



Water use strategy of *Melaleuca halmaturorum* in a saline swamp.

submitted by

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Abstract

The water use strategy of *Melaleuca halmaturorum* was investigated in the saline ephemeral swamps of South Eastern South Australia to understand (1) the effect of the wetland vegetation on the groundwater balance and (2) the survival mechanisms and reasons for the decline in health of *M. halmaturorum* in the region.

Trees were investigated over a 12-18 month period at four sites in the region which differed in groundwater salinity and degree of waterlogging. Water use was quantified primarily with the heat pulse technique combined with short term measurements of transpiration at the leaf and canopy level. The proportion of groundwater used was quantified by identifying the sources of the water in the trees using the naturally occurring stable isotopes of water and measurements of root distribution. Soil and plant water potential, soil waterlogging and groundwater fluctuations were measured to identify the conditions in the root zone and the physiological limits to plant water uptake.

Results indicated that *M. halmaturorum* used 0.7 to 4 mm/day of water (250-800 mm/yr). The differences in transpiration rate were controlled by differences in leaf area index and sapwood area among sites and depended on groundwater salinity and the presence of waterlogging. Soil water potential was dominated by osmotic potential and reached -12 MPa in the surface soils. Water use was significantly below potential evapotranspiration when groundwater salinity was high. Water was taken from saline groundwater and soil as a result of the ability of *M. halmaturorum* to reach low leaf water potentials (<-5 MPa). Evidence of soil waterlogging was found in soils at some of the sites, and where this was combined with salinity there was a further decrease in water use.

In the ephemeral swamps Duck Island, Hanson, and Lesron, *M. halmaturorum* used groundwater from the soil surface at the end of winter in response to groundwater rise and inundation of the soil profile. Water was then used from deeper in the soil profile over the summer in response to salt accumulation in the surface soils. Where groundwater salinity was lowest (Hansons and Jaffray; 8 - 14 dS/m), 1.5 to 3.5 mm/day of groundwater was used and annual groundwater use was ~280 mm. Where groundwater salinity was high (Duck Island; 63 dS/m), 0.5 to 2 mm/day of groundwater was used and annual groundwater use was ~600 mm. Where groundwater was highly saline, groundwater use by *M. halmaturorum* resulted in annual net groundwater discharge of ~100 mm. Where

groundwater was of a lower salinity, annual net groundwater discharge was estimated at ~500 mm. At Lesron, where long term waterlogging was combined with high salinity, ~0.6 mm/day of water was used from the top 20 cm of the soil surface. A large proportion of this water source may have been groundwater, carried to the root system by capillary rise, resulting in annual groundwater use of ~150 mm. As a result of the shallow rooting depth at this site, salt accumulation in the surface soil over summer resulted in a decline in health.

These processes of root water uptake in response to a falling watertable and salt accumulation were represented through a simple analytical model which simulated the change in groundwater depth (Z_{gw}) and the salt front (Z_{th}) in response to groundwater use by *M. halmaturorum*. The basic assumptions of the model were that (1) root water uptake occurred from the shallowest depth where water was available, (2) the minimum leaf water potential represented the plant threshold to water uptake and (3) the transpiration rate was constant and was dependent on the leaf area and the distance of roots from the groundwater.

It was concluded that *Melaleuca halmaturorum* used significant amounts of groundwater as a result of a combination of plant ecophysiological and site environmental characteristics. The ability to use saline groundwater was enhanced by low leaf water potentials and a dynamically responsive root system along with environmental characteristics such as annual groundwater fluctuations that maintained salinity in the root zone at baseline levels. The presence of a dynamically responsive root system allowed the rapid response to adverse conditions in the root zone and the physiological ability to take up water from saline soils resulted in the ability to use soil and groundwater over a range of salinities. The rise of groundwater to the soil surface every year resulted in the dilution and leaching of salt in the unsaturated zone. Although this groundwater was saline it was often fresher than water in the unsaturated zone. These groundwater fluctuations assisted in maintaining the health of *Melaleuca* communities in these groundwater discharge areas.

Declaration of originality

I certify that this thesis does not contain or incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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Publications associated with this thesis

Journal Papers

Mensforth L.J. and Walker G.R. (1996) Root dynamics of *Melaleuca halmaturorum* in response to fluctuating saline groundwater. *Plant and Soil*. 184(1).

Mensforth L.J., Dunin F.X. and Walker G.R. (1996) Water use strategies of *Melaleuca halmaturorum* in a saline ephemeral swamp. In prep.

Conference Papers

Mensforth L.J. and Walker G.R. (1994) Water use of plants in periodically saline and waterlogged environments. Productive use of saline land workshop. Echuca. Vic. March 14-17.

Mensforth L.J. and Walker G.R. (1995) Use of stable isotopes of water to help determine rates of soil salinisation in vegetated areas. IAEA International Symposium on Isotopes in Water Resources Management, Vienna, Austria. 20 - 24 March. pp 258-259.

Mensforth L.J. and Walker G.R. (1995) Water use strategies of *Melaleuca halmaturorum* in a saline ephemeral swamp, south Australia. Ecological Society of America Annual meeting. Snowbird, Utah. USA, 30 July - 3 August. pp 181.

Mensforth L.J. and Walker G.R. (1996) Water use of *Melaleuca halmaturorum* in a saline swamp. 4th national Conference and Workshop on the Productive use and Rehabilitation of Saline Lands. Albany, W.A., 25-30 March.

Mensforth L.J., Thorburn P.J., and Walker G.R. (1996) Groundwater - Tree Interactions in Saline Groundwater Discharge Areas: Two Case Studies. AGU WPGM, Brisbane.

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Chapter 1: General Introduction and Literature Review

1.1 General Background

The ways in which trees use water in the presence of a saline groundwater table has a number of hydrological and ecophysiological implications. From a hydrological perspective it is necessary to understand the role that vegetation plays in the water balance, in particular the groundwater balance. This may assist in an understanding of the use of trees to lower saline groundwater where dryland salinity occurs. From an ecophysiological perspective, what is of interest is the tolerance mechanisms of plants in environments where salinity and waterlogging are primary stresses. To understand how trees survive in these environments requires knowledge of above ground processes, below ground processes, and how these processes interact. This information will contribute to a general understanding of the water use strategy of trees in saline environments. To introduce this study of groundwater use by *Melaleuca halmaturorum*, I will begin by reviewing the interaction of the ecophysiological response of plants to salinity, waterlogging, and the combined influence. I will then discuss the whole plant water use strategy response where these conditions occur and finally the groundwater use by trees in saline and waterlogged areas. The particular species under investigation in this thesis, *M. halmaturorum*, will be described, as well as the region under investigation.

1.2 Ecophysiological Response to Salinity and Waterlogging

A saline environment for plants is one in which there is a high concentration of soluble salts in the soil or the solution in which plants grow (Flowers and Yeo, 1986). This reduces the free energy of the water available to the plant. High salt concentrations in the substrate can therefore reduce plant growth by osmotic effects, leading to water stress. Ion specific effects, which lead to ion imbalance or toxicity, can also reduce plant growth (Lessani and Marschner, 1978).

Waterlogging can occur with salinity in coastal swamps, in poorly drained irrigated soils, and in low lying land subject to primary or secondary salinisation (Barrett-Lennard, 1986). When an environment is waterlogged, the availability of oxygen to the plant is reduced. Gases generally diffuse 10,000 times more slowly in water than in air therefore oxygen, required for root respiration, will be less available in the rooting medium in waterlogged environments, and carbon dioxide and ethylene will tend to build up in the medium close to the root (Setter and Waters, 1989). Nutrient imbalance may also affect plants in waterlogged

environments, as some ions are made more available in the anoxic environment (Ponnamperuma, 1972). Waterlogged environments have also been observed to increase the adverse effects of salinity (i.e. Allen et al, 1996). The evidence for this salinity/waterlogging interaction will be the focus of the review of waterlogging.

Some plants have mechanisms which provide a tolerance to saline and waterlogged conditions. Many of these mechanisms influence plant water use strategies. These will be summarised in the following sections in relation to ion and water relations, water use, and root dynamics. Mechanisms of tolerance in halophytes were reviewed by Flowers et al (1977) and by Greenway and Munns (1980) for non-halophytes. For a wider review of the response of plants to flooding and waterlogging, see Hook (1984). For a review of the adaptation of plants to flooding with salt water see Wainwright (1984).

1.2.1 Ion and water relations

Excess salts in the environment result in a decrease in growth of many plants (Munns and Termatt, 1986). This is primarily caused by a decrease in new leaf expansion and subsequently by an increase in old leaf death (Munns, 1993). The decline in new leaf expansion is thought to be a result of a ^{hormonal} message from the root to the shoot in response to drought in the root zone (Munns and Termatt, 1986; Ortiz et al, 1994). Old leaf death is a secondary response and is thought to occur as a result of salt import into the leaf (Oertelli, 1968; Greenway and Munns, 1980). It has been recently argued that salt taken up by the plant does not directly control growth by affecting turgor, photosynthesis or the activity of enzymes but rather the build up of salt in the leaves hastens their death (Munns, 1993). The loss of leaves affects the supply of assimilates or hormones to the growing region, and thereby affects growth (Munns, 1993).

Many plants have mechanisms to prevent salt entering the leaf cytoplasm. These mechanisms can occur at the root cell membranes or the leaf cell membranes and serve to sequester salt in vacuoles, export it from the leaf, or transport it around the plant (Wickens and Cheesman, 1989; Braun et al, 1986; Blumwald and Poole, 1985; Garbarino and Dupont, 1988; Hajibagheri et al 1985; Watad et al, 1986; Sze, 1983; Lauchli, 1972).

Some plants are able to remove ions from the cytoplasm of leaf cells by compartmenting them in the vacuole using similar active and passive flux mechanisms as in the root cells (Munns et al, 1983; Yeo, 1981; Kolb et al, 1987; Hedrich and Schroeder, 1989; Marcar and Termaat, 1990). Compatible solutes are used in the cytoplasm to balance the potential

gradients, prevent dehydration of the cytoplasm, and maintain cell turgor (Flowers et al, 1977; Field, 1985; Morris, 1980). Compartmentation in the vacuoles of leaf cells of halophytes maintains osmotic potential, and so turgidity of the leaves, while at the same time preventing metabolic damage to the leaves (Flowers and Yeo, 1986). Compartmentation also ensures that these plants can survive through maintaining a high cell water content in the presence of a low external water potential caused by high salinity (Flowers et al, 1977). Non-halophytes, however, may rely on organic solutes for osmoregulation, because of the inability to compartmentalise ions in the leaf cells. More tolerant plants are able to osmotically adjust using Na and Cl ions, therefore not having to expend energy to produce organic solutes (Alarcon et al, 1993). Osmotic adjustment has been found to occur in response to salinity in many plants including tomato cultivars (Alarcon et al, 1994, 1993), *Casuarina* and *Allocasuarina* (Luard and El-Lakany, 1984), *Atriplex* species (Glenn et al; 1992), and mangroves (Naidoo, 1985).

Some plants may also transport Na and Cl ions out of the leaf, through salt glands or bladders in the leaf (Sutcliffe, 1986; Hill and Hill, 1976), or through phloem translocation (Lessani and Marschner, 1978). These glands and bladders are found in some *Atriplex* species and some Mangrove species (Sutcliffe, 1986).

The reduction in available oxygen in waterlogged environments will result in an energy deficiency for aerobic metabolic processes. This causes a break down of the active transport processes in cell membranes and therefore the ion permeability properties of plant cells (Setter and Waters, 1989). Waterlogging under saline conditions has been found to increase the uptake of Na and Cl into shoots and decrease K and Ca as a result of a decrease in the selectivity of K over Na (Barrett-Lennard, 1986; Kriedman and Sands, 1984; West, 1978; John et al, 1977; Galloway and Davidson, 1993; Marcar, 1993; Craig et al, 1990). The accumulation of salt in the shoot leads to shoot senescence and adverse effects on growth, as mentioned previously (John et al, 1977, West and Black, 1978; West and Taylor, 1980a; West and Taylor 1980b; Kriedemann and Sands, 1984).

Water absorption is also reduced in waterlogged environments as a result of reduced hydraulic conductivity in the radial pathway of the roots (Azaizeh et al, 1992). Therefore, plants that are under stress in water logged environments will show the symptoms of water stress (Blake and Reid, 1981). When *Atriplex amnicola* was treated with both salinity and hypoxia, there was no apparent interactive effect on leaf water potentials (Galloway and Davidson, 1993), although leaf osmotic potential was observed to decrease in response to the

combined effects of salinity and waterlogging in sunflower (Kriedemann and Sands, 1984). Salinity alone has also been shown to induce a progressive reduction in leaf water potential in many plants (Alarcon et al, 1993; Flowers and Yeo, 1986; Katerji et al, 1994). Structural modifications such as increases in wall extensibility, and permeability of the roots to water or leaf thickness, also help to maintain leaf water potentials in saline environments (Greenway and Munns, 1980).

