two-three months apart, and again randomly assigned (see Section 4.1 for details).
- The recommended effect size to be detected is a 50% greater ~~reduction~~ change in *Bembicium* numbers at the impact site than is seen <u>on average</u> at the control sites. "Effect size" refers to a 'true' difference between the impact site(s) and the control sites. The term "recommended effect size" refers to the magnitude of such a true difference which the monitoring program is designed to have a statistically acceptable chance of detecting. The "acceptable chance" is the designed statistical power of the monitoring program.
- Two errors that can occur in a monitoring program are the false detection of an impact (a type I error) or the failure to detect an impact that does exist (a type II error). Both errors are considered equally undesirable and so it is proposed that the study be

designed so that their probabilities are set equally to 0.05. In other words, the recommended statistical power for the monitoring program is 0.95.

- Thus, in this case, the recommended aim of the monitoring program is that if there were 'truly' a 50% greater change in *Bembicium nanum* abundance occurring at the impact site(s) in comparison to the control sites then the chance of the study detecting it as a significant impact at the 5% level would be 95%.
- Once an impact has occurred and the appropriate sampling been completed, a preliminary analysis using BMDP Statistical Software V5 (or a similar package) needs to be run to test for serial correlation in the data set. It is recommended that this be done through the Statistics Department, University of Adelaide. If serial correlation is present, a more extensive analysis needs to be performed (again, this would be most conveniently done by the Statistics Department), but if this problem is insignificant, then a Beyond-BACI analysis can be performed using GMAV5. The stages to be worked through in using a Beyond-BACI design are shown in Attachment B.

7. Initial Sampling for the Ongoing Monitoring Program

The initial sampling of the study sites selected for ongoing monitoring was done on the 17th of October 1996 and again on the 11th of November 1996. All study sites were censused on a single day and the data are attached as Appendix 8(a)-(d).

Support materials available to Mobil and held in the Zoology Department, University of Adelaide include:

- a data-base file set up in Microsoft Access to store and handle the data,
- a macro to calculate average abundances entered as raw values in the data-base, and which can also be adjusted to calculate standard error,
- a sampling quadrat, a metre rule, callipers and a 50m tape measure.

The GMAV5 package is owned by the University of Adelaide, and is available for use if the Monitoring Program is run through the University of Adelaide.

8. Related Literature

UBD Street Directory. Adelaide 1994. 31st Edition. (Universal Press Pty Ltd, Adelaide, Australia).

Shepherd, S.A. & Thomas, I.M. (1989) *Marine Invertebrates of Southern Australia.* Part II. (South Australian Government Printing Division, Adelaide, Australia).

Underwood, A.J. (1975) Comparative studies on the biology of *Nerita atramentosa* Reeve, *Bembicium nanum* (Lamarck) and *Cellana tramoserica* (Sowerby) (Gastropoda: Prosobranchia) in S.E. Australia. *Journal of Experimental Marine Biology and Ecology* **18**, 153-172.

Underwood, A.J. (1991) Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* **42**, 569-587.

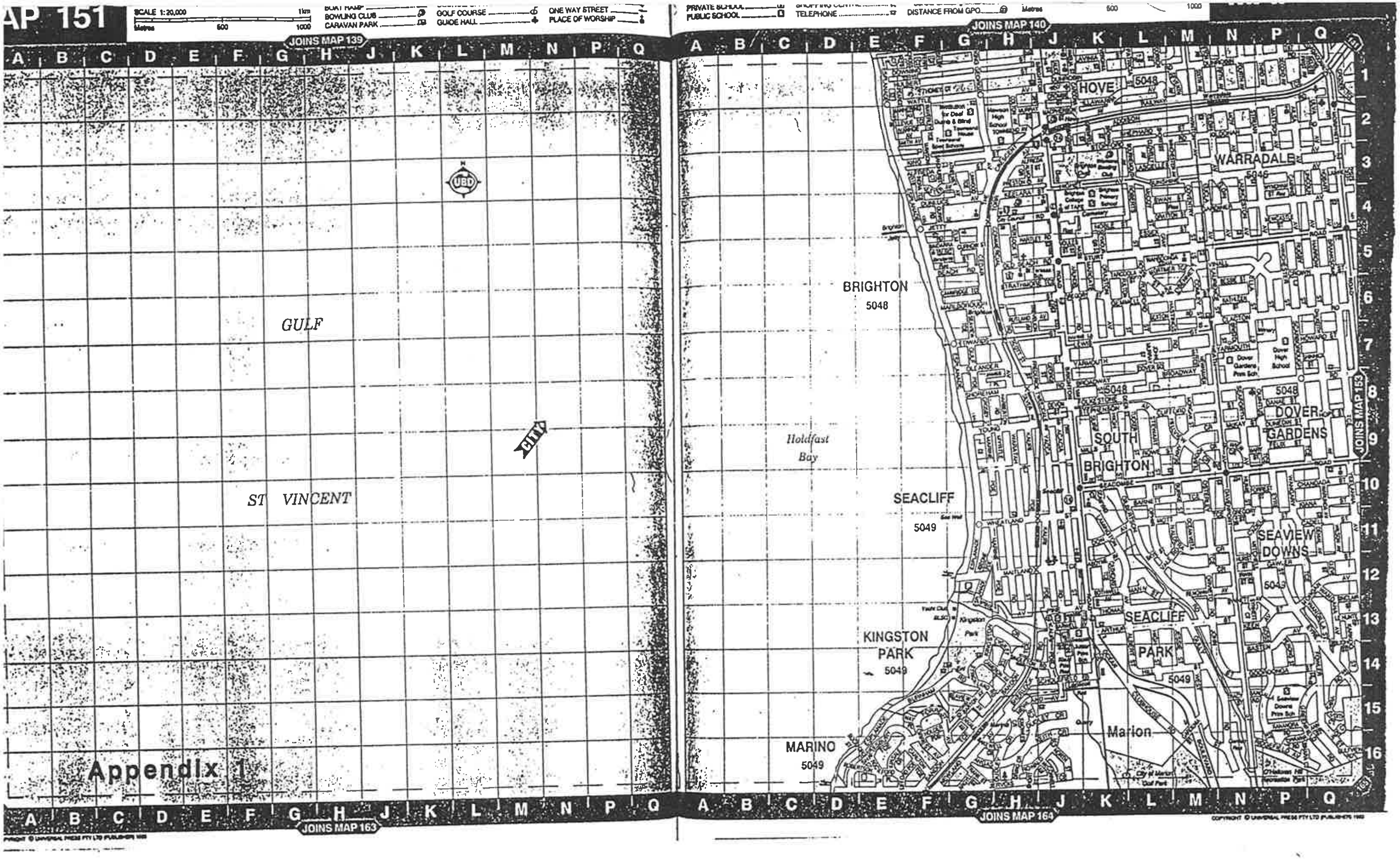
Underwood, A.J. (1992) Beyond BACI: The detection of environmental impact on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* **161**, 145-178.

Underwood, A.J. (1993) The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. *Australian Journal of Ecology* **18**, 99-116.

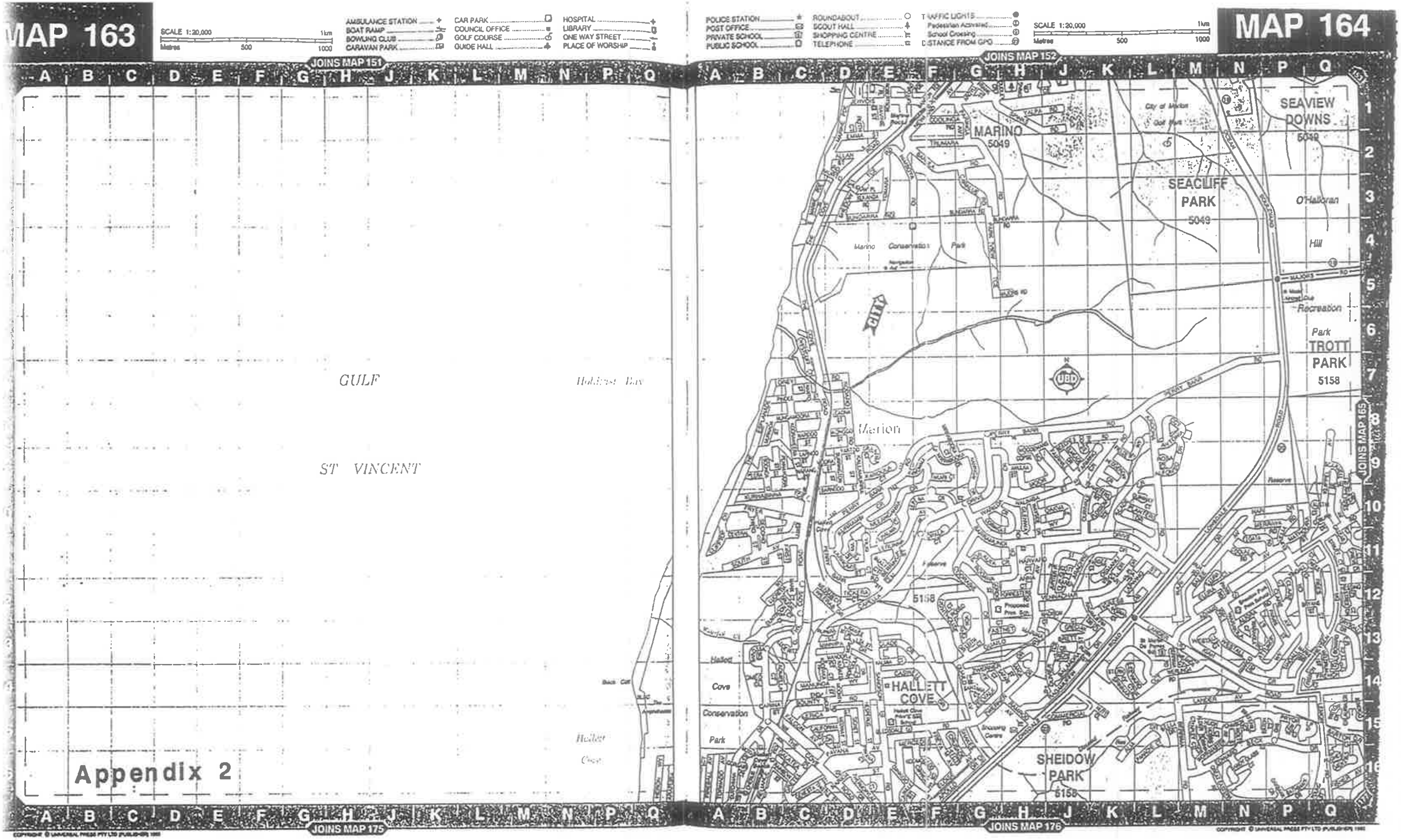
Quinn, G.P., Wescott, G.C. and Synnot, R.N. (1992) *Life on the Rocky Shores of South-Eastern Australia.* (Victorian National Parks Association, Melbourne, Australia).

Zar, J.H. (1984) *Biostatistical Analysis.* Second Edition. (Prentice-Hall International, Inc., New Jersey, U.S.A.).

APPENDICES

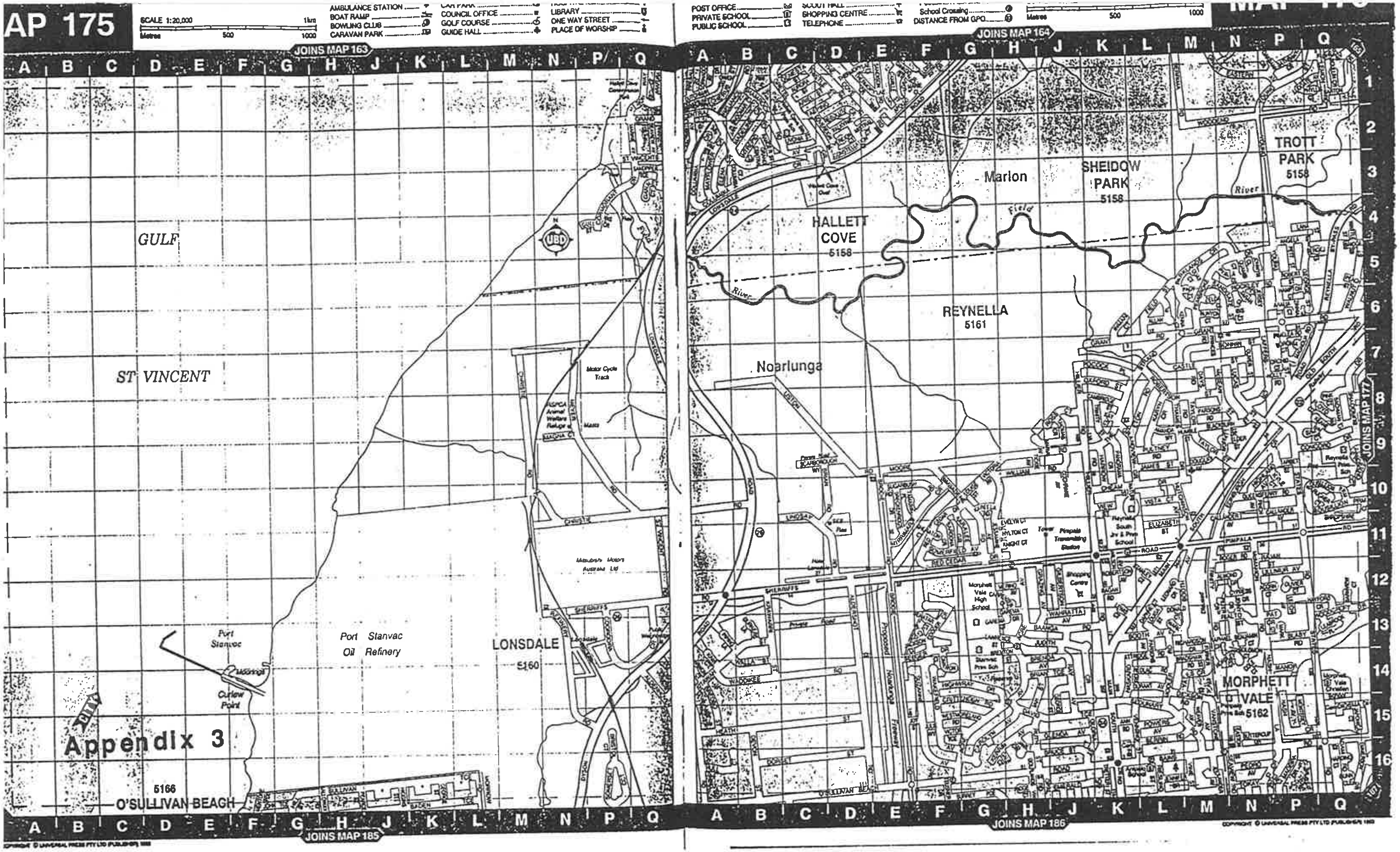

MAP 151
SCALE 1:20,000
Metres 500 1000 1km
BOAT RAMP
BOWLING CLUB
CARAVAN PARK
GOLF COURSE
GUIDE HALL
ONE WAY STREET
PLACE OF WORSHIP
PRIVATE SCHOOL
PUBLIC SCHOOL
SHOPPING CENTRE
TELEPHONE
DISTANCE FROM GPO
JOINS MAP 139
JOINS MAP 140
JOINS MAP 153
JOINS MAP 163
JOINS MAP 164
GULF
ST VINCENT
CITY
Holdfast Bay
HOVE 5048
WARRADALE 5046
BRIGHTON 5048
SOUTH BRIGHTON
DOVER GARDENS 5048
SEACLIFF 5049
SEAVIEW DOWNS 5043
SEACLIFF PARK 5049
KINGSTON PARK 5049
MARINO 5049
Marion

Appendix 1


MAP 163
SCALE 1:20,000
Metres 500 1000
1km
AMBULANCE STATION
BOAT RAMP
BOWLING CLUB
CARAVAN PARK
CAR PARK
COUNCIL OFFICE
GOLF COURSE
GUIDE HALL
HOSPITAL
LIBRARY
ONE WAY STREET
PLACE OF WORSHIP
POLICE STATION
POST OFFICE
PRIVATE SCHOOL
PUBLIC SCHOOL
ROUNDABOUT
SCOUT HALL
SHOPPING CENTRE
TELEPHONE
TRAFFIC LIGHTS
Pedestrian Activated
School Crossing
DISTANCE FROM GPO
MAP 164
JOINS MAP 151
JOINS MAP 152
JOINS MAP 165
JOINS MAP 175
JOINS MAP 176
GULF
ST VINCENT
Holdfast Bay
Hallett Cove
MARINO 5049
SEAVIEW DOWNS 5049
SEACLIFF PARK 5049
City of Marion Golf Park
O'Halloran Hill
Marino Conservation Park
Recreation Park
TROTT PARK 5158
Marion
5158
HALLETT COVE
Hallett Cove Conservation Park
SHEIDOW PARK 5158
Reserve
Shopping Centre
COPYRIGHT © UNIVERSAL PRESS PTY LTD (PUBLISHERS)