Summary: Salinity results in a reduction in water potential, and osmotic adjustment often occurs to maintain turgor. Waterlogging results in an oxygen deficiency in the roots, which causes salt to accumulate in the shoots.

1.2.2. Plant growth and water use

Water uptake is a function of leaf area and leaf conductance to water. Salinity is commonly found to reduce water use of crop plants, initially through influences on stomatal conductance, and in the long term through a decline in leaf area (as discussed above) (Munns and Termaat, 1986; Kriedemann, 1986). Water use has been found to decrease in apple trees (El-Siddig and Luedders, 1994), and evapotranspiration has been found to decrease in response to irrigation with saline water (Katerji et al, 1994; Nicolas et al, 1993). Water uptake by single lupin and radish roots is reduced as a result of salt accumulation around the root (Hamza and Aylmore, 1992). Reduced water use in trees and shrubs in response to salinity has been observed (van Hylckama, 1974; Greenwood et al, 1982; George 1991; Thorburn et al, 1993a; van der Moezel and Bell, 1991). Stomatal conductance is decreased in many plants in response to salinity (Golombek and Ludders, 1993; Pezeshki et al, 1986; Ball and Farquar, 1984 a and b; Katerji et al, 1994).

Photosynthesis is also reduced in response to salinity. Reduced stomatal conductance in *E.camaldulensis* seedlings irrigated with saline water has been associated with a reduction in photosynthesis and transpiration (van der Moezel et al, 1989). The salt marsh halophyte *Plantago maritima* L. (Flanagan and Jefferies 1988; 1989b) has reduced photosynthesis in response to salinity, which is a result of a reduction in stomatal conductance rather than in photosynthetic capacity. Water use efficiency has also been found to increase in response to salinity in a similar way as is often found under drought conditions, and this is thought to be a result of low leaf conductance (Flanagan and Jefferies, 1989a).

This low stomatal conductance is thought to be regulated in response to hormonal (ie ABA) messages from the root in soils of low water potential. ABA has been found to be

produced in response to low water potentials in the root zone caused by salt in barley, cotton and saltbush (Kefu et al, 1991). An increase in ABA in the transpiration stream correlated with a decrease in leaf transpiration, leaf conductance, and shoot growth (Kefu et al, 1991). In addition, the adaptation to osmotic stress, and production of ABA, is thought to contribute to the resistance to low root oxygen in some plants (Mizrahi et al, 1972). Decreasing the transpiration rate in response to salinity is one of the mechanisms which enables the plant to improve the leaf water status and slow down the accumulation of Na and Cl in the leaves (Munns and Termaat, 1986). Plants that do not have regulatory mechanisms such as salt glands to export salt are at the mercy of the transpiration stream as to how much salt the leaves accumulate. Therefore, the control of transpiration by stomata is likely to be important in the regulation of salt concentration in the leaf tissues (Perera et al, 1994).

Flooding alone has also been found to reduce stomatal conductance in many plants, including *Melaleuca* species (Sena Gomes and Kozlowski, 1980). The effect of salinity, combined with waterlogging on water use, has been less investigated (Barrett-Lennard, 1986). Seedlings of *Eucalyptus* species were found to reduce their leaf conductance, whole plant water use, and growth, in response to combined stresses of waterlogging and salinity (van der Moezel et al, 1989; Marcar, 1993). Sunflower has reduced stomatal conductance in response to these influences (Kriedemann and Sands, 1984). Photosynthesis rates were also reduced under salinity combined with waterlogging in *Eucalyptus* species (van der Moezel et al, 1989), and in marsh grasses (Naidoo and Mundree, 1993). Hypoxia reduced the stomatal conductance and transpiration of *Atriplex amnicola*, however high salinity combined with this did not cause further declines (Galloway and Davidson, 1993). However, where vapour pressure deficits were higher, the demand on transpiration was higher, and this resulted in a reduction in stomatal conductance in response to salinity combined with hypoxia (Ali, 1988). Waterlogging combined with salinity reduced the water uptake in apple trees (West, 1978).

Waterlogging combined with salinity reduced shoot growth in barley, which showed signs of salt damage upon waterlogging (West and Taylor, 1980a), but not in rice, which has well developed aerenchyma in the roots and stems (John et al, 1977). Growth of *Eucalyptus*, *Melaleuca*, *Casuarina* and *Acacia* seedlings was reduced in response to the combined effects of salinity and waterlogging (van der Moezel et al, 1988 and 1991; Marcar 1993; Craig et al, 1990). Growth and water use of marsh plants was also reduced under these conditions (Naidoo and Mundree, 1993; Giurgevich and Dunn, 1982; Howes et al, 1986; Haller et al, 1974; Pezeshki et al, 1987; Glenn et al, 1995; Adams and Bate, 1994). Investigations of the

effect of salinity combined with flooding on bald cypress (*Taxodium distichum*) showed that growth and assimilation decreased and plants died after 2 weeks of flooding with 10 g/l NaCl water (Pezeshki, 1990; Conner, 1994). It was suggested that for bald cypress, photosynthesis may have declined in response to relatively small increases in salt concentrations in the leaves and this may have caused leaf mortality and inhibition of root functioning (Pezeshki et al, 1988; Alam, 1993). Mangroves are adapted to anaerobic saline conditions, however, high substrate salinity has been found to reduce transpiration rates through salt accumulation (Naidoo, 1985; Ball 1988). Salinity also results in reduced photosynthesis as a result of both stomatal limitation and photosynthetic capacity (Ball and Farquar, 1984a; Ball and Farquar, 1984b). Transpiration in mangroves is closely correlated with the CO₂ assimilation rate, resulting in a high water use efficiency (Andrews and Muller, 1985).

Summary: Transpiration is reduced in response to salinity, as a result of stomatal closure and leaf decline. Waterlogging results in a further decline in water use via a decrease in root permeability, unless root aeration is increased by morphological changes.

1.2.3 Anatomy and morphology adaptations: Response of the root system

Salinity and waterlogging influences root growth and development in a number of ways. The reduction in root growth in response to salinity has been seen in many plants (Katerjiet et al, 1994). The distribution and morphology of roots also changes in saline environments. Root growth was shown to increase in the shallow depths of soils in response to salinity (Rogers and West, 1993). Many studies have shown the increase in fine roots in response to saline conditions in the soil. Waterlogging in saline environments decreases root growth, which may reduce growth of shoots (Barrett-Lennard, 1986). *Atriplex amnicola* responded to combined salinity and root zone hypoxia by reduced root growth and increased death of root apices which did not recover when re-aerated (Galloway and Davidson, 1993). However, *Myriophyllum brasiliense* showed an increase in root growth, which increased the root surface area and overcame a water deficit in response to waterlogging with saline water (Haller et al, 1974).

Roots play a role in mediating shoot growth by producing hormones that control shoot growth and conductance to water as discussed in the previous section in relation to ABA and leaf conductance (Kuiper et al, 1988 and others). Therefore, the inhibition of root growth by salinity (Kurth et al, 1986; Ziden et al, 1990; Azaizeh et al, 1992; Neumann et al, 1994) may limit shoot growth by reducing the conductance of water, nutrients, and growth regulators to the developing shoot (Wadleigh et al, 1947; Zhang and Davies, 1991; Zidan et al, 1992).

In waterlogged environments, plants need to adopt transport processes which increase the availability of oxygen to the root system. Morphological adaptations such as pneumatophores and aerenchyma are present in plants characteristic of waterlogged soils which enable them to maintain adequate internal aeration, and so maintain ion regulation and root growth (Wainwright, 1984; Naidoo and Mundree, 1993). The formation of aerenchyma external to vascular elements and the production of adventitious roots is stimulated by ethylene production (Kriedeman and Sands, 1984). This facilitates gas exchange with the aerial environment, allows oxygen to be transported to the roots, and also allows potentially toxic gases formed through anaerobic respiration, such as ethylene, to be dissipated (Drew et al, 1979; Kriedeman and Sands, 1984; Blake and Reid, 1981; Sena Gomes and Kozlowski 1980). Anatomical adaptations in the root, such as a second root endodermis which acts as a barrier to salt (Kriedeman and Sands, 1984), and barriers to oxygen leakage to conserve oxygen in the root (Youssef and Saenger, 1996), may also contribute to the salt/waterlogging tolerance of some plants.

Summary: Salinity often increases root growth, and roots are often concentrated in surface soils. Waterlogging results in anatomical and morphological changes to roots to increase aeration.

1.3 Water use strategies of trees in saline and waterlogged environments

Saline and waterlogged conditions in the field may occur naturally or as a result of man induced changes. Although the causes of soil salinity and waterlogging are diverse, there are many commonalities in the response. By reviewing existing knowledge of the plant response to salinity and waterlogging, we can better understand plant water use in saline areas. This section reviews the work on water use strategies of plants, in a variety of saline and waterlogged environments, to examine how plant water use responds in an integrated way to salinity and to waterlogging. Where plants need to tolerate saline environments (and perhaps waterlogging), they will often combine a number of plant response mechanisms to maintain water use. This is termed a "water use strategy". The following section focuses on whole plant response studies, field studies, and studies of groundwater use by plants in saline environments.

1.3.1 Natural systems

Plants in marshes and coastal systems represent the extreme of fluctuating salinity conditions. Although these systems are often altered and can become more saline or flooded, they are usually naturally anaerobic and saline as a result of tidal inundation and naturally occurring saline soils and groundwaters. Many of the plants that occupy these environments have specialised morphological adaptations which allow them to survive under conditions of salinity and waterlogging. Many of the responses are more generic, and may be useful in understanding the water use of trees in saline and waterlogged areas.

(a) Coastal environments

Mangroves include many tree species known to be tolerant of waterlogging under saline conditions. Mangroves are found in coastal environments which are usually regularly flooded with sea water. There may also be fresher water derived from rainfall in the surface soils or as lenses on top of the saline water (Waisel et al, 1986; Gill and Tomlinson, 1977). The soil salinity often fluctuates dramatically in these environments in response to tidal events and high potential evapotranspiration (PET). Substrates of the mangrove environment are often anaerobic as a result of inundation. Mangroves take up some salt through the roots but 80 % of the salt is left behind in the root zone (Waisel et al, 1986). This results in build up of salts surrounding the roots. As previously discussed (section 1.2.2) low rates of water use (0.69 to 2 mm day⁻¹) due to salinity and waterlogging have been documented for many mangroves (Miller, 1972; Wolanski and Ridd, 1986). Salinity limited transpiration has been modelled for mangroves by Passioura et al (1992). In this model a quasi-steady state is assumed in which the flow of salt into the soil by convection in the water travelling to the roots is matched by the diffusion of the concentrated salt back to the soil surface. The transpiration rate is limited by this concentration of saline water.

Many mangroves have shallow root systems and areal roots (pneumatophores) which allow oxygen diffusion to the root system below ground, maintaining aerobic processes so that water uptake is not affected by waterlogging (Chapman, 1976). However in some mangroves the source of water used varies in response to salinity. In studies of mangrove water sources, in response to availability of fresh water versus ocean water, it was found that mangroves generally used ocean water, but were capable of using fresh water when it was available (Sternberg and Swart, 1987). The water sources used by the red mangrove (*Rhizophora mangle* L.) were investigated in more detail in response to tidal inflows and rainfall along an elevation gradient. At lower elevations roots of the red mangrove (tall form) were regularly bathed in sea water which is used at all times (Lin and Sternberg, 1992 b). However where

this mangrove occurs at higher elevations (dwarf form) it uses rainfall during the wet season and sea water during the dry season at high tides. These mangroves were faced with very high soil salinities during the dry season and consequently a high water use efficiency (Lin and Sternberg, 1992 a). The use of surface water by red mangrove was further investigated by Lin and Sternberg (1994) where it was found that surface water was used at most times by both forms of red mangrove despite groundwater of lower salinity often being available. Furthermore there was little change in uptake pattern with salinisation of the root zone or freshening of the groundwater. However there was an increase in fine roots in the surface soil when rainfall was high. Anaerobic conditions are thought to be often responsible for the concentration of mangrove roots in the surface soil (Gill and Tomlinson, 1977).

The ability to withdraw water from these saline substrates is thought to be due to the generation of low leaf water potentials. Minimum leaf water potentials of -5 MPa have been found for mangroves (Scholander, 1968; Clough, 1984). Red mangrove leaf water potential has been found to decrease over summer in response to salt accumulation in the surface soils and sea water intrusion and increase in the winter in response to rainfall (Lin and Sternberg, 1992 b; 1994).