Appendix 2

Appendix 3

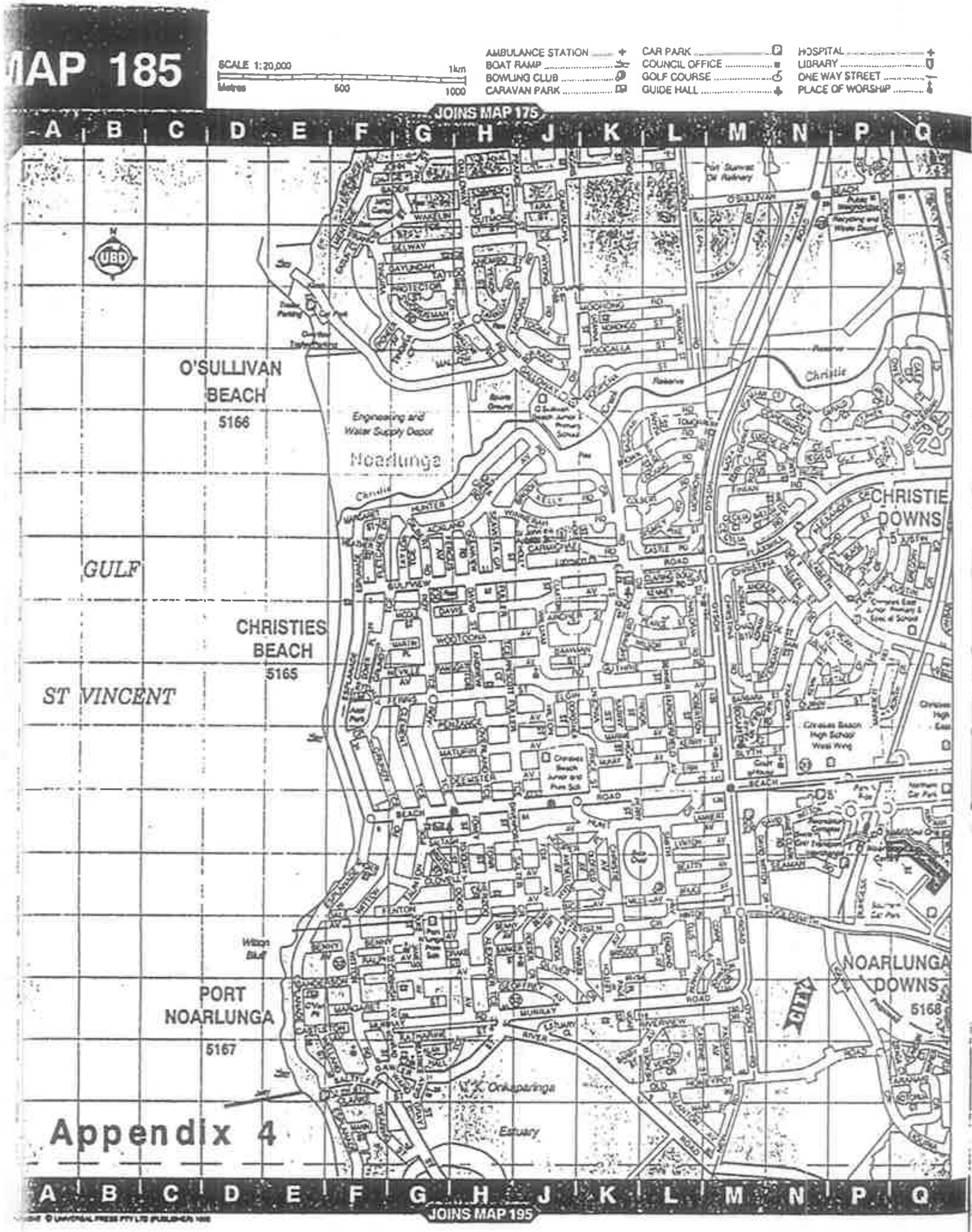

MAP 175
SCALE 1:20,000
Metres 500 1000
AMBULANCE STATION
BOAT RAMP
BOWLING CLUB
CARAVAN PARK
COUNCIL OFFICE
GOLF COURSE
GUIDE HALL
LIBRARY
ONE WAY STREET
PLACE OF WORSHIP
POST OFFICE
PRIVATE SCHOOL
PUBLIC SCHOOL
SHOPPING CENTRE
TELEPHONE
School Crossing
DISTANCE FROM GPO
JOINS MAP 163
JOINS MAP 164
JOINS MAP 177
JOINS MAP 185
JOINS MAP 186
GULF
ST VINCENT
Port Stanvac
Curlew Point
Port Stanvac Oil Refinery
LONSDALE
5160
5166
O'SULLIVAN BEACH
Motor Cycle Track
Mitsubishi Motors Australia Ltd
HALLETT COVE
5158
Marion
SHEIDOW PARK
5158
TROTT PARK
5158
Field River
REYNELLA
5161
Noarlunga
Pimpala Transmitting Station
Shopping Centre
Morphett Vale High School
MORPHETT VALE
5162
SHERRIFFS RD
PIMPALA RD
Proposed Noarlunga Freeway
LONSDALE RD
SOUTH RD

Appendix 4

MAP 185

SCALE 1:20,000 — 1km — Metres 500 1000

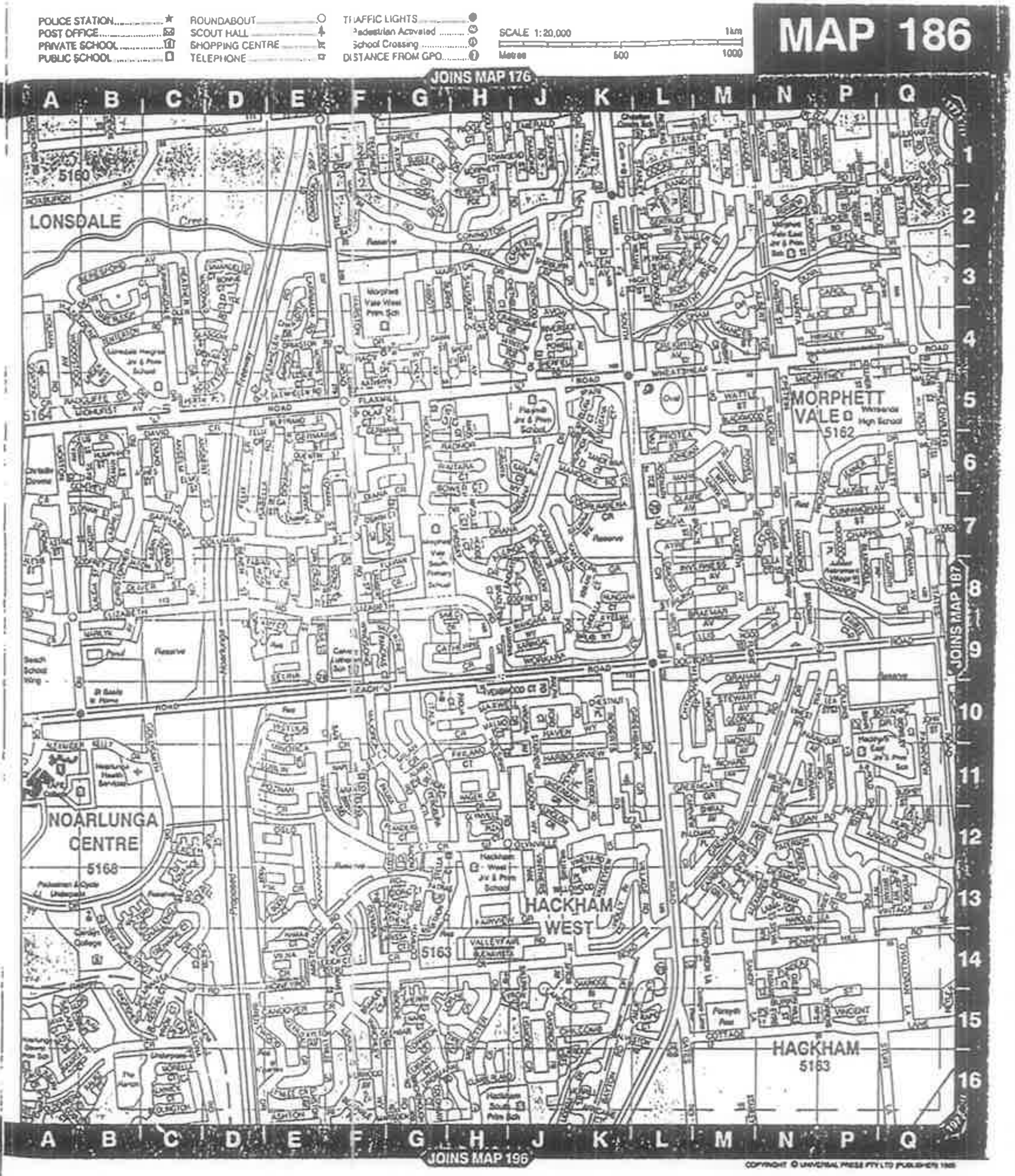
AMBULANCE STATION
BOAT RAMP
BOWLING CLUB
CARAVAN PARK
CAR PARK
COUNCIL OFFICE
GOLF COURSE
GUIDE HALL
HOSPITAL
LIBRARY
ONE WAY STREET
PLACE OF WORSHIP



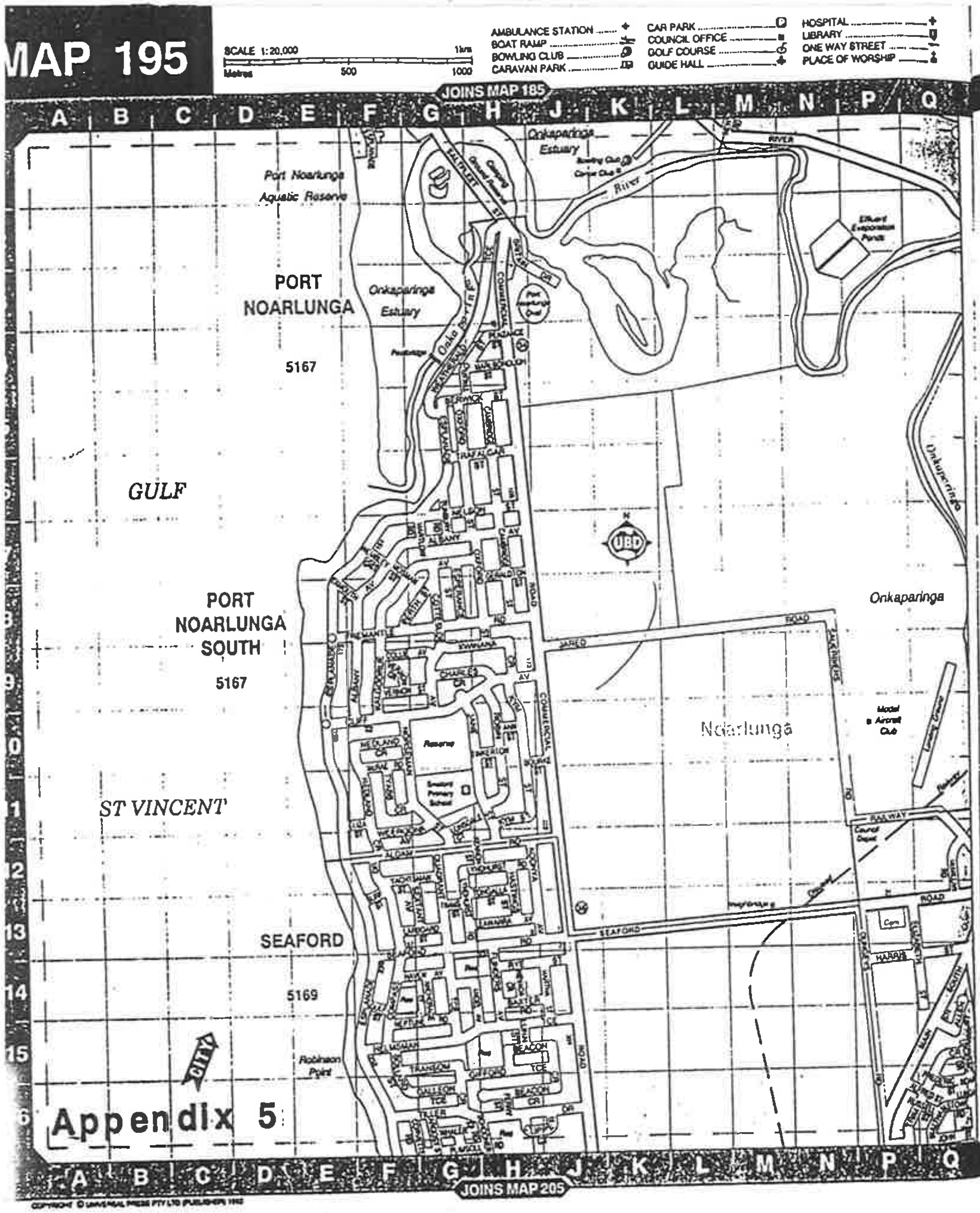
MAP 186

POLICE STATION
POST OFFICE
PRIVATE SCHOOL
PUBLIC SCHOOL
ROUNDABOUT
SCOUT HALL
SHOPPING CENTRE
TELEPHONE
TRAFFIC LIGHTS
Pedestrian Activated
School Crossing
DISTANCE FROM GPO

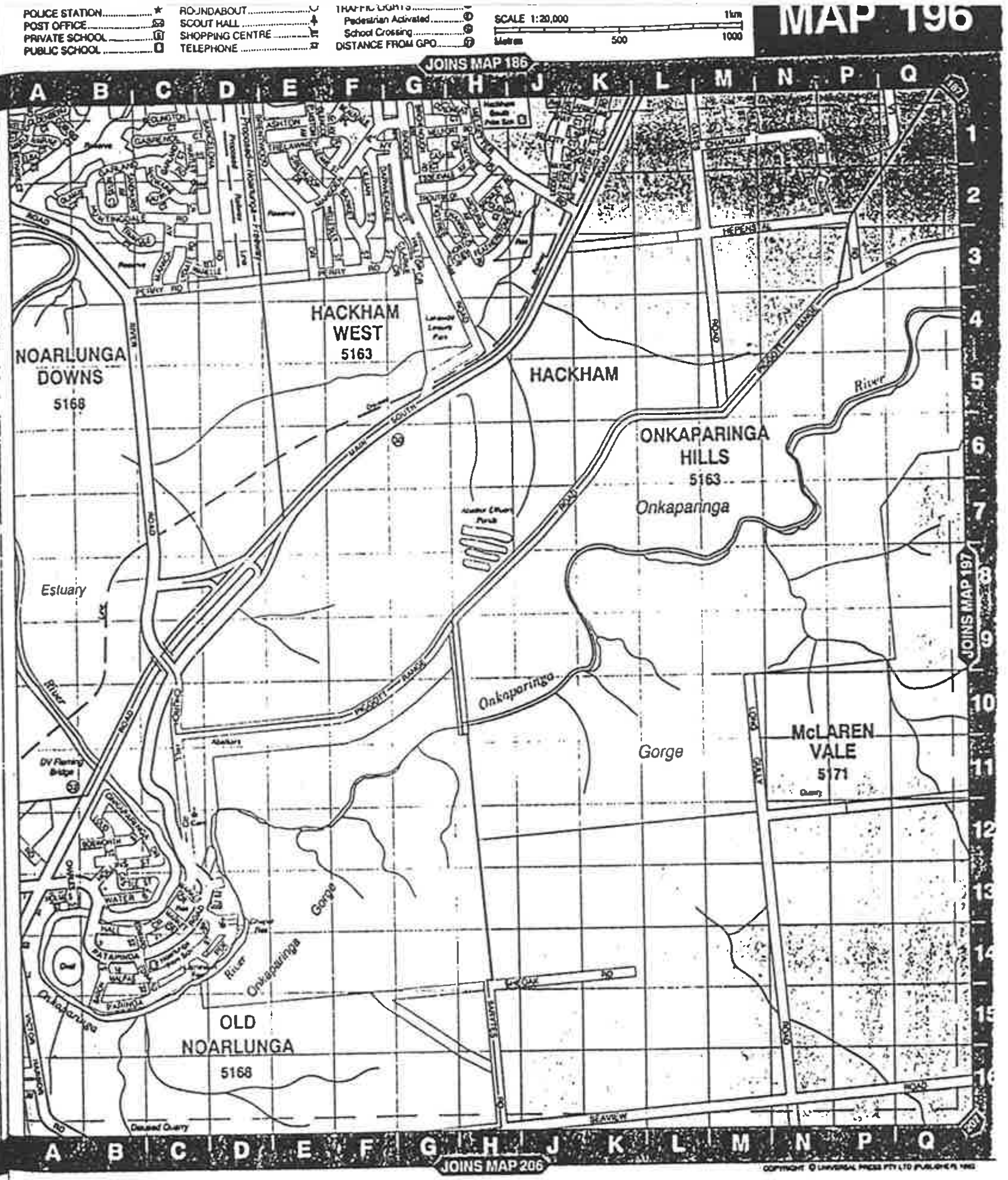
SCALE 1:20,000 — 1km — Metres 500 1000



Appendix 5



MAP 195
SCALE 1:20,000
Metres 500 1000
1km
AMBULANCE STATION
BOAT RAMP
BOWLING CLUB
CARAVAN PARK
CAR PARK
COUNCIL OFFICE
GOLF COURSE
GUIDE HALL
HOSPITAL
LIBRARY
ONE WAY STREET
PLACE OF WORSHIP
JOINS MAP 185
JOINS MAP 205
Port Noarlunga Aquatic Reserve
Onkaparinga Estuary
River
Effluent Evaporation Ponds
PORT NOARLUNGA
5167
GULF
ST VINCENT
PORT NOARLUNGA SOUTH
5167
SEAFORD
5169
Robinson Point
Noarlunga
Onkaparinga
Model Aircraft Club
COMMERCIAL
JARED ROAD
SEAFORD ROAD
RAILWAY
CITY



MAP 196
POLICE STATION
POST OFFICE
PRIVATE SCHOOL
PUBLIC SCHOOL
ROUNDABOUT
SCOUT HALL
SHOPPING CENTRE
TELEPHONE
TRAFFIC LIGHTS
Pedestrian Activated
School Crossing
DISTANCE FROM GPO
SCALE 1:20,000
Metres 500 1000
1km
JOINS MAP 186
JOINS MAP 197
JOINS MAP 206
NOARLUNGA DOWNS
5168
HACKHAM WEST
5163
HACKHAM
ONKAPARINGA HILLS
5163
Onkaparinga
Estuary
River
Onkaparinga Gorge
McLAREN VALE
5171
OLD NOARLUNGA
5168
MAIN SOUTH ROAD
PERRY RD
HEPENSTAL
PIGGOTT RANGE ROAD
SEAVIEW
Disused Quarry

Appendix 6 Raw abundances of *Bembicium nanum* used for the Beyond-BACI analysis of the sand perturbation.