Studies of plant water use strategies have also been conducted in coastal brackish and salt marshes. Tidal inundation can result in large and rapid changes in soil salinity (Jeffries et al, 1979). The studies of herbaceous wetland plants rarely discriminate between water sources. These plants are usually considered to be shallow rooted and so will only respond to changes in the substrate conditions at the soil surface. However there have been some studies which have found a different response. Arctic salt marsh plants such as *Puccinellia* species and *Carex ursina* which occur on the ocean fringe may use fresh water lenses on top of sea water so maintaining a higher plant water potential than would be expected if sea water was being used alone (Dawson and Bliss, 1987). Conversely, marsh species, where the soil was irregularly flooded, had higher than expected plant water potential. This was considered to be a result of the use of deeper, fresher water sources (DeJong and Drake, 1981). Studies of water sources of halophytes on the Dead Sea shores indicated that fresh flood waters were used selectively over saline water (Yakir and Yechiell, 1995).

Summary: Plants that occur in coastal environments have plant water use strategies that are naturally adapted to these environments. This includes low water use, low leaf water potentials, the use of fresh water sources when they become available and tolerance of waterlogged soils through anatomical adaptations to roots.

(b) Floodplain environments

Floodplains are often underlain by saline groundwater and may suffer waterlogging as a result of floods and rising groundwater. These conditions result in tree/groundwater interactions and water use strategies which may be influenced by both salinity and waterlogging. The evapotranspiration and ground water use of salt cedar (*Tamarix pentandra*) was investigated on the floodplain of the Gila River in the USA using evapotranspirometers (van Hylckama, 1974). Water use decreased (2550 to <1000 mm/yr) with a decline in water table (1.5 m to 2.7 m) depth. An increase in salinity from 10 to 30 dS/m also resulted in a 50% decrease in water use.

Salinity limited transpiration was also observed for floodplain trees on the Chowilla floodplain in South Australia. The water use strategy of *Eucalyptus largiflorens* was studied on the Chowilla floodplain of the Murray River in South Australia. Groundwater fluctuates between 2 and 4 m and is influenced by floods (2-25 years) and fluctuations in adjacent watercourses. Groundwater salinity ranges from 10 to 60 dS/m. *Eucalyptus largiflorens* is primarily reliant on saline groundwater for transpiration and combines this source with water from the surface soil after rain or a flood event (Thorburn et al, 1993a; Jolly and Walker, 1996; Richter et al, 1996). Groundwater is usually taken from the capillary fringe but roots have often been observed below the watertable and have also been observed to proliferate in the surface soils after a flood (Richter et al, 1996). The uptake of saline groundwater results in an accumulation of salt above the groundwater table (Thorburn et al, 1993a) and this progresses to the surface over time resulting in less groundwater being able to be used at the more saline sites. This process was modelled by Thorburn et al (1995). Water use was limited to 0.1 to 0.2 mm/day and most of this contributed to groundwater discharge (groundwater loss through the vertical flux of groundwater to the atmosphere by transpiration and evaporation) (Thorburn et al, 1993a). A factor controlling the groundwater uptake by trees was suggested to be the plant water potential. *Eucalyptus largiflorens* was able to reach leaf water potentials of -2.5 to -3.5 MPa permitting the uptake of water where salinities were up to 40 dS/m (-3 MPa) (Eldridge et al, 1993).

The basis of this model of salinity limited transpiration (Thorburn et al, 1995) was the interaction of floods with the process of salt accumulation. Infiltrating flood waters pushed the accumulated salt bulge back down towards the groundwater, hence maintaining the water uptake of *Eucalyptus* trees (Thorburn et al, 1995). The transpiration rate does not appear to be further affected by extended flooding (Jolly and Walker, 1996; Richter et al, 1996). This is

thought to be a result of low oxygen consumption by roots (Heinrich, 1990). Investigations of the water use strategies of *E. largiflorens* under flooded conditions indicate that soil type is instrumental in controlling the water use response through controlling the rate of infiltration of the floodwaters (Richter et al, 1996).

In the same study, the water use strategy of *Eucalyptus camaldulensis*, occurring adjacent to ephemeral and permanent watercourses, was investigated (Mensforth et al, 1994; Thorburn et al, 1994b; Thorburn and Walker, 1994). *E. camaldulensis* used saline groundwater rather than fresh creek water when situated within 20 m of the creek but when situated directly on the creek used up to 50% creek water. When overlying saline groundwater (30 dS/m) the transpiration rate was limited to 0.1 mm/day but when groundwater was of moderate salinity (10 dS/m) the transpiration rate was up to 2 mm/day. In response to rainfall *E. camaldulensis* used fresh water from the surface soil (Mensforth et al 1994). In response to flooding *E. camaldulensis* develops adventitious roots (Heinrich, 1990).

Summary: Floodplain trees use saline groundwater at rates that are limited by groundwater salinity and groundwater depth. Uptake of saline groundwater is dependent on the plant water potential threshold to water uptake, and accumulation of salt in the root zone.

1.3.2 Agricultural Systems

Few studies of the water use strategies of plants in agricultural systems in response to salinity and waterlogging have been conducted in environments that are underlain by saline groundwater. Investigations of trees, shrubs and pastures have been conducted in the field and in lysimeters to gain an understanding of their water use strategies and the implications for groundwater use.

(a) Trees and shrubs

Where trees have been planted in groundwater discharge areas, where they might interact with saline groundwater, groundwater levels have dropped (Bari and Schofield, 1991; Biddiscombe et al, 1985; George, 1991). This is often taken as evidence of groundwater uptake by the trees. Also an evapotranspiration higher than rainfall has been found in many areas where trees overlie saline groundwater (Greenwood et al, 1982, 1985 1992). Direct evidence of groundwater use by trees has rarely been shown and only a few of these studies have actually examined the water use strategies used by these trees in response to the saline groundwater (Thorburn et al, 1993a; George 1991).

Greenwood et al (1982, 1985, 1992) made numerous studies of tree water use in areas affected by secondary salinity using a ventilated chamber including studies of *Eucalyptus* plantations. Trees were investigated at up-slope and mid-slope positions in the landscape. Annual evaporation ranged from 2300 to 2700 mm/yr at the upslope, where groundwater was 8-10 m deep on average, to 1600 mm/yr at the mid slope, where groundwater was shallower but was confined by a siliceous aquiclude which roots could not penetrate (Greenwood et al, 1992). Groundwater salinity was ~2 g/L Cl (3 dS/m). These evapotranspiration rates were higher than rainfall (680 mm) indicating that up to 2000 mm/yr of groundwater was being used at these sites. However analysis of the available site groundwater and soil Cl data indicate that this may have been an overestimation of the groundwater discharge (see Thorburn, 1993 p 16), highlighting the difficulties in quantifying groundwater discharge without an understanding of the water use strategies of plants in these sorts of environments.

Further studies of root distribution (Greenwood et al, 1992) found that roots of *Eucalyptus globulus* and *E. cladocalyx* were concentrated in the surface 1 m of the soil profile at all times but extended well into the fluctuating unconfined aquifer. The authors suggested that the roots would have survived this waterlogging because the oxygen content of the groundwater was satisfactory (Greenwood et al, 1992). In the seepage area, where groundwater would have been shallowest and most saline, the trees were thought to be temporarily phreatophytic on the seasonal perched groundwater aquifer (Greenwood et al, 1992). Evidence of an upward redistribution of chloride from the groundwater at 4-6 m also provided evidence for groundwater uptake by roots at this depth.

In an investigation of the potential of trees (*Eucalyptus* species) to reclaim sandplain seeps, George (1990, 1991) measured groundwater discharge through piezometric techniques. Lower values for groundwater discharge were found than in studies by Greenwood et al (1985). However it was observed that during the study period, perched water tables were progressively lowered and the seep reclaimed despite above average rainfall (George, 1990). In this study, groundwater discharge fluxes of 0.5 mm/day (100 mm/yr) were found for *Eucalyptus* species overlying groundwater of 4.3 g/L Cl (7 dS/m) at 2 m depth.

Preliminary measurements of groundwater discharge by Fraser et al (1995) (*Eucalyptus* and *Casuarina* species) in areas with shallow saline groundwater (1-2 m deep and 8-11 dS/m) in Queensland, Australia, found transpiration rates ranged from 10-130% of rainfall and

corresponded to differences in tree growth. Transpiration remained constant throughout the 1 year study period and was limited below potential evapotranspiration (PET) by root zone salinity. Preliminary results indicated that trees were obtaining 50-100% of their water from the groundwater (Fraser et al, 1995) and groundwater discharge was estimated at 0.1-2.2 mm/day. *Casuarina glauca* was investigated in the study of Fraser et al (1995) (also Fraser and Thorburn, 1996) and was found to have higher growth rates and water use than *Eucalyptus camaldulensis* under similar groundwater conditions. *C. glauca* was found to be using at least 160 mm/yr of groundwater where groundwater salinity was 11 dS/m at 1.6 m depth.

Water table levels under trees have been compared to those under pastures to investigate the role of trees in saline areas (Bari and Schofield; 1991, 1992; Schofield and Bari; 1991). As with the other studies discussed, revegetation resulted in a lowering of water tables (decline of 1.5 m in 9 years). The yearly minimum groundwater levels decreased with the increasing proportion of afforestation and tree leaf area (Bell et al, 1990; Schofield, 1990). However it was suggested that the declining groundwater levels could also have been associated with the below average rainfall conditions during the study period (Bari and Schofield, 1991). The mechanism by which the trees reduced groundwater levels is not clear from these studies. A decline in groundwater salinity (9 to 30 %) was also observed (Schofield and Bari, 1991). This differs from the prediction by many authors (Morris and Thomson, 1983; Williamson, 1986). Some of the processes that were hypothesised to lead to this decline in salinity include horizontal flux of salt discharge from the site and deposition of salt in the unsaturated zone (Schofield and Bari, 1991).

Huperman (1995) investigated the tree/watertable interactions of *Eucalyptus* species in a plantation and found increases in salinity of the groundwater. Watertable drawdown of 2-4 m was observed under the plantation. This resulted in a reversal of the hydraulic gradient underneath the plantation, essentially converting the plantation site into a discharge area. This resulted in a build up of salinity under the trees and salinity increases in the groundwater (up to 15 dS/m). Trees were planted in 1976 and watertables under the trees started to rise after 1982 (6 years later) as a result of increasing irrigation outside of the plantation or reduced water use as a result of build up of salt around the root system (Huperman, 1995). Studies of root distribution under the plantation indicate that the highest root densities were found in the surface 50 cm. Roots were present throughout the soil profile including the permanently saturated zone and appeared to bypass saline soil

layers and access deeper, less saline groundwater in the saturated profile (Huperman, 1995). This was considered to be a possible water use strategy to avoid or delay growth reduction caused by salt accumulation.

Salt bush (*Atriplex* species) are often thought of as plants that are tolerant of arid environments but they may also be salt tolerant and waterlogging tolerant (see section 1.2). The water use strategies of *Atriplex* species in response to saline groundwater has been investigated in a number of studies. Greenwood and Beresford (1980) estimated evaporation rates from plots of *Atriplex vesicaria* of varying plant densities. Groundwater was 1.2 m deep and salinity was 24000 mg/L Cl (40 dS/m). Evaporation from plots ranged from 3.3 to 1.3 mm/day depending on plant spacing. Groundwater depth increased where plant spacing was higher (plants were denser) but the proportion of evapotranspiration that was derived from groundwater use was not calculated. Similarly, Barrett-Lennard and Galloway (1996) also observed an increase in water table depth under river salt bush plantations and attributed it to transpiration rates of 0.7 mm/day where the groundwater depth was 1.2 m (salinity not known). No estimate of groundwater use was made here either, with the role of these shrubs in recharge reduction through use of rainfall not being separated from potential groundwater use.

Slavich et al (1996) attempted to quantify groundwater discharge from *Atriplex nummularia* overlying groundwater of 10,000 mg/l Cl (17 dS/m) at ~2 m depth. Very low transpiration rates were recorded (<0.2 mm/day) and groundwater was only used at the end of summer when the surface soils were dry. Low plant water use was associated with low leaf areas, low leaf conductance and low xylem water potentials.

Summary: Tree and shrub water use is often limited by salinity and is dependent on leaf area index. There is indirect evidence for the impact of trees and shrubs on watertables where they are planted in groundwater discharge areas but it is unclear what role trees and shrubs play in saline agricultural landscapes. This includes confusion about the role of trees in the groundwater balance (control of groundwater recharge or discharge) and salt accumulation. It appears that the deeper root systems of trees may be important in groundwater use but information on tree water sources is scarce.

(b) Salt tolerant crops and pastures

While the plant types discussed up until now have been dominantly perennial, there have been investigations of ephemeral crops and pastures which have implications for the water

use strategies of plants in response to saline groundwater, particularly during the growing season, and when irrigation ceases. These studies are often carried out in lysimeter experiments, although there are some field studies. They provide useful information about the processes involved in groundwater uptake by these plants.

Talsma (1963) investigated capillary upflow (the vertical flux of water from the groundwater) under a number of pastures. Capillary upflow was found to be greater in intermediate textured soil than in clay soils of low hydraulic conductivity. Investigation of a rye-grass-sub-clover pasture found groundwater use of ~200 mm/yr where groundwater salinity was 10-20 dS/m and depth was 1.3 m.

The water use strategy of lucerne in response to fresh groundwater at a number of depths and the response to draw down after the cessation of irrigation has been investigated in lysimeter studies (Thorburn et al, 1994a; Smith et al, 1995). When a fresh watertable was maintained at 60 cm depth, leaf area index reached a maximum of 4. Water use was associated with changes in leaf area with evapotranspiration ranging from 2 to 16 mm/day (equivalent to groundwater use of 230 to 360 mm/yr). Capillary upflow was lower in clay-loam than loam and was associated with lower growth. Plants were observed to drop the free water surface through evapotranspiration which may have allowed aeration of previously unavailable soil layers (Smith et al, 1995). When the fresh groundwater was dropped to 1 m during a long period without irrigation root growth was stimulated downward and root length density increased above the water table (Smith et al, 1995). There was a marked increase in upflow as a percentage of evaporation but there was still water being taken from the surface soils (Smith et al, 1995).

Capillary upflow in the loam soil accounted for up to 55% of evaporation when the groundwater was fresh but when saline groundwater was introduced (13 dS/m) this was halved. Water use efficiency also increased with the introduction of the saline watertable. The reduction in upflow due to the saline watertable occurred despite only a small reduction in root length density above the watertable. The saline groundwater was also associated with a reduction in growth. As the salinity increased above the watertable and a "bulge" of salt was formed, the roots were replaced with numerous smaller diameter roots (Smith et al, 1995). Isotopic evidence indicated that the plants relied primarily on water of low salinity stored in the soil profile during this time, with saline groundwater flowing upward to replace this soil water (Thorburn et al, 1994a).

In a similar study of maize (King et al, 1995), saline groundwater (15 dS/m) was introduced at depths of 60, 90 and 120 cm in lysimeter studies which also incorporated four different soil types and only minimal irrigation. Depth to the saline water table determined how much water was used by the crop. Evapotranspiration usually declined with increasing watertable depth and was well correlated with plant height and dry weight (King et al, 1995). Capillary upflow from the watertable declined with increasing watertable depth and was greatest in medium to coarse textured soil. The capillary upflow as a proportion of potential evapotranspiration increased with shallower water-tables. The proportion of evapotranspiration from capillary upflow was greater with the saline water tables at 60 cm depth than with the fresh water tables at a similar depth (King et al, 1995). Capillary upflow from the watertable was correlated with an increase of salinity above the watertable.

Roots were concentrated in the soil surface 50 cm (King et al, 1995) and were denser than found in another study with fresh water tables (Smith et al, 1993). Root density below the saline water table was less than that found below fresh water tables (Smith et al, 1993). The highest proportion of shallow roots were found when groundwater was at 60 cm depth where roots appeared to prefer irrigation water to groundwater. The highest proportion of deep roots were found when groundwater was at 90 cm (King et al, 1995). Root density, when groundwater was at 120 cm, was similar to 60 cm probably because of the shallow rooting nature of maize. The distribution of roots did not limit capillary upflow (King et al, 1995)

Water use by Tall Wheat Grass was investigated in the Upper South East of South Australia in response to a shallow saline groundwater (5-7 dS/m) which fluctuated in depth between the surface and 1 m (Bleby et al, 1996). Plant water use reached a peak of 4 mm/day in summer; plants then senesced over the late summer period and winter with water use being reduced to < 0.5 mm/day. Roots were concentrated in the top 10 cm but also extended to the groundwater. Groundwater was thought to be used by the grass in summer as a result of salt accumulation in the surface soil, while soil water was used in winter and spring, a pattern also indicated by increases in surface soil roots during this time. Stomatal resistance was higher and leaf water potential was lower during the time of groundwater uptake in early Summer.

Summary: In shallow groundwater systems the groundwater use of pasture plants is dependent on rooting depth, groundwater salinity, and plant tolerance to salinity as well

as time of senescence. Higher rates of groundwater use were reported for pastures overlying shallow saline groundwater than for trees (deeper groundwater systems) because of the greater groundwater capillary upflow.

1.4 *Melaleuca halmaturorum*

The genus *Melaleuca* is a member of the family Myrtaceae and is widespread in Australian tropical, arid and cold coastal areas occurring in forms ranging from ground cover to trees. Within Australia there are ~200 species and ~8 have been recorded outside Australia in the tropical regions north of Australia. Common names of *Melaleuca* species include paperbark, honey-myrtle, and tea-tree. Many melaleucas grow near water, often in swamps and estuaries, or along stream banks, although others are found in sandy heaths of low to moderate rainfall, and in coastal areas. The invasion by *Melaleuca quinquenervia* into the freshwater wetlands of the Florida Everglades USA, displacing native species, has been associated with the ability of the species to tolerate a broad range of environmental conditions from flooding to drought, and also fire (Ewel, 1986; Hofstetter, 1991).

Members of the genus *Melaleuca* are some of the few tree species that occur on sites that are naturally waterlogged (Froend et al, 1987). These environments are also often saline and the health of mature *melaleuca* trees has been found to decline at soil salinities greater than approximately 540 mg Cl/kg (dry soil) in ephemeral wetlands in Western Australia (Froend et al, 1987). Results from these studies indicated that health of *M. strobophylla* declined as a result of dryland salinity either due to salinity or waterlogging or the two combined. Such salinisation is caused by vegetation clearance on surrounding agricultural land (Froend et al, 1987). *M. cuticularis*, considered to be tolerant to flooding, suffered mortality after 6 years of flooding (Froend and van der Moezel, 1994). A decline in health of *M. halmaturorum* in the Upper South East of South Australia is considered to be associated with an increase in soil inundation and rising saline watertables. (Webb, 1993).

Seedlings of *M. ericifolia* showed tolerance to waterlogging with seedling growth and adventitious root development actually being increased by waterlogging (Ladiges et al, 1981). Flooding of *M. quinquenervia* seedlings to 3 cm above the soil surface resulted in the production of adventitious roots and only a slight reduction in shoot growth and roots (Sena Gomes and Kozlowski, 1980). However flooding of *M. halmaturorum* seedlings to 100 % of their initial height for 6 weeks reduced growth and survival while flooding to 50 % of initial height did not (Denton and Ganf, 1994). Likewise seedlings of twenty *melaleuca* species were tested for salt and waterlogging tolerance (van der Moezel et al, 1991) and were found

to have little growth reduction under conditions of waterlogging and had higher survival rates than eucalypt species under conditions of salinity combined with waterlogging. *Melaleuca ericifolia* seedling growth declined in response to salinity (Ladiges et al, 1981).

In response to drought and salinity stress, *M. lanceolata* and *M. uncinata* showed osmotic adjustment and increased proline levels (Naidu et al, 1987). In addition to proline, nitrogen containing compatible solutes were found in 15 *Melaleuca* species that were examined (Naidu et al, 1987; Poljakoff-Mayber et al, 1987). *M. styphelioides* showed high sap flux under conditions of drought (Mishra and Sands, 1992). Drought survival in sub-tropical *M. quinquenervia* may involve increased leaf longevity (Greenway, 1994) and in *M. scabra* and *M. seriata* may involve a deep rooting system and the production of additional stems (Dodd and Heddle, 1989).

Melaleuca halmaturorum var *halmaturorum* F.muell. ex Miq. (South Australian Swamp Paperbark) occurs in the more temperate, low lying parts of South Australia, particularly the south-east, and in Western Victoria. It forms dense woodlands around the perimeters of ephemeral wetlands (Cooke, 1987), permanent wetlands (Rea, 1992), and in ephemeral often saline swamps. It favours low-lying sites and will generally grow in these sorts of environments where other trees will not grow (Holiday, 1989). It grows to 10 m high (Barlow and Cowley, 1988) and has a growth form that is usually irregular or crooked with thick whitish papery bark and a dense crown. Although the growth of seedlings was investigated under flooded (Denton and Ganf, 1994), saline and saline and waterlogged conditions (van der Moezel et al, 1991) little is known of the water use strategies of *M. halmaturorum* in response to these conditions.

Melaleuca halmaturorum was investigated in the Upper South East of South Australia (see Chapter 2). This region is under investigation as a result of massive dryland salinity problems which have resulted in a loss of agricultural productivity. *M. halmaturorum* is a dominant species on the inter-dunal flats where it dominates natural groundwater discharge areas. Its water use and specifically groundwater use, is under investigation in order to understand the role that the vegetation plays in the hydrology of the Upper South-East. Transpiration of groundwater by *M. halmaturorum* may have a significant impact on the groundwater balance especially if it uses groundwater for a large proportion of the year. If so, this information will be useful when examining the water balance of wetlands and the groundwater balance in the whole south east region of South Australia.

In addition, there has been a decline in the health of *M. halmaturorum* in some areas. Rising groundwater levels in this region may have reduced the volume of soil available for root exploration and so decreased the time taken to reach maximum soil salinities. This, combined with possible waterlogging effects, may be responsible for tree death in the region. It is important to understand the factors resulting in this decline of health of these trees along with their role in the water balance.

Summary: Members of the genus Melaleuca are tolerant to drought, salinity, waterlogging and flooding. Melaleuca halmaturorum is one of the most salt and waterlogging tolerant melaleucas and occurs in natural groundwater discharge areas of the Upper South East of South Australia. Seedlings have been shown to tolerate salinity, waterlogging and flooding however little is known of the water use strategy of mature M.halmaturorum trees in response to these conditions in the field.

In general summary;

Transpiration is often limited by salinity but little is known of the groundwater use of plants in response to salinity and waterlogging combined. The water use strategies of plants across different environments appear to be dominated by plant water potential, rooting depth, groundwater salinity and groundwater depth. The interaction of plant physiological and environmental mechanisms in groundwater uptake appears to be important where saline groundwater occurs.

1.5 Aims of this project and rationale for methodology

The general aim of this study was to identify the water use strategy of *M.halmaturorum* in response to salinity and waterlogging in the root zone and through this quantify groundwater use and the role of *M.halmaturorum* in the water balance. The hypotheses to be tested were;

- *M.halmaturorum* uses water at a rate that is limited by groundwater salinity as a result of reduced leaf area and leaf conductance.
- Water uptake is maintained by a high plant threshold to water uptake reflected in a low leaf water potential for *M.halmaturorum*.
- Groundwater is used at all times as a result of the response of the root system of *M. halmaturorum* to salt accumulation.
- When waterlogging is combined with salinity, transpiration by *M. halmaturorum* is further reduced.

The investigation was conducted by breaking the water use strategy into three components; 1) transpirational response 2) root system response 3) water relations response. These components are all related to each other but each needs to be understood in order to identify the water use strategy and therefore quantify the annual groundwater use. The quantity of groundwater used depends on the transpiration rate and the rooting depth and both will change with time. This will be determined by the dynamic changes in water use strategy as the environmental conditions change.

A series of field sampling and measurement trips were conducted over an 18 month period (October 1993 - February 1995) at four sites that differed in degree of salinity and waterlogging (see Appendix 1 for specific sampling dates). Description of these sites are outlined in Chapter 2 along with a general description of the environment of the Upper South East. One of these sites (Duck Island) was investigated intensively, the other three less so. Tree water use was quantified over the sampling period and this is outlined in Chapter 3. The partitioning of this water use into use of groundwater and rainfall is outlined in Chapter 4 and Chapter 5. Chapter 6 brings all of this information together to characterise a water use strategy for *M.halmaturorum* and quantify groundwater discharge using a model of root water uptake. Chapter 7 provides a general discussion of the results and conclusions from the study. The thesis outline is described in Fig 1.1.