			Study Sites					
Before	**Period**	**Time**	**13**	**12**	**11**	**3**	**2**	**1**
1	1	1	108	51	32	29	19	31
1	1	1	9	58	37	54	11	11
1	1	1	38	60	25	59	9	42
1	1	1	150	57	37	61	26	90
1	1	1	117	61	43	6	54	61
1	1	1	132	70	60	41	45	31
1	1	1	61	75	13	41	22	45
1	1	2	86	6	27	6	19	44
1	1	2	91	40	20	21	14	76
1	1	2	108	44	28	32	19	67
1	1	2	126	9	19	9	62	51
1	1	2	228	9	45	19	35	39
1	1	2	182	10	56	11	69	40
1	1	2	189	10	99	34	11	38
1	2	1	50	11	68	10	12	24
1	2	1	67	4	47	2	19	33
1	2	1	55	20	49	11	21	35
1	2	1	57	18	45	13	17	24
1	2	1	69	31	40	6	7	18
1	2	1	73	14	40	7	3	23
1	2	1	54	9	29	5	20	32
1	2	2	93	20	54	0	11	20
1	2	2	83	48	26	2	10	21
1	2	2	104	51	49	7	16	32
1	2	2	114	36	57	2	18	25
1	2	2	161	31	113	10	16	31
1	2	2	111	36	104	30	19	36
1	2	2	76	33	49	5	19	26
2	1	1	6	31	19	6	9	82
2	1	1	2	28	8	0	19	112
2	1	1	11	57	57	5	11	89
2	1	1	3	33	38	7	16	80
2	1	1	2	18	77	1	28	52
2	1	1	196	40	61	4	25	57
2	1	1	2	9	38	3	18	70
2	1	2	0	15	43	4	11	103
2	1	2	0	18	34	2	12	89
2	1	2	0	8	62	9	4	116
2	1	2	1	12	150	10	10	127
2	1	2	1	14	105	17	7	85
2	1	2	0	8	86	13	4	50
2	1	2	0	21	99	11	2	82
2	2	1	0	32	87	6	4	58
2	2	1	0	20	72	6	11	99
2	2	1	1	3	106	5	10	150
2	2	1	0	22	57	7	9	150
2	2	1	0	5	121	2	6	136
2	2	1	1	35	167	17	23	120
2	2	1	0	11	88	3	8	126
2	2	2	1	9	136	8	8	71
2	2	2	1	15	161	2	3	66
2	2	2	1	5	116	2	5	38
2	2	2	2	23	50	6	8	71
2	2	2	1	14	23	0	9	65
2	2	2	0	20	111	7	6	54
2	2	2	5	26	184	5	10	71

Study sites; 13= the Hallett Cove 'impact' site, 12= Marino Rocks, 11=Kingston Park, 3= PS3, 2= PS2 & 1= PS1.

Appendix 7

INSTRUCTIONS FOR RUNNING GMAV5

November 3, 1995

GMAV5 is a 5 Factor Analysis of Variance program for any complex model of orthogonal or nested, ed or random factors. Heterogeneity of variances are tested using Cochran's test and means compared using dent-Newman-Keuls tests.

There are a few restrictions on the models allowed.

1. Data must be balanced.

2. All hierarchical factors must be nested within those above them in the hierarchy.

st Steps

In order to run this application, it is necessary to have the following programs and files in the same ectory. They can be on a floppy disk drive or on a hard disk drive, but must be accessed through the same h.

GMAV5.EXE
GMSNK.EXE
BRUN61ER.EXE
COCH1TAB.SNK
COCH5TAB.SNK
DATAFOR.SNK
Q1TAB1.SNK
Q1TAB2.SNK
Q5TAB1.SNK
Q5TAB2.SNK

It is not necessary to run this program with a printer because the results of the analysis can be output to rinter or the screen.

If you are printing the results to a printer, it must be plugged into LPT1 and it must be turned on. If the nter is not plugged into LPT1 or not turned on, you will get a "device fault" or other erroneous message and program will break. You will then need to start again.

You MUST answer prompts from the keyboard using CAPITAL LETTERS, or you may get a ısensical message and the program will break. To make this easier, switch Caps Lock on before you start.

You start the program by switching to the directory containing the above files and typing GMAV5. You do this straight out of DOS or via another application such as WINDOWS. Do not change the names of any ne above files or programs.

a Entry

The program will read data filenames or header filenames up to 8 letters, but it does need extensions on se. The default extensions are "filename.hed" for header files, "filename.dta" for data files of raw data and ename.mva" for data files of means and variances or totals and variances for each cell. If you are using these ault extensions, the program will add them to the filenames automatically. Therefore, it is only necessary for to type the filename without an extension if default extensions are used. You can add your own extensions en you enter the filenames. These will override the default extensions.

The data and header information can be entered via the keyboard or via the disk drive. If entered via disk drive, they do not have to have the same path as each other nor the same path as the programs and files ed above.

Instructions for the use of GMAV5

NOTE. The path must be included in the filename for the header and data files, e.g. "a:filename" if the data come from the "a" drive or "c:\data\filename" if the data come from a directory called "data" on the "c" drive.

Header File

The header file supplies information about the design of the analysis. These data can be entered via the keyboard in answer to prompts, or from a disk. The program allows a header to be saved once entered from the keyboard, so that it can be used for future analyses.

If the header file is entered from the disk, it must be entered as a sequential ASCII file with the following information:

Datum 1	1 or 2 or 3 (1 = data being entered as raw data, 2 = data being entered as means and variances, 3 = data being entered as totals and variances).
Datum 2	Number of factors, 1 - 5.
Data 3 -	For each factor in turn: i) name of the factor ii) the number of levels of this factor iii) "O" if the factor is orthogonal; otherwise the number of the factor it is nested in, e.g. "1" if this factor is nested in factor 1 or "13" if this factor is nested in the Factor 1 X Factor 3 interaction iv) this is left blank or has the number of the factor which is nested in it, e.g. "3" if Factor 3 is nested within this factor v) "F" if this is a fixed factor; "R" if it is a random factor.
Final datum	The number of replicates. This analysis only deals with balanced sets of data.

Data file

Data can be entered in three different forms. Data can be entered from a disk as a sequential ascii file. They can also be entered from the keyboard in answer to screen prompts. If an error is made entering data from the keyboard, one can step back through the sequence by entering "e". This allows one to move back through a series of data to correct the error. All data after that point must, however, be entered again.

(i) RAW DATA are entered as a continuous set of numbers with no labels and no spaces. They must be entered in the following orders:

1 Factor	Level 1	Replicates 1........n, then
	Level 2	Replicates 1........n, then
	Level 3	Replicates 1........n,
	....	
	Last Level	Replicates 1........n.

2 Factors	Factor 1	Level 1	Factor 2 Level 1	Replicates 1........n, then
		Level 1	Level 2	Replicates 1........n, then
		Level 1	Level 3	Replicates 1........n, then
		Level 2	Level 1	Replicates 1........n, then
		Level 2	Level 2	Replicates 1........n, then
		Level 2	Level 3	Replicates 1........n

3 Factors	Factor 1 Level 1	Factor 2 Level 1	Factor 3 Level 1	Replicates 1........n, then
	Level 1	Level 1	Level 2	Replicates 1........n, then
	Level 1	Level 2	Level 1	Replicates 1........n, then
	Level 1	Level 2	Level 2	Replicates 1........n, then
	Level 2	Level 1	Level 1	Replicates 1........n, then

Level 2	Level 1	Level 2	Replicates 1........n, then
Level 2	Level 2	Level 1	Replicates 1........n, then
Level 2	Level 2	Level 2	Replicates 1........n

on for 4 Factor and 5 Factor analyses.

(ii) The data can also be entered as a sequential file of MEANS (or TOTALS) and VARIANCES for each
/hen the data are entered from the disk, all of the means (or totals) are entered, followed by the variances.

r	Level 1	mean, then
	Level 2	mean, then
	.....	
	Last level	mean, then
	Level 1	variance, then
	Level 2	variance, then
	.....	
	Last level	variance

ır	Factor 1	Level 1	Factor 2	Level 1	mean, then
		Level 1		Level 2	mean, then
		Level 2		Level 1	mean, then
		Level 2		Level 2	mean, then
		Level 1		Level 1	variance, then
		Level 1		Level 2	variance, then
		Level 2		Level 1	variance, then
		Level 2		Level 2	variance.

If means (or totals) and variances are entered from the keyboard, the prompt asks for the mean (or total)
n the variance for each cell in turn.

NOTE. Data that are entered as means (or totals) obviously cannot be transformed. You would need to
to the raw data.

l Points

The default value is 4 decimal points. This can be altered in response to a screen prompt if desired.

rmation

The data can be transformed after Cochran's test and before an analysis or after analysis and before the
re-analysed, as required. Eight different transformations are available as indicated in the program.

data

Before or after the analysis, one has the following options:

Save data to the disk if they were entered via the keyboard.

Print data on the screen or a printer.

Print means and variances on the screen or printer.

Save the means (or totals) and variances to the disk.

Save the header file to a disk.

Instructions for the use of GMAV5

Analysis

After the analysis, one has the option of printing the analysis on the screen and then to the printer or a disk. The analysis gives the Sums of Squares, Degrees of Freedom, Mean Squares, *F*-ratios and exact Probablities for each term in the model and prints out the model. If the *F*-ratio cannot be calculated for any term, then it prints "NO TEST".

One can then transform the data and re-analyse them, do S.N.K. tests on the existing data, run the program again on a different set of data or finish.

One is also given the choice of printing out the algebraic variance components from the linear model, as estimated by each Mean Square value in the analysis so that it is easy to determine which terms can be pooled to obtain appropriate or more powerful tests for higher order terms.

S.N.K. tests

If you do S.N.K. tests, then the program will automatically load and run GMSNK.EXE. This program cannot run alone because the correct models and values are handed across from GMAV5.EXE. All S.N.K. tests must, therefore, be done at the time of analysis, or the data will need to be analysed again.

The different sources of variation or terms in the model are listed and you can choose which one to do. After you have finished, choose 0 to quit S.N.K. tests and return to GMAV5 tor run another analysis or to quit altogether.

The results of the S.N.K. tests are printed on the printer or the screen. This is determined by your selection when running GMAV5. NOTE - you cannot change from selecting no printer to selecting a printer between doing the analysis and doing the S.N.K. tests. The format of these tests is as follows:

```
FACTOR      2                     S.E. = 2.7115

MEANS       12.1000               6.9000
S.E.        3.4496                1.8791

RANKS       2 - 1                                  (i.e. Rank Order)
MEANS       1 - 2                                  (i.e. Number of the two levels being compared)
            **
```

This shows that the means of all levels of Factor 2 were compared. The standard error used to calculate Q was 2.7115. There were two levels of Factor 2; Level 1 had a mean of 12.1 (S.E. 3.4); Level 2 had a mean of 6.9 (S.E. 1.9). The largest mean was in Level 1, the smallest mean was in Level 2, and the difference was significant at $P < 0.01$ (hence, **).

```
FACTOR      3(1)                  S.E. =2.6169
LEVEL          1

MEANS       5.3300                18.3300            7.2121
S.E.        3.4496                 1.8791            2.1211

RANKS       3 - 1
MEANS       2 - 1
              *

2 - 1       3 - 2
3 - 1       2 - 3
             **
```

In this example, 3(1) indicates that the means of the different levels of Factor 3 within each level of Factor 1 are going to be compared (because Factor 3 was nested in Factor 1). The "1" undemeath indicates that the means of Factor 3 in the first level of Factor 1 are being compared. The standard error used to calculate Q was 2.6169. There were three levels of Factor 3; in the first level of Factor 1, Level 1 of Factor 3 had a mean of 5.3 and

.E. of 3.4; Level 2 had a mean of 18.3 and a S.E. of 1.9; Level 3 had a mean of 7.2 and a S.E. of 2.1. The ference between the largest and smallest means (Levels 1 and 2) was significant at $P < 0.05$ (hence, *). The ference between means 1 and 3 was not significant; the difference between means 2 and 3 was significant at P .01 (hence, **).

The above procedure would be repeated for Factor 3 within each level of Factor 1.

When analysing interactions, you are asked if you want to proceed with all comparisons of every level ıach factor in every level of the other factor(s) that with which it interacts. So, you can choose to examine only ıls of Factor B in each level of Factor A, levels of Factor A in each level of Factor B or both. Answer the ıstions when you are asked.

Appendix 8. BR= bedrock or sand 'cemented' reef-rock, B= boulder, C= cobble, P/G= pebble or gravel, S/G= sand or grit.
(a)

Data Sheet for Port Stanvac Monitoring Program						% Substrate		Date	17/10/96		Recorded by:Leanne Piller
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Marino Rocks											
Quad 1		8	28	12	0	100					
Quad 2		1	5	1	0	100					
Quad 3		7	15	2	0	100					
Quad 4		2	11	1	0	100					
Quad 5		8	32	3	0	100					
Quad 6		4	14	4	0	100					
Quad 7		6	25	23	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS3											
Quad 1		9	43	4	0	100					
Quad 2		20	74	2	0	100					
Quad 3		5	95	2	0	100					
Quad 4		10	129		0	100					
Quad 5		1	93	2	0	100					
Quad 6		4	90		0	100					
Quad 7		6	75	1	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PNS											
Quad 1			10	16	0	100					
Quad 2			4	3	0	100					
Quad 3			1	3	0	100					
Quad 4			10	7	0	100					
Quad 5			10	23	0	100					
Quad 6			6	24	0	100					
Quad 7			10	31	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Robinson Point											Substrate = embedded reef-
Quad 1			2	55	0	100					rock at this site
Quad 2			3	48	0	100					
Quad 3			2	62	0	100					
Quad 4			5	53	0	100					
Quad 5			1	48	0	100					
Quad 6			2	64	0	100					
Quad 7			5	88	0	100					

Attachment A

Literature Review of Monitoring

Attachment A: Literature Review of Monitoring

1. Monitoring to Detect an Environmental Impact

In this era of technology and urbanisation, environmental disturbance by humans is on the increase. Freshwater and marine communities are especially susceptible to human induced perturbation and are frequently exposed to a range of activities that can modify their underlying biological patterns and processes (Keough and Mapstone 1995). It is only when the intrinsic patterns and processes of natural systems are understood that programs can be developed to assess and evaluate their condition under perturbed and unperturbed conditions (Karr 1987). The risk of increased environmental disturbance has been tracked by a growing public awareness (Fairweather 1993) with many countries introducing legislation requiring the implementation of monitoring programs to detect environmental change (Millard *et al.* 1985). This has prompted the development of suitable monitoring techniques. However, the design of programs to detect such disturbances has not matched the increasing demand for their use (Underwood 1989 & 1991). The initial emphasis on disturbance-induced change at the level of the organism has now shifted to a focus on population-level effects (Emlen 1989). This change in emphasis has been incorporated into the design of many environmental monitoring programs.

Environmental disturbance can occur as a result of a myriad of anthropogenic activities, defined as a human induced stress on the environment (Underwood 1989). These activities can be categorised into planned developments (such as the building of a new marina) they may be classed as public amenities and utilities (e.g. the discharge of treated sewage effluent into the ocean), they may be recreational (such as human trampling on a rocky shore), or exploitative (such as fishing or bait collection) in response to recreational needs, or they may be random events such as an accidental oil spill (Fairweather 1990, Keough and Mapstone 1995). The last of these disturbance types is the most difficult to investigate due to its unpredictable nature. Not withstanding this difficulty, a way of rapidly, reliably, and cost-effectively monitoring and detecting the impact of human activities on natural populations is needed (Underwood 1992).

A biological monitoring program can make predictions about an impact, but the only way it can be used to measure the 'real' change in a system is to compare the environmental parameter(s) of interest in the unimpacted and the impacted condition (Keough and Mapstone 1995). Assessments of impacts vary from measuring the physico-chemical composition of discharges, to rigorously planned and implemented field-orientated sampling programs utilising biological monitoring. Biological monitoring is used under the belief that sampling the biota gives information on the condition of an ecosystem (Herricks and Cairns 1982). The collection of appropriate field data, is the best way to provide evidence about a disturbance and whether or not an impact has occurred subsequent to a perturbation (Keough and Mapstone 1995).