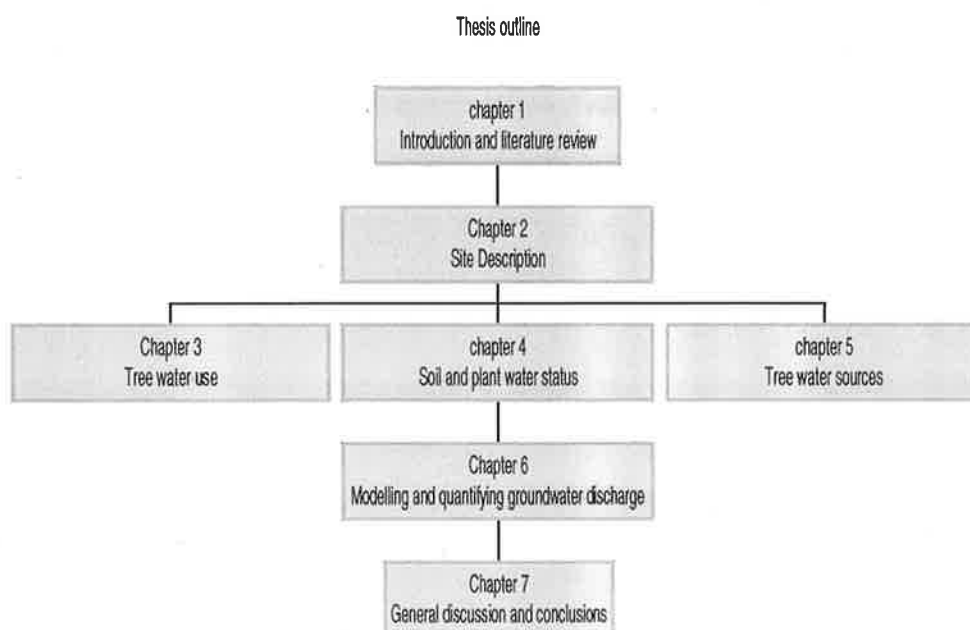


Figure 1.1: Outline of thesis chapters

Chapter 2: Site Description

2.1 Environmental Description of the Upper South East of South Australia

The Upper South East of South Australia is an area of 680 000 ha as defined by the towns of Keith, Naracoorte, Kingston and the Coast (Coorong) (Fig 2.1). Main landuses are cropping and pastoral with significant wetlands occurring amongst these farming systems (Fig 2.2).

2.1.1 Climate

The Upper South-East of South Australia has a Mediterranean climate with wet winters and dry summers. Average annual rainfall ranges from 340 mm at Keith to 420 mm at Naracoorte. Compared to other parts of South Australia, rainfall for the Upper South East has a low to moderate variability (Engineering and Water Supply Department, 1987). Potential annual evapotranspiration (PET) averages 1500 mm. Daily maximum temperatures may reach up to 40°C in summer and frosts occur in winter.

2.1.2 Topography and Soils

Taylor (1933) divided the upper south-east into three topographic zones: Hill country, plain country and swampy flats. The plain country, where it was waterlogged, contained tea-tree (*M. halmaturorum*). The swampy flats where it was less saline also contained tea-tree, along with cutting grass. In low lying swamp country, that was wet and annually flooded, samphire occurred with tea tree (Taylor, 1933).

Jackson and Litchfield (1954) described the dominant landscape in the upper south-east as being an extensive plain transected by belts of sand dunes and swamps. A flat dune system is shown in Figure 2.3. The most important topographic feature of this region is the series of stranded coast-line ridges (dunes) parallel to the present coast and less than 30 m high.

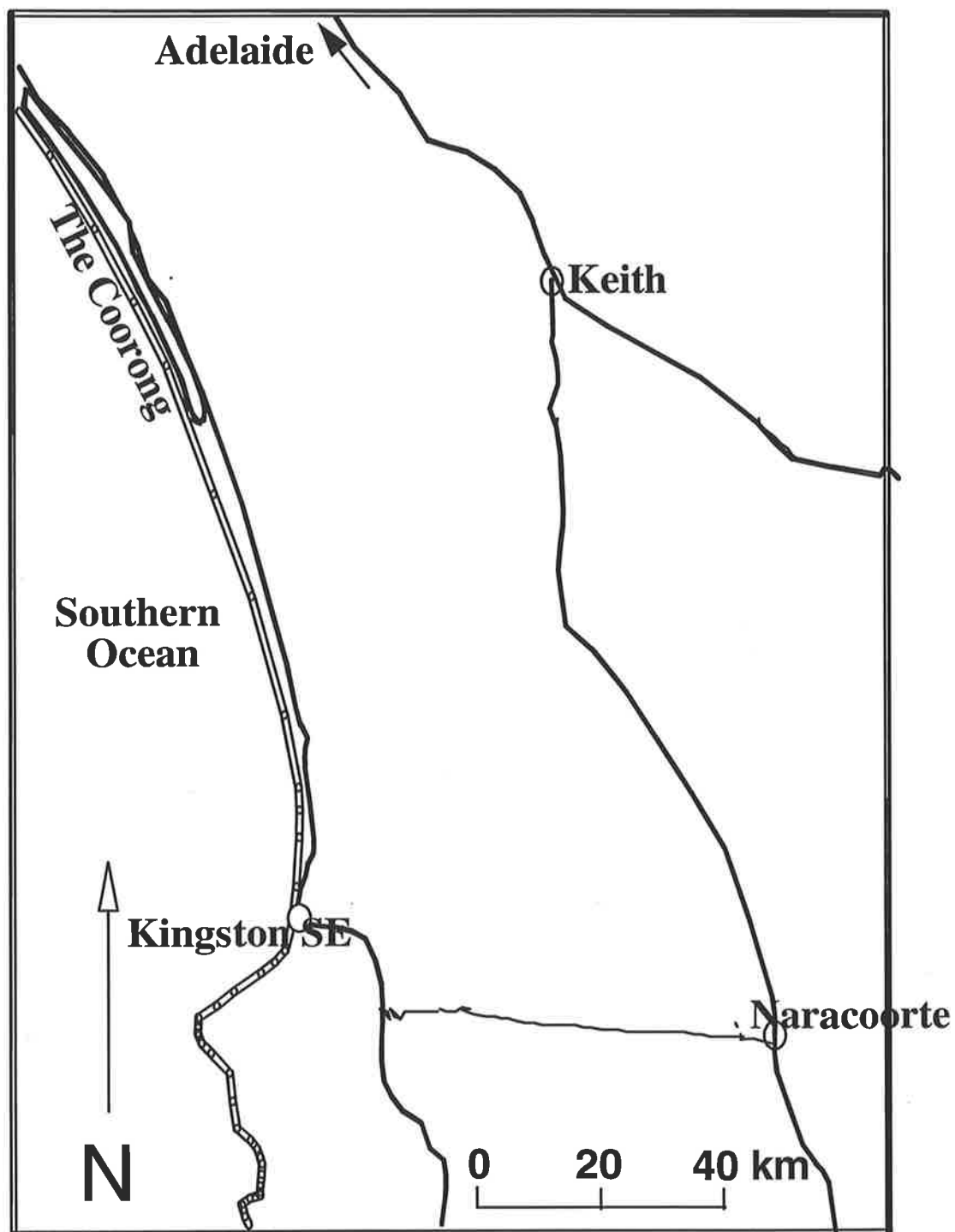


Figure 2.1: The Upper South-East of South Australia.

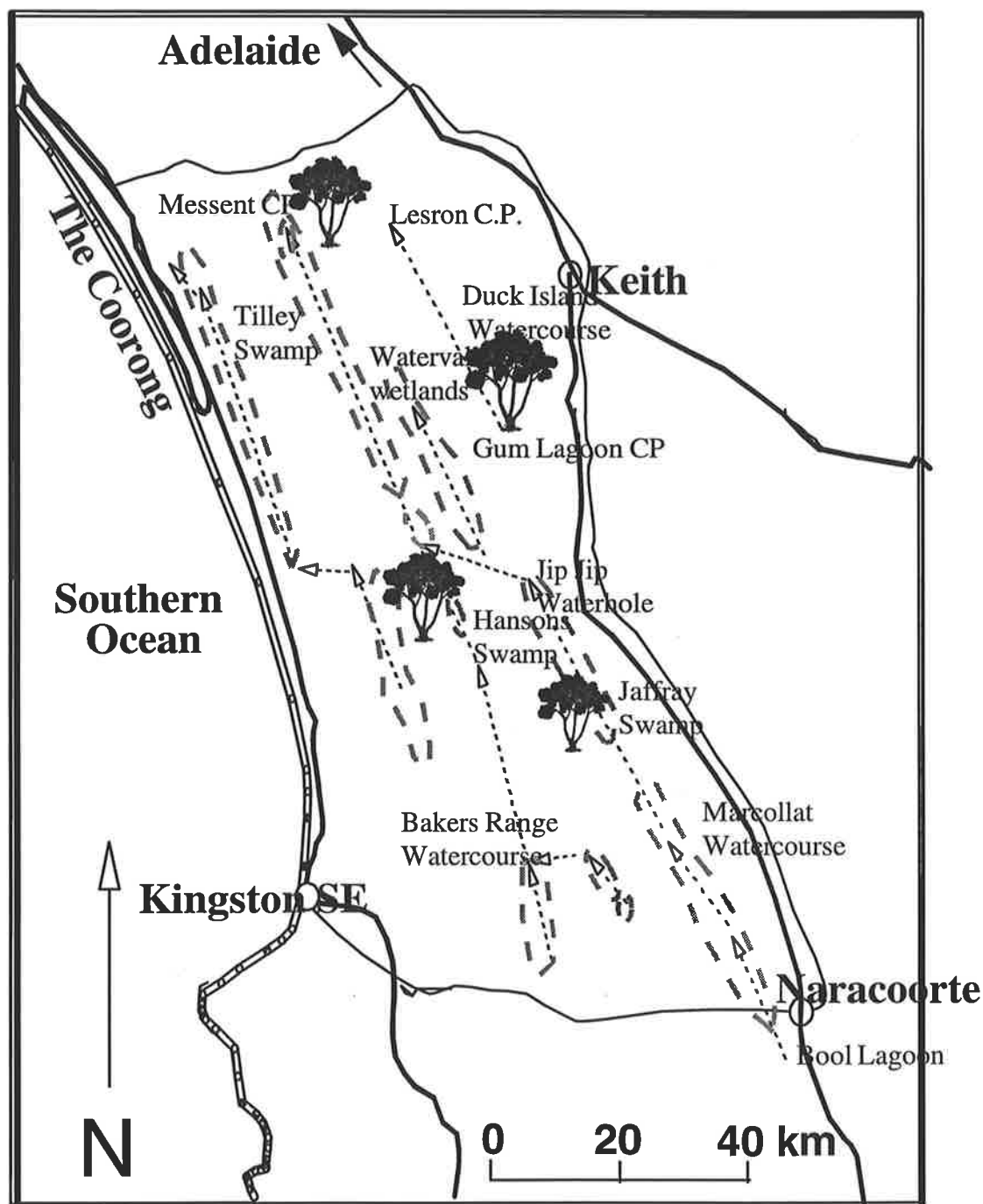


Figure 2.2: Site locations (indicated by trees), associated watercourses and wetlands (dashed lines), and surface water flows between wetlands (arrows) in the Upper South-East of South Australia.

The plains between the various ranges (flats) are 1-10 km wide and slope gently down from east to west and from south to north. In some parts the flats were smooth and featureless for miles but other parts included swamps along the western side of the plains, lagoons taking the discharge of creeks and watercourses, and lunettes on the eastern margins of the lagoons (Blackburn, 1964).

A very large proportion of the land is flat, stony and low-lying. Natural drainage is hindered by the series of ridges parallel to the coast, causing temporary flooding at the end of the wet season (see next section). This has led to the need for artificial drainage for agricultural production. Low lying areas are characterised by swampy flats and small, shallow seasonal lakes. Shallow saline groundwater historically underlay much of the area (Jackson and Litchfield; 1954) but has risen and caused dryland salinisation (see next section). In places, the water-table reaches the surface during some portion of the year and forms the seasonal lakes and saline flats typical of the Lake Ellen Association (Jackson and Litchfield; 1954).

There were two very recent episodes in geological history which have determined the topography and soil type of the region. First was the withdrawal of the sea from the limestone sedimented Murravian Gulf and the emergence of the South East as low, flat land ridged in an extreme way. As regional uplift shed the sea westwards and exposed flat land for colonisation of terrestrial plants, the parallel ridging was developed by global sea level rises which counteracted the uplift and caused temporary halts in the westward coastline migration, building the ridges at the rate of one every 100,000 years (Lange, 1981). This was followed by extensive mantling with windblown siliceous sand during the great Australian arid period 3000-9000 years ago (Crocker and Wood, 1947) or 18000 yrs ago (Dodson, 1974).

There is much spatial variation in soil type. There is often an abrupt change from black or grey clay to light grey sand which is linked to changes in topography and drainage (Blackburn, 1964). Soils are predominantly grey brown sandy at the surface with finer textured subsoils of a bleached nature overlying highly calcareous substratum. These are combined with deep sands on the dunes and medium to fine textured saline soils in the swamps. These soils on the flats are often waterlogged with saline water.

The soils of the swamp country (Lake Ellen Association; Jackson and Litchfield; 1954) were described by Taylor (1933). The swamp country occupied the low-lying flats which

were permanently swampy or annually flooded in winter. They were distinguished, according to the degree of flooding and salinity, as flats with cutting grass with or without small tea-tree or flats with samphire, tall tea tree and salt lakes. They include a great variety of very poorly drained saline soils, occurring on low lying flats, many of which are inundated by salty water throughout a portion of each year due to the shallow watertables. Surface soils were saline, medium textured and large amounts of lime was present at shallow depths. Some degree of waterlogging, at least in the lower horizon is always present with the saline soils resulting in mottling and discolouration of the subsoils (Jackson and Litchfield, 1954). The vegetation is usually samphire (*Salicornia* species) and *Melaleuca halmaturorum*. The soils of this swamp country are alkaline (pH 9) and saline and consist of a dark grey sand (up to 12 inches) or loam overlying a dark grey clay or clay loam, a grey clay (35% clay) and then limestone. The chief constituent of the soluble salt is sodium chloride (Taylor, 1933). The Monkoora soil association, which is characterised by saline subsoils also may carry melaleuca swamp vegetation (Jackson and Litchfield, 1954). The Monkoora sand (Taylor, 1933) generally consists of a shallow surface grey sand over a white sand and greyish yellow sandy or medium textured clay. This is underlined by a limestone. The soils are usually saline and sometimes waterlogged and the salinity is related to the dominance of *M.halmaturorum*.

When these initial investigations were undertaken (Taylor, 1933; Jackson and Litchfield, 1954), the effect of salt did not appear to be spreading to adjacent soils and it appeared that leaching and drainage had reached a natural equilibrium on the flats with the mature formation of saline flats and swamps. Today it appears that the rising groundwater has enhanced the spread of these landforms to adjacent parts of the landscape.

2.1.3 Hydrology

(a) Surface water

The Mediterranean climatic conditions combined with the geomorphology of the region produces a hydrological regime where winter rains fill the interdunal flats and summer temperatures dry them out. Winter precipitation is the most critical factor in establishing the amount and length of time a wetland is inundated and evaporation during summer is critical in defining the capillary rise of groundwater to the surface in dried wetlands and so the deposition of salt. Due to these climatic conditions most of the wetlands are only seasonally or semi-permanently inundated.

Surface water flows are produced when winter rainfalls are high, intense and late in the winter season. Settlement in the Upper South East has resulted in increased surface flows. This, combined with high watertables, has caused increased catchment wetness, groundwater recharge, increased surface water flows reaching the downstream end of watercourses and increased wetland storage (Clark et al, 1991). Surface water moves along watercourses (flowing SE to NW) which consist of a series of swamps located on the western side of the interdunal flats (South East Drainage Board, 1980; Jensen et al, 1983; Clarke et al, 1991) (Fig 2.2). In very wet years entire inter-dunal areas may be flooded. During winter, water flows westward on each flat and then ponds against the dune range. Surface water flows almost at right angles to groundwater flows (towards the coast) because of the dune ranges that prevent flow of surface water to the coast. When this happens the low inter-flat passages can breach and waters flow in a NW direction at a rate dependent on the extent of the drainage works and on the volume of water generated. The inter-dunal flats are connected through openings in the dune systems, so that the water course system is contiguous from the south to the north of the region (Fig 2.2). Surface water flows from south to north where a continuous dune complex blocks further northward movement. In very wet years water can flow west to Salt Creek and the Coorong, but generally the northern end of the water course system is the terminus for the entire system.

Historically very large areas of inundation were needed to produce these water flows. Higher runoff as a result of vegetation clearance and drainage diversions have increased this process. In response, local land holders created diversion drains and stop-banks to hasten the movement of surface water from their land (USED SFMPSC, 1993). This occurred along the length of the water courses and resulted in increased flow of water to the northern terminal area of the system. High annual flow in 1988-1991 caused larger than usual periods of inundation of the flats, accumulation of water in the landlocked ends of the water courses and therefore elevation of watertables leading to dryland salinisation during summer. In addition extensive areas of wetland habitat along the watercourses are now receiving water more frequently, increasing the period of inundation. High flows can be explained by the seasonal timing of the rainfall (wet winters), increased runoff from drainage works and higher groundwater levels under the flats.

Surface water quality changes with season and flow conditions. Low flow conditions will result in higher levels of salinity in the surface water as a result of seepage of shallow groundwater and runoff from upper parts of the catchment. Conditions are more saline in

the Lesron Conservation Park (Fig 2.2) due to evaporative concentration of ponded surface water and shallow groundwater through summer. Salinities in Jip Jip (Fig 2.2) range ranged from 1000 mg/L Cl (2 dS/m EC) at the end of winter to 8000 mg/L (13 dS/m EC) in summer. At Cortina Lakes in the Watervalley Wetlands (Fig 2.2) surface water salinities has reached up to 100 dS/m EC at the end of summer (White and Brake, 1995). As groundwater salinity levels increase towards the north-west of the Upper South East (Nicolson, 1993) the wetlands located in that region are at risk of salinisation problems, because of runoff and groundwater.

(b) Groundwater

The groundwater system in the Upper South East is a regional system with perturbations due to local recharge and discharge (Fig 2.3). Groundwater is found in the unconfined aquifer system and the deeper confined aquifer which consists of limestone and unconsolidated sediments (Shepherd, 1978). Groundwater flows in a W to NW direction toward the coast at right angles to the surface flow (Fig 2.4) and is relatively slow (estimated to be 0.001-0.01 m day⁻¹). The slow movement is in response to low gradient and transmissivity of the aquifer. The groundwater hydraulic gradients are not uniform over the whole area. The differences in hydraulic gradients result from variations in the rock type, thickness of the aquifer and differences in local aquifer recharge and discharge rates. There is a low hydraulic gradient in the Lesron area associated with the higher evaporative loss of groundwater from the shallow watertable in the area (MacKenzie and Stadter, 1992).

In addition to the lateral groundwater flow, recharge also occurs when rainfall (P) exceeds potential evapotranspiration (PET) (April-October). Groundwater rises to the soil surface in most years due to recharge through the dunes and surface flows along the water courses within the flats. Recharge depends on soil type, watertable depth, nature of the vegetation cover and land management practices. Recharge can be as high as 100 mm/yr under degraded annual pastures and as low as a few mm/yr under lucerne and native vegetation. Groundwater recharge also occurs from surface runoff from dunes, infiltration into dunes, and from swamps and wetlands. Recharge on the interdunal flats has been estimated at 100 mm/yr (MacKenzie and Stadter, 1992).

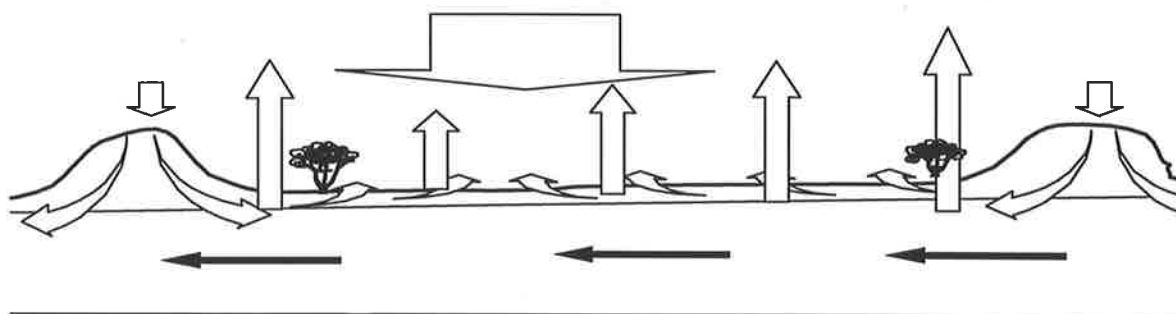


Figure 2.3: Cross section of a dune/ inter-dunal flat complex in the upper south-east of South Australia indicating groundwater recharge (downward arrows), groundwater discharge (upward arrows) and other groundwater flows (Kennett Smith et al, 1995).

The slow rate of groundwater flow in the region appears to preclude significant discharge of local recharge through lateral movement. Therefore recharge to the water table on the flats must discharge through evaporation and transpiration. The main groundwater discharge process is evaporative loss of groundwater where groundwater is within 2 m of the soil surface (USEDSEMPSC, 1993). Capillary rise causes salt to be carried up and deposited throughout the soil profile as water evaporates, resulting in dryland salinisation. This process depends ^{on} soil type, vegetation, water table depth and evaporative rates. Kennett-Smith et al (1995) suggested that the groundwater discharge from the flats is effectively the sum of the recharge through both the dunes and the flats (Fig 2.3). Discharge through the lateral flow of groundwater is predicted to be much less than 10% of the discharge through evaporation (Unpublished model data Kennett-Smith et al). The main evaporative groundwater discharge rates occur in the interdunal flats, Lesron area and the ephemeral lagoons of the Coorong (USEDSEMPSC, 1993).

The clearance of native vegetation, loss of lucerne from the aphid infestation of the early 1970's and the development of non-wetting sands have resulted in considerable increases in recharge rates to the watertable aquifer. Clearing the dune systems of native perennial vegetation and replacing it with annual pastures has been shown to increase recharge by at least an order of magnitude (Walker et al., 1992). Jackson and Litchfield (1954) in their investigation of the potential land use of part of the Coonalpyn Downs warned that saline soils were already present and it would be important to prevent the level of groundwater in the district from rising, as this would be disastrous for large areas. They also recognised

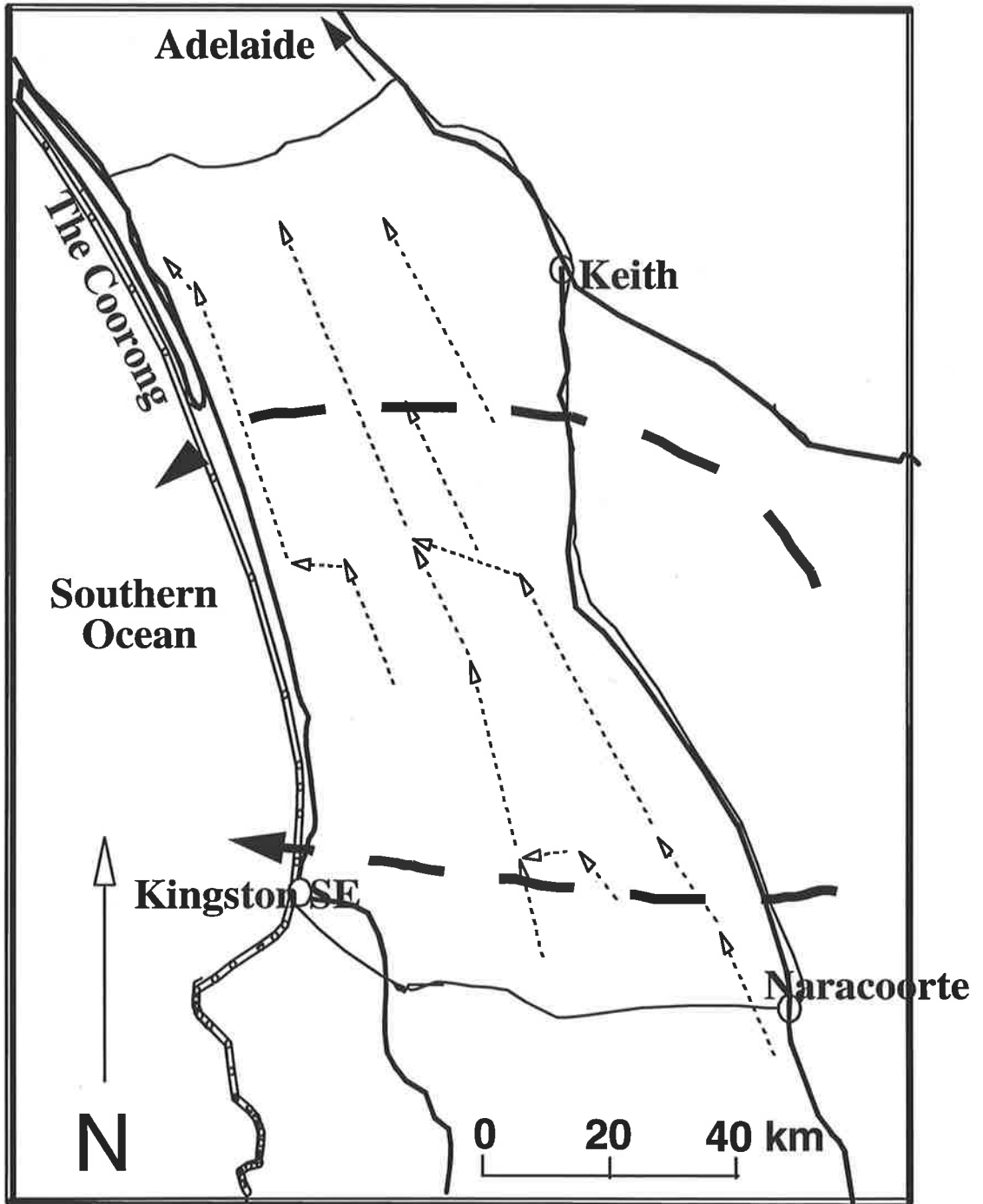


Figure 2.4: Surface water flows (dotted line) and groundwater flows (solid line) in the Upper South-East of South Australia.

the importance of maintaining native vegetation on recharge areas, and warned that the removal of native vegetation from these areas would result in undesirable changes in the groundwater level over wide areas (Jackson and Litchfield, 1954).