Monitoring programs can function as mechanisms of environmental assessment, damage prevention (via feedback into management decisions), allocation of damage responsibility, and environmental conservation (Constable 1991, Peterson 1993). However, regardless of the primary function of a monitoring program, it is imperative that it is capable of detecting the impact in question (Lewis 1978, Underwood 1991). This central need has fuelled the refining of monitoring designs from the simple design of Green (1979) through to the complex Beyond-BACI designs advocated by Underwood (1991, 1992 & 1993).

1.1 Scope and Objectives of Monitoring

When designing a monitoring program it is essential that it is able to provide clear evidence about the magnitude and existence of 'real' environmental impacts. To successfully achieve this aim, a clear understanding of the variations in the response variables expected under natural and anthropogenic conditions needs to be gained. It is also important to be aware of likely responses to trivial and important perturbations, and to select variables that are easy to measure, sensitive to the impact, yet are relatively constant in the unimpacted condition (Keough and Mapstone 1995).

A major difficulty in detecting an environmental impact lies in the natural variation ('noise') which is inherent in any community and which can mask trends associated with a particular disturbance (Underwood 1993). The greater this natural background variability the more difficult it is to detect impact-induced change, and the more costly and extensive the monitoring design needs to be (Keough and Mapstone 1995). Variability is a natural characteristic of a population and needs to be considered on a range of scales. It can operate over different spatial and temporal scales and can manifest as alterations in the time course of population abundances in different localities (Underwood 1992). Another difficulty when dealing with natural systems is that many interacting factors, some of them unsuspected, may be acting and may mask or confound change arising as a result of the investigated perturbation (Hilborn and Stearns 1982).

A monitoring design is inadequate if it fails to take account of high levels of background variation, is unable to detect a biologically important impact, or is oversensitive to biologically trivial impacts (Keough and Mapstone 1995). Therefore, in order to be effective, a monitoring program needs to balance the size of the impact that it is required to detect (the 'effect size') against the biological consequences of that magnitude of change and its ability, or power, to detect that change (Keough and Mapstone 1995). The monitoring program must also consider what scale the impact is likely to operate over (temporally and spatially), and the underlying processes that are likely to be affected by the impact and then focus the program at the appropriate level (Underwood 1991, 1992 & 1993).

Scale considerations are crucial in designing a monitoring program. Isolating changes of interest from background variation can be difficult since the variation seen is often the outcome of processes operating at several scales (Underwood and Kennelly 1990, Karlson and Hurd 1993). Therefore, the spatial and temporal scales selected for sampling can affect the results of a monitoring program and how they are interpreted (Millard *et al.* 1985, Young 1990). The ideal scale of focus should be at the functional level at which an organism is likely to respond to its environment (Andrew and Mapstone 1987, Young 1990).

Spatial and temporal scales over which a perturbation is likely to be felt can be identified by using modelling. Processes like physical transport (of contaminants and larvae) and life history parameters of indicator populations (such as longevity, age structure, rates of reproduction and mortality) can be modelled and used to identify the scales of importance for a particular animal and contaminant (Walters 1993).

A monitoring program can be optimised to cover a range of temporal and spatial scales (Underwood 1991. 1992, 1993). The monitoring designs of Underwood are of particular interest in their ability to incorporate temporal and spatial considerations. Such designs are able to help establish a statistically rigorous way of monitoring and testing for a disturbance-induced effect (Ward and Jacoby 1992).

1.2 The Importance of Baseline Studies

An environmental impact for our purposes can be viewed as a change in the environment over a given time as a result of direct or indirect human activity (Keough and Mapstonc 1995). To be able to detect an environmental change the baseline condition of the area of interest needs to be established and used as a yard-stick against which changes can be compared and assessed in context (Ward and Jacoby 1992, Rong-Quen *et al.* 1994). However, since the underlying ecological processes in a community are often slow and complex, a long-term data-set is recommended (Rong-Quen *et al.* 1994). This is particularly relevant to rocky shores where a long-term data set (i.e. 10 years) may be required to identify any trends due to extreme variability in processes such as recruitment (Rong-Quen *et al.* 1994). A shorter sampling time may not only fail to show clear patterns but may also give misleading results (Southward 1991). Baseline data can be used to assess variation at a range of scales and can be useful in optimising the sampling design of a monitoring program, for example by planning the number of locations and replicates needed (Underwood and Kennelly 1990).

It is important that clear decision criteria are defined well before a monitoring program is implemented. For example the expected magnitude and direction of change that is expected with a particular development should be discussed at an early stage (Keough and Mapstone 1995). The level of change that is to be tolerated needs to be defined *a priori*, and only then can the observed change be compared to the baseline data. This avoids a biased monitoring program and prevents a *post hoc* subjective allocation of effect size (Keough and Mapstone 1995).

1.3 Causality and Impact-Induced Change

A major fault found with many monitoring programs that have detected an 'effect' in response to a human activity, is the lack of a clearly established causality link between the disturbance and the change (Underwood and Peterson 1988, Underwood 1991). Another problem identified by Underwood (1991) is the focus of monitoring programs on changes (in particular decreases) in the average abundance of organisms. A decline in population abundance can occur in response to an impact, but it is not the only change that is possible. In fact, any <u>change</u> in population means, in either direction, that correlates with a perturbation must be considered as an impact response (Underwood 1991).

Impacts may not induce changes in mean abundance but instead may manifest as changes in the temporal and spatial variability of populations (Underwood 1991, 1992, 1993, 1994). For example, Warwick and Clarke (1993) noted increased variability in meiobenthos assemblages in response to experimental exposure to organic enrichment, and found similar responses in a variety of other organisms exposed to different perturbations in natural habitats. They concluded that increased variability can be a characteristic signal seen in stressed assemblages. Therefore, procedures that focus on changes in mean abundance may fail to detect such an impact. Underwood (1991) argues that a disturbance may result in changes in temporal variance, resulting in altered rates or magnitudes of fluctuations in organism abundance around the 'long-run' averages. Perturbation may also act to change the frequency or timing of major population parameters such as recruitment of juveniles into a coastal population (see Underwood and Denley 1984, Underwood and Fairweather 1989), which causes a resultant change in the time course of the particular population (Underwood 1991).

The intertidal area is particularly susceptible to anthropogenic perturbation but changes occurring in response to such disturbances are difficult to quantify due to the stochastic nature of this environment and its assemblages. Variation is manifested by spatial patchiness and fluctuations in species abundance over time in response to such processes as unpredictable recruitment. Disturbance-induced fluctuations may manifest in a susceptible population as increasing temporal variance or altered time courses of organisms rather than as simple changes in the average abundances of a stressed population. A monitoring program capable of detecting anthropogenic change against such a 'noisy' signal requires a clear link between the sampling variable and the disturbance, a long-term data set and a design such as that advocated by Underwood, which is able to partition the variation of interest from natural variation.

2. The Rocky Intertidal: A Review

2.1 The Rocky Intertidal Region: A General Description

The intertidal region is defined as that area of the sea-shore that is influenced by the high and low spring tides (Carefoot and Simpson 1977). It is an extreme, unique and dynamic environment at the interface between land and sea. The two main processes that produce environmental gradients are tides and waves (Carefoot and Simpson 1977, Menge and Farrell 1989, Underwood 1994a, Underwood and Chapman 1995).

The ebb and flow of the tide results in daily changes in the conditions that animals and plants living in the intertidal area must face, in particular varied periods of immersion and emersion (and therefore air exposure and desiccation) (Womersley and Thomas 1976, Carefoot and Simpson 1977, Underwood and Chapman 1995, Chapman and Underwood 1996). Another tidal characteristic that can influence habitat and associated organisms is the variation in tidal range, the extremes of which are represented by the neap tides (which have low range) and the spring tides (which have an extreme range). Variation in tidal range occurs as a monthly pattern of small tides followed by a series of larger tides before diverting back to smaller tides, in response to gravitational forces induced by the sun (Underwood and Chapman 1995). The direct alignment of the moon and the sun with the earth results in the extreme tides of spring (in a summation gravitational effect), while the position of the moon at right angles to the sun results in the small neap tides (Underwood and Chapman 1995). The timing of tidal ebb and flow occurs progressively later each day due to the moon-earth orientation and relationship (Underwood and Chapman 1995). Therefore intertidal organisms face varied tidal fluctuations and resultant changes in conditions (such as immersion and emersion periods) on a range of scales (Black 1979).

Waves can also have a major influence on conditions in the intertidal region of the shore. Wave action can be spatially and temporally very variable, and its destructive forces can modify plant and animal communities in a variety of ways. These include clearing areas for colonisation and favouring tightly adherent organisms, such as barnacles, in exposed coastal regions (Underwood and Chapman 1995).

Intertidal communities covary in time and space, and are typically patchy in distribution on a range of scales. This is largely due to the action of variable structuring forces (both physical and biological) interacting with spatial variation in habitat (Schoch and Dethier 1996).

2.2 Habitats Within the Rocky Intertidal Region

Hard substrata within the intertidal region is typified by boulders (possibly interspersed with cobble, pebble or sand), reefs and rocky extensions of land masses. Artificial hard substrates (such as wharfs, breakwaters and boat ramps) can also provide habitat for intertidal assemblages (Rong-Quen *et al.* 1994).

The hard substrata type and character, in combination with the degree of wave exposure, results in a range of habitat types which support a wide array of animals and plants (Rong-Quen *et al.* 1994).. Rocky intertidal habitats commonly consist of broad expanses of rock platforms which have been shaped by wave action over many years. Rock which is relatively soft (such as sandstone or shale) is more readily eroded by waves, and results in rock platforms that are typically broad and steeply sloped at the seaward end where they are constantly exposed to waves and erosional activity even at low tide. The landward edge of such platforms is often bordered by a cliff, which forms where wave action has not yet eroded the rock. In contrast, balsite and granite rocks are harder and more resistant to erosional forces, resulting in very steep shores (Underwood and Chapman 1995). Tidal pools and boulder shores are two other habitats that are common to rocky intertidal areas.

2.3 Advantages of Sampling the Rocky Intertidal Area

Whether the rocky intertidal area has been targeted for sampling to investigate a perturbation or to experimentally investigate ecological processes (such as competition, disturbance or predation) it is an ideal medium to focus on for a number of reasons. It is often densely inhabited by macro-organisms, such as algae, molluscs and gastropods (Rong-Quen *et al.* 1994), and is the closest and most easily accessed area of the sea (Carefoot and Simpson 1977). Hard substrate organisms are easier to access, see, identify, quantify and census than benthic fauna or infauna, and can be non-destructively censused.

Another benefit of sampling in the intertidal zone is that the majority of animals are sessile or have restricted distribution ranges and mobility. This means it is unlikely that they would be able to move away to avoid a perturbation, such as a pollutant entering there environment, making them ideal agents to use in biological monitoring. Some animals such as mussels are able to accumulate and biofocus contaminants which can also be a useful feature in pollutant monitoring (Rong-Quen *et al.* 1994).

3. Disturbance and Environmental Monitoring

3.1 Environmental Disturbance

Stress can be defined as a biological change in a population in response to a particular trigger (Underwood 1989). It is difficult to identify and monitor stresses in natural populations due to the inherent natural variation in time and space which generally characterises them (Underwood 1989). It is important to differentiate between disturbances that trigger a response (stress) in the target population and those that fail to do so (Underwood 1989).

A disturbance can be defined as a fluctuation or perturbation in an environment that can, but does not always, result in a biological change (Underwood 1989). If a biological change does occur, it can manifest in a range of ways such as altered species abundance (in either direction), altered diversity or species dominance, or some other change in community structure (Skilleter 1995). However, for the purposes of clarity in the discussion of disturbance, the focus will be at the level of the population.

3.2 Disturbance Types

Disturbances can be defined by the effect that they elicit on the environment and the target population. The effects that arise will depend on the target population, its condition at the time of perturbation, and the characteristics of the perturbation (Skilleter 1995).

3.2.1 Disturbance Defined by Effects

Defining disturbance by the effects that are generated gives rise to three categories; Type I, Type II and 'Catastrophic'. Type I disturbances fail to illicit a response in the environment, Type II disturbances result in a change (which may be temporary, long term, or permanent), and 'Catastrophic' disturbance results in total destruction of the population and its habitat (Underwood 1989).

Changes in a population may be a direct response to a disturbance, such as oil smothering molluscs, or changes may arise as an indirect response. Examples falling into this second category generally occur as a result of altered availability of resources, such as food or substrate, or physical changes to the environment, such as overturning intertidal boulders and inducing shading effects in algae that were previously able to meet their photosynthetic needs (Skilleter 1995). Disturbance can be in the form of physical agents, but can also occur as a biological agent, such as a blue-green algal bloom impacting on other planktonic species in an estuary (Skilleter 1995).

3.2.2 Disturbance Defined by Duration

Disturbances can also be defined by the duration of their influence on a population (Skilleter 1995). By this definition they can be of two main types; pulse and press (refer to Bender *et al.* 1984 and Underwood 1989 for examples of pulse and press perturbation experiments). Pulse disturbances are of sudden onset and short duration, with the disturbance usually easing rapidly. A disturbance of this type would be illustrated by an operational oil spill at Port Stanvac, with oil beaching on intertidal rock where it remains for two tidal cycles before being swept from the area. A press disturbance has an extended duration (it is chronic over the period in question) and is likely to induce long-term changes. An example of this type of disturbance is an ongoing near-coastal release of treated sewage discharge impacting on a coral reef community (Grigg 1994). It must be remembered that these disturbance definitions are relative to the impacted population, and a two week discharge of oil could be perceived as a press event to an organism with a two week turnover time, and a pulse disturbance to an intertidal mollusc with a ten year life history (Skilleter 1995).

3.3 The Importance of Disturbance

Disturbances range on a continuum from massive destructive events such as large oil spills, cyclones and tidal waves, which have obvious large scale effects on the environment, to smaller scale events such as a wave overturning a boulder on a rocky shore (Skilleter 1995). Disturbance events can have an important role to play in natural systems. Their primary function is to provide opportunities for new organisms to become established as space is cleared or predators are removed (Dayton 1971, Sousa 1984). The provision of colonisable 'free' space is particularly important is sessile communities, such as barnacle dominated sites, where space is densely occupied and is the primary limiting resource (Denley and Underwood 1979). Chance events such as storms, unseasonable hot weather, or the movement of boulders (McGuiness 1987a & b) can all act to open up intertidal space without otherwise damaging the environment. An oil spill disturbance can also open up space by killing or dislodging animals, but may physically change the environment and render it unsuitable for colonisation by a particular species. Natural disturbance tends to operate patchily so that mosaics of disturbed areas are interspersed by non-disturbed areas (Dethier 1984, Skilleter 1995). This can facilitate maintenance of diversity by affording refuge space to different species on an intertidal shore (Dethier 1984).

3.4 The Intensity, Timing and Frequency of Disturbance

Disturbances can differ in the intensity, timing and frequency with which they occur. These characteristics can, in turn, affect the response occurring in the target population, and its ability to recover from the stress e.g. the extent to which successional mechanisms can progress (Sousa 1984, Underwood 1989).

3.4.1 Intensity

The intensity of a disturbance can result in differential impacts on the area that is perturbed. A very intense event such as massive storm waves, would be capable of clearing whole plants (such as kelp) from the surface of rocks they crash against, whereas a less intense episode may only remove portions of fronds (Kennelly 1987). Therefore, the disturbance intensity can influence the successional changes following the perturbation event and subsequent recovery.

3.4.2 Timing

The seasonal timing of a disturbance can also be an important determinant of the response and recovery made by an impacted population (Jara and Moreno 1984, Kennelly 1987, Skilleter 1995). The study by Kennelly (1987) illustrated the importance of the temporal aspects of disturbance events on kelp dominated communities in Sydney. It was found that removal of the kelp overstorey from sections of the shore, to simulate storm wave activity, in spring, summer and autumn, resulted in initial increases in microalgal and invertebrate cover, and eventual dominance by turf species of alga. In contrast, clearance of the substrate in winter, when kelp recruitment was intense, resulted in simultaneous colonisation of the bare space by kelp, filamentous algae and turf algae, with the kelp rapidly dominating to form a canopy that led to the decline of the turf species. Both patterns of succession can be defined as inhibitive, with the final dominance by the respective algal forms excluding the other species (Kennelly 1987). After two years, the turf dominated community which resulted from a disturbance at a time other than winter, was eventually overgrown by kelps. Since storm-induced perturbation is unpredictable on the east coast of temperate Australia, it is the algal species which have propagules in the water for extended times (such as *Ulva lactuca*) that will be the best overall opportunistic recruiters into newly disturbed space in the intertidal zone (Skilleter 1995). However if the disturbance coincides with a time of high recruitment for a particular plant or animal, even if there is only a narrow window of recruitment opportunity, this will be sufficient for the successful initial colonisation of the bare area by the species in question (Skilleter 1995).

The successional stage of an assemblage and the age and physiological state of its component organisms can also have a bearing on the susceptibility of organisms to perturbation and their ability to recover from such an event (Skilleter 1995). For example, an old stressed animal will be more readily dislodged by a storm event than an equivalent young, healthy counterpart (Skilleter 1995).

3.4.3 Frequency

The frequency of the disturbance can also affect how well a population is able to recover. Some populations may be better able to cope with frequent disturbances and in this case would be deemed to be stable (refer to next section) (Underwood 1989). A stable population is one that is able to recover to its pre-impact condition before the next disturbance intervenes. It is apparent that more frequent disturbances allow less recovery time, a situation which, if it persists, may drive a population to extinction at a perturbed location (Underwood 1989).