The removal of the native vegetation on both the dunes and the inter-dunal flats has resulted in increased recharge to the water table beneath both areas. Data over several years indicates that the groundwater table has been rising in the north-west of the Upper South-East (MacKenzie and Stadter, 1992) and is expected to continue to rise. This has caused groundwater rises over most of the region ($0.05-0.1 \text{ m yr}^{-1}$). As water tables rose surface flooding and waterlogging increased, reducing agricultural production. On the inter-dunal flats water tables over much of the region are now within 1 m of the soil surface for most of the year.

Local variations in groundwater salinity are common and result from changes in the magnitude of local recharge and discharge rates and land management practices. Salinities range from 5 dS/m EC in the South to 80 dS/m EC in the North (Fig 2.5). High salinities result from evaporative discharge from the aquifer, poorly developed surface water drainage, and inflows of surface water from upstream catchments. The lower salinities are associated with the main dune ranges and the eastern side of the interdunal flats in the southern part of the study area. The groundwater salinity within the remaining areas of the interdunal flats is higher due to the evaporative discharge of groundwater from the areas.

The depth to groundwater varies both seasonally and geographically. Seasonal fluctuations range from 0.05 to 1.5 m. The depth to watertable is related to the topographic elevation, with shallow groundwater levels occurring in lower lying areas such as the interdunal flats and landlocked depressions within the dune ranges. There has been a rising of groundwater levels ranging from 0.5 to 1 m every 10 years as a result of increased recharge to the aquifer. Groundwater levels in regions with a shallow depth to groundwater such as the interdunal flats and the Mt Charles/ Bunbury locality have remained static over the monitoring period apart from normal seasonal fluctuations (0.5 - 2.0 m). This may be because the increase in aquifer recharge is balanced by an increased evaporative groundwater discharge and/or increased groundwater outflow from these areas. Monitoring periods may also have been too short to pick up the groundwater rises in these areas. There is also a rise in groundwater next to some wetlands e.g. the Mandina marshes, Bonneys Camp and Jip Jip. The groundwater elevations in each successive interdunal flat

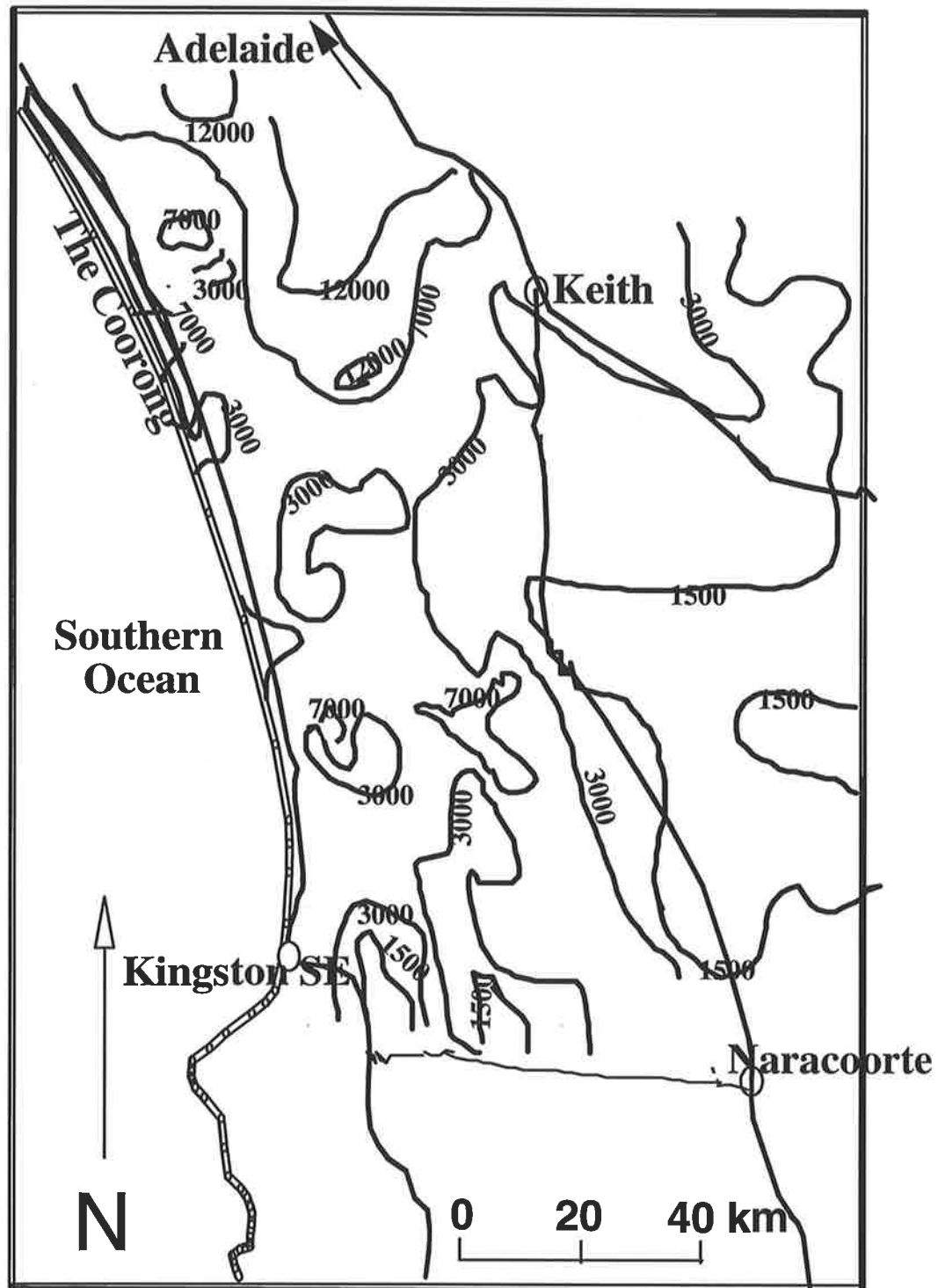


Figure 2.5: General patterns of groundwater salinity (mg/L) in the Upper South-East of South Australia (adapted from USEDSFMPSC, 1993)

within the southern part of the study area are lower than those in the preceding eastern flat with a steeper hydraulic gradient through the dune range.

2.1.4 Vegetation of the Upper South East

The native vegetation of the Upper South-East was historically considered to have high species and community variation (Litchfield, 1956). As the climatic gradients and changes in soil fertility were apparently slight over large tracts, it was considered that the internal water relations of the soils or their substrata, in particular the groundwater depth and salinity, along with the topography and soil type, governed the distribution of many of the larger plants (Litchfield, 1956). A more recent study of the upper south east (Sparrow 1991) identified 13 vegetation complexes. For the Marcollat water course (Fig 2.2) the most important complexes are:

- *Banksia ornata* - *Allocasuarina pusilla* found on siliceous sands or sands over alkaline clays with rainfall 400 - 600 mm p.a. Associated with typically heathland species e.g. *Leptospermum myrsinoides*, *Phyllota pleurandroides*, *Correa reflexa*.
- *Eucalyptus incrassata* - *Melaleuca uncinata* found on calcareous loams and clay loams; rainfall < 500 mm p.a. Associated species *E. foecunda*, *E. dumosa*, *E. rugosa*, *Melaleuca acuminata*.
- *Melaleuca brevifolia* found on grey, saline, heavy clays in seasonally inundated interdune corridors; rain fall 500 - 600 mm p.a. Other species include *Baumea juncea*, *Gahnia trifida/Gahnia filum*, *Leptocarpus brownii*.
- *Melaleuca halmaturorum* found on very saline grey heavy clays in seasonally inundated interdune corridors; rain fall 550 mm p.a. Other species include *Sarcocornia spp.*, *Wilsonia backhousei*, *Tetraria capillaris*.
- *Eucalyptus camaldulensis* found on red-brown to yellow clays or around water holes on heavy mottled grey clays; rainfall 500 - 650 mm p.a. Other species include mostly exotic pasture grasses and weeds, with many annual halophytic natives such as *Triglochin striata*.

Today there is only 15% remnant vegetation left, with most occurring on the flats. A dominant feature of the interdune areas of the Marcollat water course is the presence of

Eucalyptus camaldulensis as well as *Melaleuca hamaturorum*, *M. brevifolia*, *M. uncinata* and *M. oraria*. The understorey is heath-like on the raised sandy areas but has generally been replaced by halophytic annual species in the low lying areas where the pasture species (tall wheat grass, barley grass and *Puccinellia*) are often stunted. The *Melaleuca* complexes are associated with a trend towards increasing clay content, pH, total soluble salts, calcium carbonate and an annual seasonal flooding pattern, whilst the *Eucalyptus* and *Banksia* complexes are associated with areas of increasing sand content, lower pH and generally absence of seasonal flooding. This vegetation pattern supports the hypothesis that soil type, salinity and seasonal flooding patterns are the main determinants of the floristic composition.

The *Melaleuca* species are associated with land types which are waterlogged for appreciable periods and are often saline. However some species also experience seasonal desiccation. Low lying flats with shallow soils often originally supported small trees of dry land tea-tree (*M. brevifolia*). Low lying saline sand plain supported a low broom bush (*M. oraria*) or where subsoil clay is heavier *M. uncinata* and mallee. *M. halmaturorum* appeared around salt lakes or highly saline hollows or flats and today is closely associated with highly saline habitats with shallow seasonal watertables where the only other plant species present are samphires (Jackson and Litchfield, 1954; Sparrow, 1991). *M. halmaturorum* often makes a dense fringing of low forest or tall scrub around salt marshes and salt lakes. This species can occur when the watertable is <0.5 m below the surface and may be obligate on shallow groundwater (< 2 m; Loan, 1993). The *Melaleuca* species are distributed as follows;

- *M. uncinata*: occupies sandplain and hillslopes with degraded soils (solodic and solonetzic sand-sheet) with tight clay subsoils under sand. Often extends into other mallee and woodland communities
- *M. brevifolia* (was *M. fasciculiflora*, *M. oraria* and *M. neglecta*) reaches a high frequency and is a lone dominant on much of the saline and seasonally waterlogged soils occupied by Monkoora sands in the South. The relative tolerances of *M. halmaturorum* and *M. brevifolia* to high salinity and /or very poor drainage in these areas is apparent from their sharply defined fringing distributions around some of the salt marshes or salt lakes with adjacent sand rises. *M. halmaturorum* forms an inner band and *M. brevifolia* an intermediate one between the former and mallee heath or woodland on the rising slope. Where there is improved drainage other communities exist, but *M. brevifolia* will extend sparse populations into these areas. *M. brevifolia* was found to be absent from

soils of high groundwater levels and salinity (Loan, 1993). The health deteriorated at some sites but it was not possible to identify the reason (Loan, 1993).

- *M. lanceolata* (was *M. pubescens*): This species has the greater part of its distribution on freely to excessively drained soils, but also occurs on waterlogged and saline calcimorphic soils in the interdunal corridor, approaching the tolerance of *M. halmaturorum*. A common factor in all recordings of associated soils is alkalinity and the presence of free lime in either the profile or the substratum. *M. lanceolata* appears to be less tolerant of both salinity and waterlogging than *M. halmaturorum* and occurs further up slope where soil salinity is lower and groundwater is deeper (Loan, 1993).

- *M. wilsonii*: with mallee communities on poorly drained soils

- *M. gibbosa*: In broombush-sedge communities on poorly drained flats. The habitats of the species elsewhere indicates tolerance towards high water-tables.

- *M. halmaturorum*: as elsewhere in both littoral and inland areas the species is closely associated with highly saline habitats with shallow seasonal watertables. This species occurs when the watertable is <0.5 m below the surface and may be obligate on groundwater < 2 m (Loan, 1993). It often makes a dense fringing of low forest or tall scrub around salt marshes and salt lakes. Entry onto the marsh floor probably indicates slightly improved drainage. *M. halmaturorum* has been found to be predominant on highly saline soils in frequently inundated areas, *Gahnia* on less saline soils where rainfall exceeds 600 mm p.a. and *M. brevifolia* on the same where rainfall is less than 600 mm p.a. (therefore death of *M. brevifolia* occurs where salinity increases) (Sparrow, 1991). *M. halmaturorum* has an apparently wide ranging tolerance to salinity and waterlogging which is indicated by its presence at soil salinity levels over 8000 mg/L where the only other plant species present are samphires.

Poor condition of remnant *Melaleuca* stands should be taken as indicative of very saline conditions which will not support agricultural species. A more sensitive indicator of salinisation are stressed *Eucalyptus* complexes whereas the presence of the *Banksia* complex would indicate soils unaffected by rising salinity levels.