3.4.5 Recovery After Disturbance

The planktonic strategies adopted by many intertidal organisms are important, in that they can assist in the recovery of a perturbed intertidal area. If local extinction of a particular species occurs as a result of disturbance, new recruits can be carried in the plankton to recolonise the disturbed habitat if its condition allows (Kennelly 1987, Skilleter 1995). Larger more generalised disturbances may result in populations that have difficulty recovering from the disturbance, never recover, or are replaced by an entirely different biological structure (Skilleter 1995).

Underwood (1989) identified three features displayed by populations that affect their ability to recover from perturbation. The first of these is 'inertia', which equates to the response generated by a disturbance of a specified intensity, frequency and type (Selye 1973). The inertia of a population can be determined objectively by identifying the threshold level above which a response occurs to a specific size and type of perturbation. Two other population attributes are 'stability' and 'resilience', and these determine whether the population will recover from disturbance-induced change (Underwood 1989). Recovery of a perturbed population is marked by the return of its abundance to its equilibrium (pre-impact) level. The rate of recovery is specifically defined in reference to the magnitude of a disturbance, and is termed the 'stability' of the population (Underwood 1989). The 'resilience' of a population is a measure of its ability to recover from different magnitudes of disturbance, and the greater the magnitude of the disturbance that a population can successfully recover from, the more resilient it is (Underwood 1989).

3.5 Disturbance Size: Important Versus Trivial Impacts

How important a disturbance is deemed is a subjective judgement that tends to be biased by the ecological and economic values of those who are examining it. This bias needs to be addressed in the design of monitoring programs which should be sensitive to important impacts (as defined *a priori* ideally on biological and economic grounds) but not oversensitive to smaller trivial responses (Keough and Mapstone 1995). The ability of a population to recover from a certain magnitude disturbance within a realistic time frame should be factored into the determination of important versus trivial impacts (see example in Underwood 1992).

3.6 Coastal Disturbances

The easy accessibility of the intertidal area makes it susceptible to a number of anthropogenic perturbation pressures (Ghazanshahi *et al.* 1983, Kingsford *et al.* 1991). Heavy recreational use (e.g. foot traffic and harvesting of intertidal species) can extensively change the community by selectively removing favoured species and modifying natural competitive outcomes and other underlying ecological processes (Carefoot and Simpson 1977, Beauchamp and Gowing 1982, Castilla and Bustmante 1989, Kay and Liddle 1989, Addessi 1994, Brosnan and Crumrine 1994).

The close physical relationship between the sea and the land results in the former receiving many terrestrial derived pollutants such as sewage from coastal areas, effluent from industry, land based runoff in stormwater (freshwater plus its effluent nutrient and particulate load), sedimentation, and pollutant loads via rivers and estuaries (Carefoot and Simpson 1977). Any or all of these pollutants, in combination with recreational shore usage, can affect the delicate ecology of the ocean and coastal areas.

Coastal oil refineries can introduce pollution by the accidental release of crude or refined petroleum into the marine environment. The fate and effect of oil in the intertidal zone will now be discussed in more detail.

3.7 Oil as a Coastal Disturbance

The ocean is subjected to increasing pollutant exposure. Oil is just one of these pollutants and it is a source of anthropogenic stress to a wide range of invertebrate communities (Suchanek 1993). Oil can enter the sea from tanker operations, other shipping operations, offshore oil production, and coastal oil refineries (Dawson 1980). Wars, particularly the recent (1991) Gulf War in Kuwait, can be another source of anthropogenic oil pollution (Ehrhardt and Burns 1993). Regardless of the source, it has been estimated that about 5 million tonnes of petroleum hydrocarbons enter the marine environment world-wide annually (Clarke 1989). Oil can also enter the sea from natural (biogenic) sources or seeps (Burns and Smith 1980, Gunkel and Gassmann 1980, Volkman *et al.* 1992).

The Amoco Cadiz supertanker accident occurred off the coast of Brittany (France) in 1978 and about a third of the 233,000 metric tonnes of oil spilled is estimated to have contaminated beaches, rocky shores and other parts of the marine environment (Ganning *et al.* 1984). Numerous papers have investigated the implications of this spill on the coastline (including Ward *et al.* 1980, Hayes *et al.* 1993, Krupp and Jones 1993, Kureishy 1993, Literathy 1993, Sauer *et al.* 1993). Similar tanker oil spills have occurred since the Amoco Cadiz, including the tanker Aegean Sea which spilt crude oil off the north coast of Spain in 1992 (Suchanek 1993), and the U.S. tanker Braer which grounded off the Shetlands in 1993 (Ritchie 1993). At the time of this report, a Russian tanker spilt a large volume of oil off the western coast of Japan which fouled 800km of coastline.

Oil is essentially a mixture of complex compounds with varying properties and toxicities (Suchanek 1993). Crude oil consists of a complex mixture of hydrocarbons, with 4 to 26 carbon atoms in each molecule. The arrangement of these hydrocarbon molecules can take the form of straight chains, branching chains, or cyclic chains (including polycyclic aromatic hydrocarbons (PAH) some of which are known carcinogens) (Clark 1989). As well as the hydrogen and carbon molecules, hydrocarbons may contain up to 25% of non-hydrocarbons (such as sulphur and vanadium). The properties and nature of crude oils vary depending on the source of the oil, and may also vary through time within a single oil field (Clark 1989).

To generate the refined oil product, crude oil is put through a distillation process to remove different components which have variable boiling ranges. Products include light gaseline (used as the basis of petrol), bunker fuels, naphtha and tars (Clark 1989). All components of crude oil are able to be biodegraded by the action of bacteria, some yeasts and fungi. The more complex, high molecular weight, cyclic compounds are the slowest to degrade (Clark 1989). It has been experimentally shown that the most severe toxic effects occurring in plant and animal communities have been in response to oil spills involving low boiling point compounds, in particular aromatics (Baker 1991). Toxic effects are especially severe when the oil involved is a light oil that is confined to a small area (Baker 1991). Heavy oils, such as some crude oils and Bunker C fuel oils, tend to have a greater impact through physical smothering than through their toxicity (Baker 1991).

When oil is spilt on the sea it forms a thin surface film known as a slick. The rapidity of oil spread and slick thickness is a function of the sea temperature and the type of oil, with light oils spreading faster and forming a thinner slick than a more waxy oil (Clark 1989). Spilt oil changes its composition over time, as some of its components evaporate and others mix with water. The first components to evaporate are the light (low molecular weight) volatile components, while water soluble components mix in with the water column, and insoluble components emulsify to form droplets (Clark 1989, Suchanek 1993). The greater the agitation experienced by the oil due to wave action, the greater the rate of the emulsification, and in very agitated conditions the oil can form an aerated mass termed a 'mousse' which often increases the original volume (Suchanek 1993). The heavy residues of crude oil form tar balls ranging from 1mm-20cm in diameter. As emulsified drops, the oil presents a large surface-area to volume ratio for natural biodegradation to occur, whereas the tar balls and mousse provide only a relatively small surface-area to volume ratio for this process (Clark 1989).

Intertidal invertebrate assemblages are likely to contact oil from super tanker spills or coastal refinery operational spills as it is carried ashore by the combination of wind, tide, water current, and wave action (Suchanek 1993). These assemblages are especially vulnerable to the floating component of the oil (particularly mousse) which can coat and suffocate them, while the sinking component of the oil can be very harmful to subtidal assemblages (Suchanek 1993). Oil naturally undergoes weathering and biodegradation by indigenous marine bacteria, but the latter process is generally slow (Suchanek 1993). Oil toxicity is reduced by weathering, so the longer oil is at sea before it beaches, the less toxic it will be to the organisms it contacts (Baker 1991). This is well illustrated by the observation that barnacles, periwinkles and limpets are able to tolerate the presence of weathered residual oil without any apparent ill-effects (Baker 1991).

Other variables that can affect the impact of an oil spill are the energy level of the shore and its substrate type (Baker 1991). A rocky, high energy shore will tend to be less affected and to recover rapidly from an oil spill due to the rock preventing oil absorption and the strong wave activity which mechanically removes oil. In contrast, sheltered shores will tend to retain oil due to the diminished wave action and enhanced algal cover which will facilitate oil retention (Baker 1991). Mangrove communities which tend to be very sheltered and carry large volumes of sediments and vegetation are prone to severe effects from oil contamination (Garrity and Levings 1993). If oil penetrates into the substratum the residence time is likely to be increased. The high porosity of freely draining sand, gravel or stones will facilitate sub-surface oil penetration, allowing oil to be adsorbed onto sub-surface grains and retained and weathered over many years (Baker 1991).

Oil pollution can affect individual organisms by inducing death, physiological effects or cytogenic effects (Suchanek 1993). At the population level the effects seen range from altered abundance, altered age structure, genetic variability, reduced recruitment, and modified competitive and predative interactions (Suchanek 1993).

It is likely that the most immediate effect of an oil spill on invertebrates will be physical. Heavy mortality across a range of invertebrate groups has been reported as a consequence of coating with fresh crude oil (Baker 1991). The oil coats the animals and may prevent respiration. Similar physical smothering effects can occur with intertidal plants and newly settled spores (Baker 1991). Oil adherence may also impede the mobility of motile animals or cause them to become dislodged and carried away by wave or current action to positions where they may be subject to additional stresses, such as desiccation or predation (Suchanek 1993).

Invertebrate mortality may also occur as a direct consequence of oil toxicity to a particular animal. In general the smaller larval and juvenile stages are likely to be more affected by oiling than more mature lifestages (Rong-Quen *et al.* 1994). Any changes in individual and population parameters are likely to flow on to community-level changes (Warwick 1986, 1988a&b). Such changes are dependent on which particular species is affected by the oil, and how severe this effect is, with major population shifts altering community interactions and structure (Suchanek 1993).

Many studies on the effect of oil on benthic organisms have been carried out in the laboratory. Identified oil responses in corals have included a decrease in growth rates, reproduction and colonisation capacity (Loya & Rinkevich 1979, Peters *et al.* 1981), abnormal feeding mechanisms (Reimer 1975) and excessive mucus secretion (Peters *et al.* 1981). Sublethal responses of marine invertebrates to oil can produce obvious population-level change. Common physiological functions affected by sublethal oil contamination include: reproduction, growth, respiration, excretion, chemoreception, feeding, movement, response to stimuli and disease susceptibility (Suchanek 1993). A similar range of altered physiological effects have been seen in corals subjected to sublethal oiling (Rong-Quen *et al.* 1994). A number of studies have detected more serious consequences, in terms of intertidal assemblage recovery, in areas subjected to heavy mechanical debridement and extensive use of dispersants in association with an oil spill (Rong-Quen *et al.* 1994).

A web of interaction factors both biotic and abiotic determine the biological consequences of an oil spill. These include the type and amount of oil and its condition (e.g. degree of weathering), physical environmental factors (e.g. substrate type), prevailing weather conditions, nature of biota, seasonal factors, prior exposure of the area to oil , the presence of other pollutants and the way the spill cleanup was handled (Loya & Rinkevich 1980, Baker 1991, Suchanek 1993).

4. Development of Environmental Monitoring Designs

Over the years the need for effective monitoring programs has led to a review of existing monitoring designs. Particularly in the last few years some quite complex designs which are statistically quite rigorous have come into favour and been extensively discussed in the literature (including Underwood 1991, 1992, 1993 & 1994, Stewart-Oaten *et al.* 1986, Green 1993). Analysis of variance (ANOVA) is a common technique used to analyse data generated from many of the (univariate) monitoring designs aiming to detect anthropogenic change. ANOVA acts to partition the various factors of interest that may be contributing to the observations and separate these factors from the 'noise' in the data set by a series of relevant statistical tests (Zar 1984, Millard *et al.* 1985). The evolution and design of the most widely used techniques in environmental monitoring are discussed in the following sections.

4.1 Basic Design

The earliest monitoring design used in environmental impact detection consisted of a single post-impact sampling. Such a design violates many of the criteria discussed by Green (1979). The most basic design used a paired set of sites consisting of a single 'control' and a single 'impact' site which were monitored a single time after an impact. Subsampling within each of these sites results in pseudoreplication rather than true replication (see Hurlbert 1984). The primary flaw in such a design is that it is not possible to differentiate between an impact and natural spatial variation (Keough and Mapstone 1995). This basic design can be improved by using multiple controls and a single impact location or multiple control and multiple impact sites, but there is still no measure of change and it is possible that the control and impact groups were different before the impact intervened (Keough and Mapstone 1995). The only case where this basic design is useful is a situation where there is no pre-impact data and an assessment of impact is made *post hoc*. In such a situation the minimal requirements would be multiple control sites and a single impact site, and maximising the number of control sites (weighted against the costs and gains of this strategy) is recommended (Keough and Mapstone 1995).

4.2 The BACI and BACIP Designs

Spatial variation is a natural phenomenon in systems (Eberhardt 1978) and could result in coincident changes in 'control' and 'impact' sites after an activity commenced even if the activity being monitored failed to have a major impact (Keough and Mapstone 1995). Thus, it was necessary to control for pre-impact differences between sites in environmental impact studies and the **B**efore **A**fter **C**ontrol **I**mpact (BACI) design was born. In its most basic form this design consisted of a single pre-impact sampling time in concert with a single post-impact sampling time in each of two treatment groups; 'control' and 'impact' (Green 1979). The thinking behind this design is that an impact should cause a statistical interaction from 'before' to 'after' the disturbance which is different in the 'impact' location compared with the control (reference) site (Keough and Mapstone 1995). This basic BACI design has been criticised by many environmental biologists for its lack of temporal and spatial replication which does not allow a valid test of the interaction between 'before-after' and 'control-impact' treatments (Bernstein and Zalinski 1983, Hurlbert 1984, Stewart-Oaten *et al.* 1986, Eberhardt and Thomas 1991). It should be noted that Green identified this design as meeting the minimal requirements of a monitoring program and did in fact advocate spatial and temporal replication where possible (Green 1979 & 1993). The BACI design can be extended to community-level data (see Faith *et al.* 1991).

Bernstein and Zalinski (1983) and Stewart-Oaten *et al.* (1986) both advocated using temporal sampling to overcome some of the deficiencies in the more basic BACI design. One control (C) and one impact site (I) were sampled a number of times before and after the perturbation, with both sites sampled simultaneously at each sampling time. The analysis statistically contrasted the means of C-I differences between the 'before' and 'after' time periods to assess if differences changed coincidently with the commencement of the perturbation (Stewart-Oaten *et al.* 1986). This version of the BACI design has been used extensively in environmental monitoring studies (Green 1993), and addresses the stochastic nature of a population which is unlikely to remain static through time even in the unperturbed state (Keough and Mapstone 1995).

Since the design uses paired control (which could be a single site or the mean of a set of sites) and impact locations it became known as the **B**efore **A**fter **C**ontrol **I**mpact **P**aired (BACIP) design. It was first used to assess the impact of the San Onofre Nuclear Generating Station (SONGS) cooling water discharge into the Southern California Bight (Peterson 1993). Subsampling in a BACIP monitoring program does not increase the degrees of freedom of the main test or directly influence the power of the analysis, although it does provide a more accurate and less biased estimate of the mean at a particular time (Keough and Mapstone 1995).

Stewart-Oaten *et al.* (1986) recommended using infrequent and randomised sampling times to achieve sampling independence and reduce the risk of coinciding with regular cyclic changes occurring in a population. The BACIP approach to environmental monitoring is useful when only two sites can be used for a monitoring program, but it does not allow a statistical determination of whether site-time interaction is due to treatment or site effects, a major flaw in a marine system which is often characterised by asynchronous population fluctuations (Underwood 1991). This problem can only be overcome by the use of a number of control sites and (if possible), a number of impact sites (Green 1993). Another difficulty with the BACIP design is its failure to deal with a change at the impact location which is unrelated to the perturbation and is coincident with the start of the activity, but does not occur at the control site (Keough and Mapstone 1995).

The BACIP design is based on three major assumptions; no serial autocorrelation (or serial correlation) exists between samples, there is no temporal trend in C-I differences before or after the perturbation, and variances are normal and heterogeneously distributed (Keough and Mapstone 1995). If the last of these assumptions is violated it can be overcome by data transformations, or if this fails to correct the problem, use of a non-parametric analysis (see Zar 1984). The first two assumptions require closer consideration and represent serious problems if violated.

ANOVA (which is basically an extension of a t-test) assumes that deviations of the observations from their true means (errors) are uncorrelated in time and space (Zar 1984, Millard *et al.* 1985). However, patterns in nature, and observations in monitoring, often show temporal and spatial correlation (see Millard *et al.* 1985 concerning aquatic monitoring programs). It has also been shown, by using Monte Carlo simulations, that the presence of either spatially or temporally correlated data can significantly affect the outcome of ANOVA tests (Millard *et al.* 1985). To avoid serial autocorrelation, a sampling interval must be chosen that is long enough for there to have been some turnover of individuals or species, through migration, mortality or recruitment (Underwood 1993, Keough and Mapstone 1995). The initial choice of sampling times can be reassessed after several sampling occasions, usually towards the end of the pre-impact period. For example, the Durbin-Watson test can detect auto-correlation, and if this problem is present, some sampling times can be eliminated until the test shows the problem has been overcome, after which the new sampling time intervals are repeated in the post-impact monitoring (Keough and Mapstone 1995). A more satisfactory option, in that it avoids discarding data, is the use of an analysis that incorporates autocorrelation. BMDP Statistical Software is a package operated by Adelaide University's Statistical Department that incorporates this facility in its design (pers. comm. Phil Leppard).

To avoid autocorrelation it is necessary to consider the organism being sampled and its longevity when allocating sampling times (Underwood 1993). For very long-lived organisms the most appropriate sampling period may be at intervals of greater than a year which would make it unlikely that short term effects will be detected or that the program will be long enough to collect a reasonable time series (Keough and Mapstone 1995). For short lived or highly mobile organisms counts taken at short intervals may show little autocorrelation (Keough and Mapstone 1995).

Trends in C-I differences before or after the perturbation will invalidate the statistical analysis used in temporally replicated BACI designs, and may not be detected until late in the monitoring program. Appropriate data transformations may remove such trends but bring their own problems such as loss of important biological information and an increase in variance and subsequent loss of statistical power and potentially abandonment of the analysis (Keough and Mapstone 1995). It is possible in such a situation to analyse the trends themselves by considering the samples through time not as random from 'before' and 'after' periods but instead as two ordered series, and by using orthogonal polynomials to resolve the actual trends through time (Keough and Mapstone 1995).

4.3 MBACI

MBACI is the design recommended by (Keough and Mapstone 1995). It uses multiple control and (if possible) impact locations and is analogous to the Beyond-BACI design discussed extensively by Underwood (1991, 1992 & 1993) except that it does not use nested spatial and temporal scales, instead focusing on a single designated spatial and temporal scale.

4.4 Beyond-BACI

The next step on from the BACIP design is to use multiple control locations sampled multiple times before and after an impact occurs. Such a design (Underwood 1991, 1992 & 1993) results in combining the temporal replication found in the BACIP design with greater spatial replication in the form of multiple control locations. This in itself can result in problems such as difficulty finding suitable similar sites to act as controls as well as increasing sampling costs (Keough and Mapstone 1995). Underwood (1993) advocates the use of multiple randomly chosen control locations selected from a set of appropriate locations, in our case a rocky intertidal habitat with a similar suite of organisms. If the number of potential control locations is small then it is possible that in the statistical analysis this may become a fixed rather than a random factor. If however the number of locations that are used as controls are less than the total number of potential locations then this factor can be considered a random factor (Underwood 1993).

4.4.1 Beyond-BACI and temporal and spatial considerations

The Beyond-BACI designs advocated by Underwood improve on the earlier monitoring designs by considering temporal and spatial scales. Underwood states that the previous focus on detecting changes in the average values of the parameter in question may not always be the most important consideration as it may be that an impact is detected as a change in variance (Underwood 1991, 1992, 1993). The analysis is basically a repeated measures ANOVA, where the contribution of the various factors (including two or more time scales and spatial scales) is incorporated, allowing a complex partitioning of variance.

In order to conceptualise how Underwood's complex designs work it is necessary to consider the differences between a press and a pulse disturbance. Pulse disturbances operate over a shorter time scale than press disturbances, and recovery following a pulse event tends to be more rapid. Pulse effects can be detected by allocating sampling effort to an appropriately short sampling schedule ('times') which is nested within a longer sampling schedule ('periods'). In this way sampling consists of a series of 'before' and 'after' periods divided into distinct intervals with a series of random sampling times nested within each period.

Temporal Scales

The designs advocated by Underwood are able to investigate and detect most realistic environmental changes (by the partitioning of sampling effort into a combination of relevant temporal scales) even if little is known about what type of change is likely in the face of a particular perturbation (Keough and Mapstone 1995). The preferred option is to know (e.g. through prior experimentation) the type of change that is most likely to arise as a response to a disturbance. This knowledge then allows optimisation of resources to the best design possible in terms of sampling costs and the power to detect an impact at the temporal scale of interest (Keough and Mapstone 1995). For example, a rapid pulse event will be more efficiently detected by a Beyond-BACI design that uses many intervals ('periods') with a few times nested in the longer time factor. This design would not be as useful to detect a slower pulse or a press disturbance (Keough and Mapstone 1995).

The difficulty in using temporal sampling is that time becomes a variable of interest. As discussed previously this can lead to the problem of serial autocorrelation which violates one of the underlying assumptions of ANOVA (Zar 1984). In the presence of this problem samples are not independent within and between different temporal treatments (Green 1993). Stewart-Oaten *et al.* (1986) agree with Underwood that randomisation of sampling times within a temporal monitoring program is optimal, but believe that the primary aim of allocation of temporal sampling effort should be directed to minimising serial autocorrelation, which could be achieved by using an appropriate fixed sampling interval (and having the sampling time treated as a fixed effect). These authors point out the difficulty of picking truly random sampling times and believe it is important to take account of seasonal patterns in a population. Again a consideration of the scale of the study is necessary, as randomisation of sampling through time within seasons (as long as serial correlation is avoided) could be appropriate (Stewart-Oaten *et al.* 1986).

Spatial Scales

Underwood's suite of Beyond-BACI monitoring designs give consideration to spatial scales as well as temporal scales. Some perturbations may have an impact that is of interest at more than one spatial scale. The spatial scale (or scales) of interest are dictated by the character of the disturbance (dispersion and discharge type) and the medium in which it occurs (Keough and Mapstone 1995). For example, two spatial scales of interest could be generated by an oil spill, with a small localised impact being 'acceptable' while damage at the scale of an entire reef is seen as an ecological disaster (Keough and Mapstone 1995). Underwood's Beyond-BACI design can be manipulated to cover the two spatial scales used in the previous example, but will require an alteration in sampling effort. It is important that an *a priori* consideration of the aims of a monitoring program, and a prior knowledge of the disturbance and the likely effects it will generate is gained, so that optimal resource allocation can be partitioned into the design of the program at appropriate temporal and spatial scales.

Keough and Mapstone (1995) believe that the MBACI design has advantages over the more complex hierarchical designs of Underwood (in that they save effort and resources). Underwood (1991 & 1993) addresses some of the problems associated with optimising his complex designs. The MBACI design may be appropriate to detect a range of impacts and should be used preferentially when it is adequate to the disturbance being monitored. However, the Beyond-BACI designs have the advantage of allowing partitioning of variance over a range of important scales and can allow detection of complex 'mixes' of disturbance (such as combination pulse and press events) (Keough and Mapstone 1995). Choice of the most appropriate design for a monitoring program should be based on the type and amount of disturbance that is likely to occur, the duration and extent of change that is predicted over different spatial and temporal scales, and balanced against power and resource considerations.

5. The Best Design for a Monitoring Program for Port Stanvac

The literature review of monitoring designs suggested using a Beyond-BACI approach to monitoring for an oil spill at Port Stanvac. This should not entail a large increase in sampling effort in return for an ability to differentiate variance induced by perturbation on a range of temporal scales. Preliminary monitoring focused on two different 'zones' within each designated site and two temporal scales. The spatial scale of interest in the preliminary monitoring is at the level of the 'reef'. Other design considerations include 'acceptable' error rates and the power of the design to detect the impact of interest.

A major challenge in detecting an environmental impact is to differentiate the effect of interest from natural temporal and spatial variation (noise), and to differentiate between trivial and important impacts (Osenberg *et al.* 1994, Keough and Mapstone 1995). In order to achieve this it is necessary to choose an appropriate variable to monitor, and to gain some knowledge of the fluctuation range under perturbed and unperturbed conditions over a number of temporal and spatial scales.

5.1 Statistical Power, Acceptable Error Rates, Effect Size and Sampling Size

Null hypotheses are statements of no change, in other words that a perturbation has not produced an alteration in the parameter being assessed. A null hypothesis provides a reference point against which the alternative hypothesis, that an impact has occurred, can be compared (Strong 1980).

An ecological monitoring program uses a statistic derived from sampling observation to compare with a theoretical distribution (Fairweather 1991). This is done to test the null hypothesis (no difference) that a certain anthropogenic activity has no impact on the environment, and a decision is then made to reject or accept the null hypothesis (Fairweather 1991).

In a statistical sense there are four outcomes of a monitoring program (Table 1). These include two 'true' outcomes and two errors. There are two errors that can occur with statistical inference; Type I error: incorrect rejection of a (true) null hypothesis, and Type II error: retention of a (false) null hypothesis (Toft and Shea 1983, Zar 1984). Errors arise as a result of the natural variability, or 'real error', which is inherent in any system, and can also occur as a consequence of sampling error, or 'measured error' (Keough and Mapstone 1995). Variability can occur in the data that masks or mimics the effect of a 'real' impact. The two errors have their own costs, and need to be considered so that the risks of both are kept in check (refer to Andrew & Mapstone 1987, Berstein & Zalinski 1983, Rotenberry & Wiens 1985, Toft & Shea 1983). Since variation can occur both spatially and temporally it is necessary to allocate sampling effort to the spatial and temporal scales that have been identified as important during the planning and pilot-study phases of a monitoring program (Keough and Mapstone 1995).

The focus on a preset α error rate with no consideration of type II errors, which have equally severe consequences, has been the tendency in a large number of scientific studies (Mapstone 1995). Decisions about environmental impacts have important consequences whether they are based on correct or incorrect results (Fairweather 1991). It is therefore necessary to consider the consequences of the two error types as part of the monitoring program and the ratio of alpha to beta should reflect the relative seriousness of the two types of error. Alpha and Beta levels are related (see Table 1). Performing a statistical test at a significance value of $\alpha=0.01$ instead of 0.05 will result in a decrease in power. By convention many workers opt for a power of 80% $\beta=0.20$, $\alpha=0.05$ which gives a 4:1 ratio for error rates (Zar 1984), but since both error types have their own dangers, it is better to consider the consequences of each and then set the desired error rates *a priori* (Mapstone 1995).

<u>Effect size</u> is the degree to which the parameter being measured is present in the population or the magnitude of the departure from the null hypothesis (Cohen 1977, Rotenberry and Wiens 1985). As the size of the effect increases the ability to detect the effect (the power) also increases (Rotenberry and Wiens 1985). The difficulty lies in determining how large an effect is to be expected. In the absence of any theoretical considerations that are independent of the hypothesis being tested , selection of an effect size becomes subjective and arbitrary (Rotenberry and Wiens 1985). It is desirable that there is an experimental basis for selecting a particular effect size. Effect size should be based on biological considerations and should be meaningful (in a biological or economical sense) rather than be based on a statistical or procedural decision (Mapstone 1995).

The <u>statistical power</u> of a monitoring program is a measure of the likelihood that an impact would be detected when one really does exist (Keough and Mapstone 1995). Power is a measure of how well a statistical procedure can differentiate between a situation and the null hypothesis and can therefore be defined as 1 minus the probability of a Type II error (Toft and Shea 1983, Gerrodette 1987, Peterman 1990). It should be noted that if a statistical analysis does reject the null hypothesis at the designated alpha level then no determination of the power of the analysis is necessary (Cohen 1973).

Statistical power analysis is necessary due to the probabilistic nature of statistical inference and its inherent error risk. Power analysis is required to indicate the optimal replication and can also be valuable to test if the planned monitoring has the required sensitivity to use statistical tests to evaluate null hypotheses (Bernstein and Zalinski 1983). Operationally power analysis is important during planning of a monitoring program to avoid wasted time, effort and resources, and to optimise a design (Toft and Shea 1983). It can also be used to interpret results when a null hypothesis is retained (Toft and Shea 1983, Peterman 1989 & 1990).

Statistical power analysis can be done before the start of data collection programs (*a priori*) or after the data is gathered (*a posteriori*). Using the relationship between power, alpha, ES, N (number of replicates) and s^2 (standard deviation) any of these parameters can be calculated if the rest are known or assumed (Winer 1971, Peterman 1990). An *a priori* power analysis is often used to determine the sample size necessary to achieve an acceptably high power (see Gerrodette 1987) and can be used to estimate the power of proposed monitoring programs (Peterman 1990). It can also be used to determine the magnitude of treatment perturbations that would be necessary to again achieve high power (see Underwood 1981, Peterman and Routledge 1983). An *a posteriori* power analysis is used to interpret the outcomes of a statistical analysis that has failed to reject a null hypothesis (Peterman 1989 & 1990).

Table 1 The four outcomes (1-4) of a statistical analysis designed to test a null hypothesis. The probability of each outcomes is presented in parentheses. Adapted from Toft and Shea (1983).

	Decision Made	
Actual situation	Null hypothesis retained	Null hypothesis rejected
Null hypothesis true	1. Correct (1-α)	2. Type I error (α)
Null hypothesis false	3. Type II error (β)	4. Correct (1-β)*

* (1-β) = power of the analysis

In recent years the realisation that the power of an analysis is an important consideration in environmental impact studies and experiments in general has been realised and addressed (Toft and Shea 1983, Peterman 1990, Fairweather 1991, Taylor and Gerrodette 1993). This is of particularly importance as monitoring programs are now having to stand up to greater legal and scientific scrutiny (Mapstone 1995). Power analysis can be valuable when planning a monitoring program, especially in the use of pilot study data to determine an adequate sampling design for detection of an effect with an acceptable probability 1-β.

5.2 Design Recommendations for the Monitoring Program at Port Stanvac

A Beyond-BACI design is recommended for the monitoring program at Port Stanvac, using two main temporal scales, these being 'Times' which will be two to three weeks apart and nested in 'Periods' which will be two to three months apart. Two 'Times' will reside in each sampling 'Period'. Such a design and allocation of sampling effort is likely to be capable of detecting a short-term pulse disturbance such as an oil spill, with the most likely change being detected at the temporal scale of 'Times'.

The Type I and Type II errors inherent in any statistical test are considered to be equally undesirable in a monitoring program and so it is recommended that both be set at 0.05. Therefore, the recommended statistical power for the monitoring program is 0.95. The only animal suitable for use as an indicator of environmental change is the prosobranch gastropod *Bembicium nanum*, and the effect size of interest is a 50% greater change in *Bembicium nanum* abundance than is seen on average in control sites.

6. References

Addessi, L. (1994) Human disturbance and long-term changes on a rocky intertidal community. *Ecological Applications* **4**, 786-797.

Andrew, N.L. and Mapstone, B.D. (1987) Sampling and the description of spatial pattern in marine ecology. *Oceanography and Marine Biology: Annual Review* **25**, 39-90.

Baker, J.M. (1991) Guidelines on biological impacts of oil pollution. *International Petroleum Industry Environmental Conservation Association (IPIECA) Report Series.* Volume **1**, 1-15.

Beauchamp, K.A. and Gowing, M.M. (1982) A quantitative assessment of human trampling effects on a rocky intertidal community. *Marine Environmental Research* 7, 279-293.

Bender, E.A., Case, T.J. and Gilpin, M.E. (1984) Perturbation experiments in community ecology: theory and practice. *Ecology* **65**, 1-13.

Bernstein, B.B. and Zalinski, J. (1983) An optimal sampling design and power tests for environmental biologists. *Journal of Environmental Management* **16**, 35-43.

Bernstein, B.B. and Zalinski, J. (1983) An optimum sampling design and power tests for environmental biologists. *Journal of Environmental Management* **16**, 35-43.

Black, R. (1979) Competition between intertidal limpets: an intrusive niche on a steep resource gradient. *Journal of Animal Ecology* **48**, 401-411.

Brosnan, D.M. and Crumrine, L.L. (1994) Effects of trampling on marine rocky shore communities. *Journal of Experimental Marine Biology and Ecology* **177**, 79-97.

Burns, K.A. and Smith, J.L. (1980) Hydrocarbons in Victorian coastal waters. *Australian Journal of Marine and Freshwater Research* **31**, 251-256.

Carefoot, T. H. and Simpson R. D. (1977) *Seashore Ecology.* University of Queensland Press, London.

Castilla, J.C. and Bustmante, R.H. (1989) Human exclusion from rocky intertidal of Las Cruces, central Chile: effects on *Durvillaea antarctica* (Phaeophyta, Durvilleales). *Marine Ecology Progress Series* **50**, 203-214.

Chapman, M.G. and Underwood A.J. (1996). Influences of tidal conditions, temperature and desiccation on patterns of aggregation of the high-shore periwinkle, *Littorina unifasciata*, in New South Wales, Australia. *Journal of Experimental Marine Biology and Ecology* **196**, 213-237.

Clark, R.B. (1989) *Marine Pollution.* 2nd Edition. Oxford Scientific Publications, Clarendon Press, Oxford.
Constable, A.J. (1991) The role of science in environmental protection. *Australian Journal of Marine and Freshwater Research* **42**, 527-538.

Cohen, J. (1973) Statistical power analysis and research results. *American Educational Research Journal* **10**, 225-230.

Dawson, J. (1980) *Superspill, the Future of Ocean Pollution.* Jane's, London.

Dayton, P.K. (1971). Competition, disturbance and community organization: the provision and subsequent utilization of space in a rocky intertidal community. *Ecological Monographs* **41**, 351-389.

Denley, E.J. and Underwood, A.J. (1979) Experiments on factors influencing settlement, survivaal and growth of two species of barnacle in NSW. *Journal of Experimental Marine Biology and Ecology* **36**, 269-293.

Dethier, M.N (1984) Disturbance and recovery in intertidal pools: maintenance of mosaic patterns. *Ecological Monographs* **54**, 99-118.

Dethier, M.N (1984) Disturbance and recovery in intertidal pools: maintenance of mosaic patterns. *Ecological Monographs* **54**, 99-118.

Eberhardt, L.L (1978) Appraising variability in population studies. *Journal of Wildlife Management* **42**, 207-238.

Eberhardt, L.L and Thomas, J.M. (1991) Designing environmental field studies. *Ecological Monographs* **61**, 53-73.

Ehrhardt, M.G. and Burns, K.A. (1993) Hydrocarbons and related photo-oxidation products in Saudi Arabian Gulf coastal waters and hydrocarbons in underlying sediments and bioindicator bivalves. *Marine Pollution Bulletin* **27**, 187-197.

Emlen, J.M. (1989) Terrestrial population models for ecological risk assessment : a state of the art review. *Environmental Toxicology and Chemistry* **8**, 831-842.

Fairweather, P.G. (1990) Ecological changes due to our use of the coast: research needs versus effort. *Proceedings of the Ecological Society of Australia* **16**, 71-77.
Fairweather, P.G. (1991) Statistical power and design requirements for environmental monitoring. *Australian Journal of Marine and Freshwater Research* **42**, 555-567.

Fairweather, P.G. (1993) Links between ecology and ecophilosophy, ethics and the requirements of environmental management. *Australian Journal of Ecology* **18**, 3-19.

Faith, D.P., Humphrey, C.L. and Dostine, P.L. (1991) Statistical power and BACI designs in biological monitoring: Comparative evaluation of measures of community dissimilarity based on benthic macroinvertebrate communities in Rockhole Mine Creek, Northern Territory, Australia. *Australian Journal of Marine and Freshwater Research* **42**, 589-602.

Ganning, B., Reish, D.J. and Straughan,. D. (1984) Recovery and restoration of rocky shores, sandy beaches, tidal flata, and shallow subtidal bottoms impacted by oil spills. **In** *Restoration of Habitats Impacted by Oil Spills*. J.L. Cairns and A.L. Buikema (Eds). Butterworth, Boston, pp. 7-36.

Garrity, S.D. and Levings, S.C. (1993) Effects of an oil spill on some organisms living on mangrove (*Rhizophora mangle* L.) roots in low wave-energy habitats in Caribbean Panama. *Marine Environmental Research* **35**, 251-271.

Gerrodette, T. (1987) A power analysis for detecting trends. *Ecology* **68**, 1364-1372.

Ghazanshahi, J., Huchel, T.D. and Devinny, J.S. (1983) Alteration of southern California rocky shore ecosystems by public recreational use. *Journal of Environmental Management* **16**, 379-394.

Green, R.H. (1979) *Sampling Design and Statistical Methods for Environmental Biologists*. Wiley, New York.

Green, R.H. (1993) Application of repeated measures designs in environmental impact and monitoring studies. *Australian Journal of Ecology* **18**, 81-98.

Grigg, R.W. (1994) Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. *Marine Ecology Progress Series* **103**, 25-34.

Gunkel, W. and Gassmann, G. (1980) Oil, oil dispersants and related substances in the marine environment. *Helgolander Meeresuntersuchungen* **33**, 164-181.

Hayes, M.O., Michel, J., Montello, T.M., Aurand, D.V., Al-Mansi, A.M., Al-Moamen, A.H., Sauer, T.C. and Thayer, G.W. (1993) Distribution and weathering of shoreline oil one year after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 135-142.

Herricks, E.E. and Cairns, J. Jr. (1982) Biological monitoring. Part III- Receiving system methodology based on community structure. *Water Reseach or Resources* **16**, 141-153.

Hilborn, R. and Stearns, S.C. (1982) On inference in ecology and evolutionary biology: the problem of multiple causes. *Acta Biotheoretica* **31**, 145-164.

Hurlbert, S.H. (1984) Pseudoreplication and the design of ecological field experiments. *Ecological Monographs* **54**, 187-211.

Jara, H.F. and Moreno, C.A. (1984) Herbivory and structure in a midlittoral rocky community: a case in southern Chile. *Ecology* **65**, 28-38.

Karlson, R.H. and Hurd, L.E. (1993) Disturbance, coral reef communities, and changing coral reef paradigms. *Coral Reefs* **12**, 117-125.

Karr, J.R. (1987) Biological monitoring and environmental assessment: a conceptual framework. *Environmental Management* **11**, 249-256.

Kay, A.M. and Liddle, M.J. (1989) Impact of human trampling in different zones of a coral reef flat. *Environmental Management* **13**, 509-520.

Kennelly, S.J. (1987) Physical disturbances in an Australian kelp community. I. Temporal effects. *Marine Ecology Progress Series* **40**, 145-153.

Keough, M.J. and Mapstone, B.D. (1995) *Protocols for designing marine ecological monitoring programs associated with BEK mills*. National Pulp Mills Research Program Technical Report No. 11. CSIRO, Canberra.

Kingsford, M.J., Underwood, A.J. and Kennelly, S.J. (1991) Humans as predators on rocky reefs in New South Wales, Australia. *Marine Ecology Progress Series* **72**, 1-14.

Krupp, F. and Jones, D.A. (1993) The creation of a marine sanctuary after the 1991 Gulf War oil spill. *Marine Pollution Bulletin* **27**, 315-323.

Kureishy, T.W. (1993) Concentration of heavy metals in marine organisms around Qatar before and after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 183-186.

Lewis, J.R. (1978) The implications of community structure for benthic monitoring studies. *Marine Pollution Bulletin* **9**, 64-67.

Literathy, P. (1993) Considerations for the assessment of environmental consequences of the 1991 Gulf War. *Marine Pollution Bulletin* **27**, 349-356.

Loya, Y. and Rinkevich, R. (1980) Abortion effects incoral induced by oil pollution. *Marine Ecology Progress Series* **3**, 167-180.
Mapstone, B.D. (1995) Scalable decision rules for environmental impact studies: effect size, type I, and type II errors. *Ecological Applications* **5**, 401-410.

McGuiness, K.A. (1987a) Disturbance and organisms on boulders I. Patterns in the environment and the community. *Oecologia* (Berlin) **71**, 409-419.

McGuiness, K.A. (1987b) Disturbance and organisms on boulders II. Causes of patterns in diversity and abundance. *Oecologia* (Berlin) **71**, 409-419.

Menge, B.A. and Farrell, T.M. (1989) Community structure and interaction webs in shallow marine hard-bottom communities: test of an environmental stress model. ***Adv. Ecol. Res.*** **19**, 189-262.

Millard, S.P., Yearsley, J.R. and Lettenmaier, D.P. (1985) Space-time correlation and its effects on methods for detecting aquatic ecological change. *Canadian Journal of Fisheries and Aquatic Science* **42**, 1391-1400.

Osenberg, C.W., Schmitt, R.J., Holbrook, S.J., Abu-Saba, K.E. and Flegal, A.R. (1994) Detection of environmental impacts: natural variability, effect size, and power analysis. *Ecological Applications* **4**, 16-30.

Peterman, R.M. (1989) Application of statistical power analysis to the Oregon coho salmon (*Oncorhynchus kisutch*) problem. *Canadian Journal of Fisheries and Aquatic Sciences* **46**, 1183-1187.

Peterman, R.M. (1990) Statistical power analysis can improve fisheries research and management. *Canadian Journal of Fisheries and Aquatic Science* **47**, 2-15.

Peterman, R.M. and Routledge, R.D.(1983) Experimental management of Oregon coho salmon (*Oncorhynchus kisutch*): designing for yield of information. *Canadian Journal of Fisheries and Aquatic Sciences* **40**, 1212-1223.

Peters, E.C., Meyers, P.A., Yevich, P.P. and Blake, N.J. (1981) Bioaccumulation and histopathological effects of oil on a stony coral. *Marine Pollution Bulletin* **12**, 333-339.

Peterson, C.H. (1993) Improvement of environmental impact analysis by application of principles derived from manipulative ecology: Lessons from coastal marine case histories. *Australian Journal of Ecology* **18**, 21-52.

Reimer, A.A. (1975) Effects of crude oil on corals. *Marine Pollution Bulletin* **6**, 39-43.

Ritchie, W. (1993) Environmental impacts of the *Braer* oil spill and development of a strategy for the monitoring of change and recovery. *Marine Policy* **17**, 434-448.
Rong-Quen, J., Chang-Feng, D. and Kun-Hsiung, C. (1994). Monitoring of hard substrate communities. **In** *Biomonitoring of Coastal Waters and Estuaries*. Ed. K.J..M. Kramer. CRC Press, Boca Raton pp 285-310.

Rotenberry, J.T. and Wiens, J.A. (1985) Statistical power analysis and community-wide patterns. *American Naturalist* **125**, 164-168.

Sauer, T.C., Brown, J.S., Boehm, P.D., Aurand, D.V., Michel, J. and Hayes, M.O. (1993) Hydrocarbon source identification and weathering characterization of intertidal and subtidal sediments along the Saudi Arabian coast after the Gulf War oil spill. *Marine Pollution Bulletin* **27**, 117-134.

Schoch, G.C. and Dethier, M.N (1996) Scaling up: the statistical linkage between organismal abundance and geomorphology on rocky intertidal shorelines. *Journal of Experimental Marine Biology and Ecology* **201**, 37-72.

Selye, H. (1973) The evolution of a stress concept. *American Scientist* **61**, 692-699.

Skilleter, G.A. (1995) Environmental disturbance (Chapter 17) **In** *Coastal Marine Ecology of Temperate Australia*. A.J. Underwood and M.G. Chapman (Eds) University of New South Wales Press Ltd, Sydney. pp 263-276.

Sousa, W. (1984) The role of disturbance in natural communities. *Annual Review of Ecology and Systematics* **15**, 353-392.

Southward, A.J. (1991) Forty years of changes in species composition and population density of barnacles on a rocky shore near Plymouth. *Journal of the Marine Biological Association of the U.K.* **71**, 495-513.

Stewart-Oaten, A., Murdoch, W.W. and Parker, K.R. (1986) Environmental impact assessment: 'pseudoreplication' in time? *Ecology* **67**, 929-940.

Strong, D.R. Jr. (1980) Null hypotheses in ecology. *Synthese* **43**, 271-285.

Suchanek, T.H. (1993) Oil impacts on marine invertebrate populations and communities. *American Zoologist* **33**, 510-523.

Taylor, B.A. and Gerrodette, T. (1993) The uses of statistical power in conservation biology: the Vaquita and Northern Spotted Owl. *Conservation Biology* **7**, 489-500.

Toft, C..A. and Shea, P.J. (1983) Detecting community-wide patterns: estimating power strengthens statistical inference. *American Naturalist* **122**, 618-625.

Underwood, A.J. (1981) Techniques of analysis of variance in experimental marine biology and ecology. *Oceanography and Marine Biology: Annual Review* **19**, 513-605.

Underwood, A.J. (1989) The analysis of stress in natural populations. *Biological Journal of the Linnean Society* **37**, 51-98.

Underwood, A.J. (1991) Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* **42**, 569-587.

Underwood, A.J. (1992) Beyond-BACI: the detection of environmental impacts on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* **161**, 145-178.

Underwood, A.J. (1993) The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. *Australian Journal of Ecology* **18**, 99-116.

Underwood, A.J. (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. *Ecological Applications* **4**, 3-15.

Underwood, A.J. (1994a) Rocky intertidal shores. **In** *Marine Biology*. L.S. Hammond and R.N. Synot (Eds) Longman Cheshire Pty. Ltd., Melbourne, pp. 272-296.

Underwood, A.J. and Chapman, M.G. (1995) Rocky shores. **In** *Coastal Marine Ecology of Temperate Australia*. A.J. Underwood and M.G. Chapman (Eds) University of New South Wales Press Ltd, Sydney, pp. 55-82.

Underwood, A.J. and Denley, E.J. (1984). Paradigm, explanations and generalisations in models for the structure of intertidal communities on rocky shores. **In** *Ecological Communities:conceptual issues and the evidence*. D.R. Strong jr, D. Simberloff, L.G. Abele and A.B. Thistle (Eds). Princeton University Press, New Jersey, U.S.A., pp. 151-180.

Underwood, A.J. and Fairweather, P.G. (1989) Supply-side ecology and benthic marine assemblages. *Trends in Ecology and Evolution* **4**, 16-20.

Underwood, A.J. and Kennelly, S.J. (1990) Pilot Studies for designs of human disturbance of intertidal habitats in New South Wales. *Australian Journal of Marine and Freshwater Research* **41**, 165-173.

Underwood, A.J. and Peterson, C.H. (1988) Towards an ecological framework for investigating pollution. *Marine Ecology Progress Series* **46**, 227-234.

Volkman, J.K., Holdsworth, D.G., Neill, G.P. and Bavor H.J.Jr (1992). Identification of natural, arthropogenic and petroleum hydrocarbons in aquatic sediments. *The Science of the Total Environment*, **112**, 203-219.
Walters, C.J. (1993) Dynamic models and large scale field experiments in environmental impact assessment and management. *Australian Journal of Ecology* **18**, 53-61.

Ward, D.M., Atlas, R.M., Boehm, P.D. and Calder, J.A. (1980) Microbial biodegradation and chemical evolution of oil from the Amoco spill. *Ambio* **9**, 277-283.

Ward, T.J. and Jacoby, C.A. (1992) A strategy for assessment and management of marine ecosystems: Baseline and monitoring studies in Jervois Bay, a temperate Australian embayment. *Marine Pollution Bulletin* **25**, 163-171.

Warwick, R.M. (1986) A new method for detecting pollution effects on marine macrobenthic communities. *Marine Biology* **92**, 557-562.

Warwick, R.M. (1988a) Analysis of community attributes of the macrobenthos of Frierfjord/Langesundfjord at taxonomic levels higher than species. *Marine Ecology Progress Series* **46**, 167-170.

Warwick, R.M. (1988b) The level of taxonomic discrimination required to detect pollution effects on marine benthic communities. *Marine Pollution Bulletin* **19**, 259-268.

Warwick, R.M. and Clarke, K.R. (1993) Increased variability as a symptom of stress in marine communities. *Journal of Experimental Marine Biology and Ecology* **172**, 215-226.

Winer, B.J. (1971) *Statistical Principles in Experimental Design.* 3rd edition. McGraw-Hill, New York.

Womersley, H.B.S. and Thomas, I.M. (1976) Intertidal ecology. **In** *Natural History of the Adelaide Region.* C.R. Twidale, M.J. Tyler and B.P. Webb (Eds). Royal Society of South Australia Inc., Adelaide, pp. 175-185.

Young, C.M. (1990) Larval predation by epifauna on temperate reefs: scale, power and the scarcity of measurable effects. *Australian Journal of Ecology* **15**, 413-426.

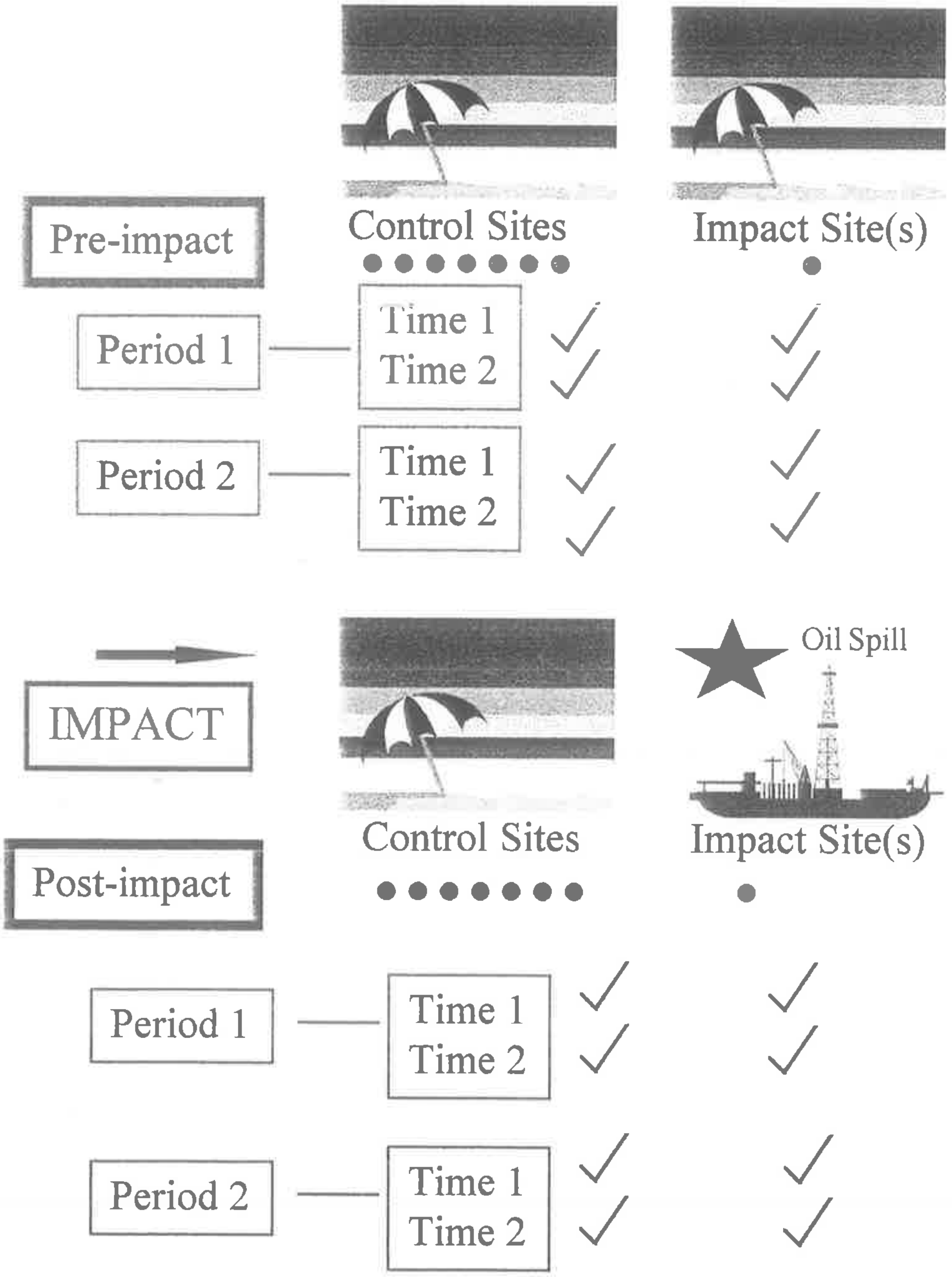
Zar, J.H. (1984) *Biostatistical Analysis*. Second Edition. Prentice-Hall International, Inc., New Jersey, U.S.A.

Attachment B

Flow Chart for an Oil-Spill Impact

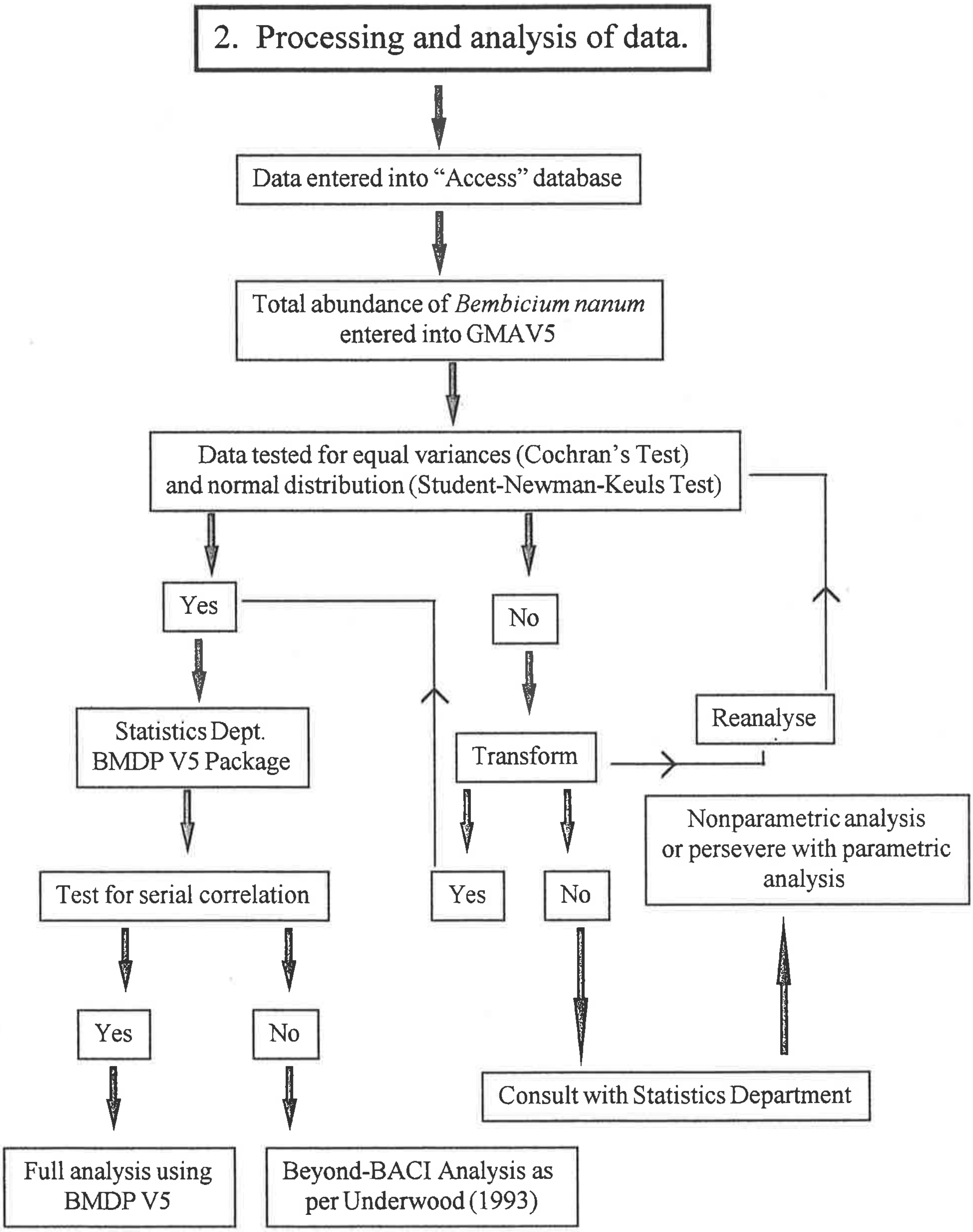
Attachment B. Flow Chart Indicating Stages Involved in Intertidal Monitoring for an Oil-Spill Impact.

1. Sampling Schedule



✓ = abundance counts of *Bembicium nanum* using 7 x $0.25m^2$ quadrats.

Attachment B. Flow Chart Indicating Stages Involved in Intertidal Monitoring for an Oil-Spill Impact.



A Monitoring Program for Port Stanvac, Gulf St Vincent.

Background

Mobil's Port Stanvac Oil Refinery receives crude oil for refinement and exports refined oil and other products. One of the potential problems associated with refinery operation is accidental release of oil into the marine environment. In the event of oil entering the ocean it is likely to impact on the rocky intertidal region. Therefore, an intertidal monitoring program is needed in Gulf St Vincent (GSV).

In addition to oil, other human and natural disturbances can affect intertidal assemblages in GSV. These include sand dredging, natural sand drift, the Mitsubishi storm water outfall (which gives an intermittent, seasonal discharge of water runoff), the SA Water secondary treated sewage discharge from Christies Beach, refinery effluent outfall, and creek inputs (e.g. Christies Creek and Onkaparinga River Estuary). The private ownership of the refinery can also affect intertidal animals and plants by protecting them from the trampling and collection pressure that occurs in similar, but publicly accessed, areas.

Aims

The specific aims of this project are to:

1. Establish the baseline (existing) condition of the intertidal area at Port Stanvac with respect to suitable indicator organisms.
2. Design an ongoing monitoring program capable of detecting an oil spill impact and differentiating this from effects associated with confounding factors.
3. Investigate the impact of trampling and collection pressure on animals whose characteristics and ecology suggest a propensity for being affected by such pressures.

The third aim will not be discussed in this summary report.

Bioindicator Animal(s)

Environmental stress (such as oil pollution) can be viewed as a biological phenomenon since it acts on living organisms. Pollutants initially affect the health of individual organisms but changes at this level can accumulate and result in higher level changes e.g. at population level. This monitoring program will use a population level approach.

The small herbivorous marine gastropod *Bembicium nanum* was the only species present in sufficient densities at the majority of study sites to be used as a biological indicator. It shows some response to oil exposure (petrol and crude) but was not extremely sensitive, and does not travel large distances (and thus is unlikely to be able to avoid local oil exposure). It also has a similar lifestyle to the majority of gastropods at the study sites, potentially representing more general change in an affected area.

Project Phases

1. Pilot Study: site identification and determination of optimal sampling protocols.
2. Preliminary Monitoring: examination of GSV sites for differences over time both within and between sites.
3. Modelling: computer simulation of oil transport to identify likely grounding sites (in collaboration with Dr. Bye, Flinders University).
4. Recommendations for ongoing monitoring.

Further Information

Leanne Piller
Dept. of Zoology, University of Adelaide
ph. 8303 3998 or 8337 4705 (hm)
Email: lpiller@zoology.adelaide.edu.au

Results

Pilot Study

Nine sites, extending from Kingston Park to Robinson Point, were chosen for ongoing monitoring during 1995 and 1996. The sites include three within the boundaries of Port Stanvac.

Optimal size and number of quadrats and relevant physical parameters were selected for use in the preliminary monitoring. Three different sized quadrats and three methods of organism census were trialled.

Preliminary Monitoring of GSV Sites

- Community data were obtained, but animals were the primary focus of the study.
- A 15 month study of chosen sites was conducted using optimal sampling strategies.
- Two sub-zones within the mid-eulittoral zone were monitored using a Beyond-BACI design (see below).
- Sites showed similar assemblages in the 'upper' sub-zone, with small herbivorous gastropods tending to be numerically dominant, in particular *Bembicium nanum*.
- Sites were differentially affected by disturbances during this phase of the project, including a northward sand drift and storm movement of mobile substrate.

The Best Monitoring Design for Port Stanvac

A Beyond-BACI design is recommended for the preliminary and ongoing monitoring program (Underwood 1991, 1992 & 1993). This involves using a single 'impact' site and multiple 'control' sites, sampled many times before and after an impact occurs. The purpose of this design is to detect whether there are changes at the 'impact' site and if these changes are greater than would be expected on average at the 'control' sites. Data collected during the sampling is analysed using a statistical procedure known as Analysis of Variance (ANOVA).

Modelling

- There were some seasonal patterns in oil transport but this was highly variable depending on the time of release and prevalent wind, wave and tidal conditions.
- Therefore, retention of a broad spread of sites within GSV is recommended.

Recommendations for the Ongoing Monitoring Program

- Ongoing monitoring using a Beyond-BACI design.
- 8 rocky sites extending from Kingston Park to Robinson Point are suitable for ongoing monitoring.
- The designated area at each study site should be sampled using optimal sampling strategies.
- In the event of an oil spill the affected site(s) should serve as impact site(s) while the remaining sites would act as controls.
- All sites should be sampled on the same day at low tide for each sampling time.
- The animal to be sampled is *Bembicium nanum* and the number in each of four size classes should be recorded.
- The presence of oil should be subjectively assessed (on a scale of 0-4).
- The impact to be detected is a 50% greater change (±) in the abundance of *Bembicium nanum* at the impact site(s) than is seen on average at 'control' sites.

Related Literature

Underwood, A.J. (1991) Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* **42**, 569-587.

Underwood, A.J. (1992) Beyond BACI: The detection of environmental impact on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* **161**, 145-178.

Underwood, A.J. (1993) The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. *Australian Journal of Ecology* **18**, 99-116.

BR= bedrock or sand 'cemented' reef-rock, B= boulder, C= cobble, P/G= pebble or gravel, S/G= sand or grit.

Data Sheet for Port Stanvac Monitoring Program						% Substrate		Date			Recorded by:
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site											
Quad 1											
Quad 2											
Quad 3											
Quad 4											
Quad 5											
Quad 6											
Quad 7											
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site											
Quad 1											
Quad 2											
Quad 3											
Quad 4											
Quad 5											
Quad 6											
Quad 7											
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site											
Quad 1											
Quad 2											
Quad 3											
Quad 4											
Quad 5											
Quad 6											
Quad 7											
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site											
Quad 1											
Quad 2											
Quad 3											
Quad 4											
Quad 5											
Quad 6											
Quad 7											

Oil-0=nil, 1=old weathered tar, 2= fresh oil sheen, 3= oil as obvious thin film, 4= oil as thick film (thicker and in greater volume than 3)

BR= bedrock or sand 'cemented' reef-rock, B= boulder, C= cobble, P/G= pebble or gravel, S/G= sand or grit.

Data Sheet for Port Stanvac Monitoring Program				Date	11/11/96	% Substrate					Recorded by:Leanne Piller
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Kingston Park											
Quad 1		2	24		0	100					
Quad 2			109	1	0	100					
Quad 3		4	45		0	100					
Quad 4		3	77		0	100					
Quad 5			85		0	95		5			
Quad 6		3	79		0	100					
Quad 7		1	52	1	0	98			2		
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Marino											
Quad 1		2	22	4	0	100					
Quad 2		10	49	10	0	100					
Quad 3		10	34	17	0	100					
Quad 4		13	47	18	0	100					
Quad 5		9	12	3	0	95		5			
Quad 6		6	29	4	0	98		2			
Quad 7		15	47	6	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Hallett Cove											
Quad 1		2	26		0		30	60		10	
Quad 2		4	21		0			95		5	
Quad 3		2	11		0			95		5	
Quad 4		5	31		0			100			
Quad 5		2	32		0		20	75		5	
Quad 6		1	29		0			95	2	3	
Quad 7			28		0			100			
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PNS											
Quad 1			7	20	0	100					
Quad 2			12	15	0	100					
Quad 3			5	6	0	100					
Quad 4			17	24	0	100					
Quad 5			6	12	0	100					
Quad 6			6	3	0	100					
Quad 7			3	8	0	100					

Oil-0=nil, 1=old weathered tar, 2= fresh oil sheen, 3= oil as obvious thin film, 4= oil as thick film (thicker and in greater volume than 3)

BR= bedrock or sand 'cemented' reef-rock, B= boulder, C= cobble, P/G= pebble or gravel, S/G= sand or grit.

Data Sheet for Port Stanvac Monitoring Program				Date	11/11/96	% Substrate					Recorded by:Leanne Piller
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Robinson Point											
Quad 1			5	39	0	95				5	embedded reef-rock
Quad 2			2	50	0	98				2	stable substrate
Quad 3			5	78	0	100					
Quad 4			2	61	0	100					
Quad 5			1	47	0	100					
Quad 6			9	89	0	100					
Quad 7			2	92	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS1											
Quad 1		17	66		0	100					
Quad 2		55	77		0	100					
Quad 3		32	57		0	95		5			
Quad 4		19	67		0	100					
Quad 5		26	90		0	98			2		
Quad 6		21	85		0	100					
Quad 7		17	78		0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS2											
Quad 1		17	99		0	100					
Quad 2		16	76		0	100					
Quad 3		7	119		0	100					
Quad 4		8	92		0	100					
Quad 5		15	98		0	100					
Quad 6		14	60		0	100					
Quad 7		2	54		0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS3											
Quad 1		7	37	4	0	100					
Quad 2		4	54	9	0	100					
Quad 3		7	55	2	0	100					
Quad 4		1	40	3	0	100					
Quad 5		9	50	3	0	100					
Quad 6		6	79	3	0	100					
Quad 7		4	89	3	0	100					

BR= bedrock or sand 'cemented' reef-rock, B= boulder, C= cobble, P/G= pebble or gravel, S/G= sand or grit.

Data Sheet for Port Stanvac Monitoring Program				Date	17/10/96	% Substrate					Recorded by:Leanne Piller
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site KP											
Quad 1		1	22		0	100					
Quad 2		1	43	2	0	100					
Quad 3		3	23		0	100					
Quad 4			22		0	95		5			
Quad 5			38		0	100					
Quad 6		4	75		0	100					
Quad 7		1	45	1	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Hallett Cove											
Quad 1		1	9		0		20	70	5	5	
Quad 2		2	18		0		33	55	5	7	
Quad 3			18		0		50	50			
Quad 4		1	15		0		15	75	5	5	
Quad 5		1	24	1	0		45	50		5	
Quad 6		1	13		0		20	75		5	
Quad 7		4	24		0		20	70	5	5	
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS1											
Quad 1		9	96		0	100					
Quad 2		13	105		0	100					
Quad 3		21	128		0	100					
Quad 4		10	110		0	100					
Quad 5		8	85		0	100					
Quad 6		6	105		0	100					
Quad 7		5	131		0	95			5		
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS2											
Quad 1		27	101	1	0	100					
Quad 2		48	77		0	100					
Quad 3		39	108		0	100					
Quad 4		50	95		0	100					
Quad 5		33	83		0	100					
Quad 6		50	79		0	100					
Quad 7		42	97		0	100					

Oil-0=nil, 1=old weathered tar, 2= fresh oil sheen, 3= oil as obvious thin film, 4= oil as thick film (thicker and in greater volume than 3)

BR= bedrock or sand 'cemented' reef-rock, B= boulder, C= cobble, P/G= pebble or gravel, S/G= sand or grit.

Data Sheet for Port Stanvac Monitoring Program						% Substrate		Date	17/10/96		Recorded by:Leanne Piller
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Marino											
Quad 1		8	28	12	0	100					
Quad 2		1	5	1	0	100					
Quad 3		7	15	2	0	100					
Quad 4		2	11	1	0	100					
Quad 5		8	32	3	0	100					
Quad 6		4	14	4	0	100					
Quad 7		6	25	23	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PS3											
Quad 1		9	43	4	0	100					
Quad 2		20	74	2	0	100					
Quad 3		5	95	2	0	100					
Quad 4		10	129		0	100					
Quad 5		1	93	2	0	100					
Quad 6		4	90		0	100					
Quad 7		6	75	1	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site PNS											
Quad 1			10	16	0	100					
Quad 2			4	3	0	100					
Quad 3			1	3	0	100					
Quad 4			10	7	0	100					
Quad 5			10	23	0	100					
Quad 6			6	24	0	100					
Quad 7			10	31	0	100					
Bembicium nanum	new	small	med	large	Oil (0-4)	BR	B	C	P/G	S/G	Comments
Site Robinson Point											Substrate = embedded reef-
Quad 1			2	55	0	100					rock at this site
Quad 2			3	48	0	100					
Quad 3			2	62	0	100					
Quad 4			5	53	0	100					
Quad 5			1	48	0	100					
Quad 6			2	64	0	100					
Quad 7			5	88	0	100					

Oil-0=nil, 1=old weathered tar, 2= fresh oil sheen, 3= oil as obvious thin film, 4= oil as thick film (thicker and in greater volume than 3)