2.1.5 Effect of Rising Groundwater on *Melaleuca* communities

Rising groundwater has resulted in increased surface soil salinity, flooding and waterlogging. Despite the high tolerance of *M. halmaturorum* to these conditions the changes can result in the death of trees species and alterations in community composition.

Soil salinisation occurs when the evaporative discharge of groundwater (particularly saline groundwater) at the soil surface exceeds the combined effect of leaching of salt from the soil through rainfall, and redistribution of salt through the effects of rising and falling water tables. It is generally acknowledged that where saline water tables are within 1-2 m of the soil surface for much of the year salinisation will occur.

When water tables rise to the soil surface, salts stored in the soil are dissolved in the rising groundwater. As the water table falls the residual salinity of the soil is that of the groundwater. However, in the case of saline groundwater the water left in the soil is saline (1 - 60 dS m⁻¹). Therefore, to reduce salinity, significant leaching of these residual salts must occur. Soil data show that some leaching of the upper 30 cm of the soil does occur in the upper south east soils (unpublished data). However, this is not sufficient to counteract the continuous supply of saline water through capillary rise from the shallow saline groundwater. Consequently, evaporation (and salt build up) continues even as the water table is falling. Moreover, transpiring vegetation increases the salinity further by excluding salt from the water it extracts. These processes result in a cycling of salts from the top of the water table to the soil surface and back, and an increase in the mass of salt stored in the top 2 m or so of the soil profile.

There is little information on the extent of salt removal from wetlands through surface flow. However, salt which is transported in this way will be re-deposited down-stream and can contribute to soil salinisation. This contribution will be additive to the effect of low ground surface elevation in the north of the region which increases the evaporative discharge in this area. In conjunction with this, these systems are often the termini for surface flows. Together these conditions produce a higher rate of soil salinisation.

As explained earlier the wetlands of the upper south-east can be categorised as either ephemeral or permanent and net groundwater recharge (groundwater is recharged from the wetland) or discharge systems (groundwater is discharged into the wetland). There appear to be net groundwater discharge and net groundwater recharge areas in both the ephemeral

and permanent wetlands of the USE. The interactions that each type of wetland has with the underlying groundwater system can be summarised as follows (see Fig 2.2):

- Ephemeral system - net groundwater discharge *eg* Duck Island, Hansons Swamp, parts of Lesron Conservation Park, Tilley Swamp
- Ephemeral system - net groundwater recharge *eg* parts of Jaffray Swamp.
- Permanent system - net groundwater recharge *eg* parts of Jaffray Swamp, Jip Jip Waterhole, Cortina Lakes
- Permanent system - net groundwater discharge *eg* parts of Lesron CP, Jacks Camp

In net groundwater recharge areas in permanent wetlands, salinisation should not be a problem because leaching should exceed the rate of salt build-up. However, in the net groundwater discharge areas, salinisation will continue to increase until some balance is reached. The rate of salinisation will depend on the depth to the groundwater and any local freshening of the upper part of the water table. Note that even in net recharge areas there is discharge occurring during drier months of the year.

The net recharge wetlands usually “leak” through a semi-permeable base. This may result in groundwater mounding next to the wetland. Water in these wetlands will remain fresh as long as salt exported through seepage is the same as that imported through rainfall or inward seepage of saline groundwater. The other type of permanent wetland, namely a swamp, is one which is an expression of the water table. A swamp is defined as a wetland in which the ground surface is below the water table level. These wetlands will reflect the surrounding water salinity if groundwater flow through the wetland is relatively fast. However, if groundwater flow is slow, local rainfall and fresh water lens seeps may make such wetlands notably fresher than the groundwater. In both the net recharge cases, if water tables become elevated (relative to some historical level) salinity increases may occur due to increased inflow of saline groundwater.

In permanent wetlands where there is a net discharge of groundwater, salinity will not increase if the flow of groundwater through the wetland is sufficient to remove the excess salts. This is likely to occur in swamps. However, net discharge of groundwater from permanent wetlands with a sealed bed will result in salinisation unless sufficient fresh surface water flow occurs.

(a) Health of mature *M. halmaturorum*

The health of the *Melaleuca* communities affected by these changing conditions has recently been investigated in the Upper South East. In the North of the region, as explained above, surface water terminates at the end of winter and groundwater is closer to the surface because of this increased recharge. As a result, watertables are at or above the surface at the end of winter causing high evaporative discharge of groundwater over the summer months. This has led to constant soil salinisation over the summer period. Surface water salinities have also increased as a result of greater surface soil salinity and runoff to the terminal basin (Webb, 1993).

This process has resulted in a decline in the health of the *Melaleuca* vegetation (Webb, 1993). Vegetation health appeared to be determined by elevation (topography) and soil type which influence capillary rise of salt into the surface soil. *M. halmaturorum* in this area was most severely affected because of its preference for the low lying areas of the interdunal plain with clay soils which are constantly saturated due to shallow saline watertables (60-70 dS/m EC). The vegetation appears to be most vulnerable to degradation during periods of extreme moisture stress when the saline groundwater is close to the surface and subject to evaporation (Webb, 1993).

(b) Community composition and regeneration of *M. halmaturorum*

If increased salinity and waterlogging result in the death or degradation of mature individuals at lower elevations, then the continued survival of the population is dependent on the successful recruitment of seedlings at higher elevations (Froend and van der Moezel, 1994). The community composition may therefore change in response to these conditions. It is often found that during the dry season species richness declines with increasing salinity and the number of species declines as salinities increase. Species more tolerant of high salinity levels will invade the areas where the vegetation is less tolerant to these changes (Loan, 1993).

Investigations in the North-West of the Upper South East where salinities are high have found that where these *Melaleuca* communities have become degraded there is a reduction in diversity and the understorey species have suffered in health with a shift to salt tolerant species, particularly samphires (Webb, 1993). Where *M. brevifolia*, which usually occupies higher ground, occurs in close association with *M. halmaturorum* on lower-lying areas the species has died (Webb, 1993). Stressed sites support a greater number and mixture of species as a result of the higher number of introduced species that occur and regeneration

of *M. halmaturorum* is limited (Webb, 1993). Sites that were classed as "dead" contained a lower number of species and a deterioration in the health of the understorey (Webb, 1993). As salinity increases many of the herbs die out leaving opportunities for invading weeds which in turn die out leaving only halophytic vegetation. The community is generally a mixture of introduced and salt tolerant plants with a greater diversity and abundance of samphire (Webb, 1993). Healthy *M. halmaturorum* sites support a greater range of small herbaceous plants and a healthier understorey than at stressed or "dead" sites.

Investigations of *M. halmaturorum* at Bool Lagoon (just south of Naracoorte; Fig 2.2) indicate that regeneration is via an aerial seed bank. The species flowers in spring/early summer, and seeds mature over summer. Seeds are retained on the mature tree but when dislodged (often by bird activity) germinate on exposed mud flats but appear not to germinate under flood. This is supported by studies of other *Melaleuca* species where submergence has resulted in the delaying of germination (Ladiges et al, 1981). The viability of the seeds from flowering trees at Bool Lagoon was high (ca.80 %; Ganf & Muller unpublished). However, the probability of finding a seedling was dependent upon the life stage of the tree. No seedlings were found in the vicinity of young trees, nor were they found in association with old trees. Most seedlings were found with mature trees with an intact trunk, prolific leaf growth, and flowering with a dense canopy. Although many of the trees at Bool Lagoon have persistent viable seed banks and germination is a frequent occurrence, the survival of seedlings is poor. Denton & Ganf (1994) demonstrated that young seedlings (ca.6 months) died if top flooded for longer than 3 weeks, older seedlings (1 and 2 years) were more resistant to top flooding but survival was poor (0 - 14%) if flooded for 9 to 12 weeks.

The present level of knowledge suggests that regeneration of *M. halmaturorum* is dependent upon the age structure of the woodland, and the coincidence of seed drop onto exposed flats which permits the establishment of seedlings to a height greater than the surface water depth encountered during winter floods. These observations have been used with success to encourage the regeneration of seedlings at Bool Lagoon. Although these observations are generally applicable to *M. halmaturorum* regeneration in the Marcollat watercourse, they will be influenced by soil and surface water salinities leading to episodic germination and establishment events. Unless factors leading to successful flowering and seed set occur at the optimum time for germination and establishment, the window of opportunity for regeneration will not open (Froend et al 1993, Ganf and Muller

unpublished). In addition, factors such as grazing can also influence regeneration. However studies by Cooke (1987) found that *M.halmaturorum* was not as sensitive to grazing by rabbits as other species because of the high seedling tolerance to grazing and the seasonally flooded habitat.

How salinity influences regeneration is largely unknown. However, observations in the Upper South East (Loan, 1993) suggest that *M. halmaturorum* regenerates at medium to high soil salinities in low lying areas where other species have died due to rising ground water. In addition its tolerance to salinity and waterlogging may explain why it has displaced the less tolerant *M. brevifolia* in Tilley's Swamp. However in the highly saline North of the Upper South East, the regeneration of individuals of *M. halmaturorum* is apparently limited by high soil salinity levels, elevated ground water and reduced seasonal fluctuations in watertable levels (Webb, 1993). Investigations found a range of *M. halmaturorum* age classes occurred at the healthy sites (where subsoil salinity was lower but surface soils salinities were often high; Webb, 1993) indicating a regenerating sustainable population, while regeneration was limited in the stressed sites and regenerates were unhealthy. This may indicate that subsurface salinity is the dominant factor in limiting regeneration rather than surface soil salinity. Investigations of the germination requirements for other *Melaleuca* species have found that salinity often inhibits germination (Ladiges et al, 1981; van der Moezel and Bell, 1987)

The interaction between water regime, surface water salinities and subsoil salinities is complex. However, the available data indicate that salinity is a major factor limiting the regeneration and inducing death of much of the native flora (as well as pasture species) in the Marcollat watercourse. This suggests that the concentration of subsurface salts severely limits the growth, survival and establishment of the vegetation (van der Moezel et al., 1991) in much of the low lying areas of the Marcollat watercourse. In the current study *M. halmaturorum*, regeneration was not observed at any of the study sites (see next section). The sites were therefore dominated by mature individuals. Based on tree ring analysis, mature *M.halmaturorum* trees were considered to be greater than 30 years old at all sites, and at some sites trees were thought to be ~80 years old (Olga Barbourina, unpublished data).

2.2 Description of specific study sites.

Four sites were chosen based on predicted conditions of salinity and waterlogging from hydrological information (see Fig 2.2). These were Duck Island, Lesron CP, Hansons Swamp and Jaffray Swamp. As groundwater salinity increases from south to north (by up to 100 dS/m EC) of the study area, two sites were chosen in the high groundwater salinity region of the north and two in the south where groundwater salinity is lower. Soils at sites in the current study consisted of a sandy clay with a hard calcrete layer at 30-50 cm depth. Soils were sandier at Lesron than at Hansons and Duck Island. Soils at Jeffrey consisted of very tight clays at depth in the profile. All soils were considered to be saline and waterlogged to some extent (see section 2.2). Of these paired sites in each region, one was chosen that was thought to be waterlogged for a significant amount of time and one was chosen that was thought to be less waterlogged. This was determined by general regional elevation information and knowledge of the position in the catchment where the wetland was situated. The Lesron Conservation park site was situated in the terminus of the Duck Island catchment which received the majority of surface water flows from the southern part of the region. This also resulted in higher groundwater levels in wet years. The Duck Island site was situated mid-catchment and so received throughflow of surface water. There was therefore thought to be less potential for waterlogging (Fig 2.6). The Hansons Swamp site was situated in the Watervalley wetlands watercourse catchment and although was not an obvious terminus for surface water (Fig 2.2) had very flat elevation (Fig 2.6). Surface flows were therefore very slow during the winter allowing water to lie for appreciable lengths of time. In comparison the Jaffray Swamp site was at a higher elevation, was less frequently flooded, and has the potential for less waterlogging. The Jaffray Swamp site was hydrologically different than the other sites as it was a seasonal wetland which in many years had permanent water. The *Melaleuca* vegetation investigated at this site was on an elevated peninsula (Fig 2.6) and so was not often flooded. The other sites were ephemeral wetlands (swamps) and were flooded every year as groundwater apparently comes to the surface and is met by rainfall resulting in surface flows, but was always dry during summer.

The sites were described by a general vegetation survey and topographical elevation survey in February 1995. A 120 m transect at Duck Island and Lesron and 250 m transect at Hansons was surveyed in a N-S direction to incorporate the investigation trees (chapter 3-5), the piezometers (groundwater observation), and the topographical variation at each of the sites (Figure 2.6). A transect was not measured at Jaffray as a vegetation survey had been recently conducted (McGibbon, unpublished data), but elevation was measured at two

positions at the Jaffray Swamp site. Along the transects elevation was measured with a dumpy level and related to the Australian datum height (AHD) with known elevations at the piezometers which were at each of the sites (data from SA Dept of Mines and Energy). Elevation generally decreased from the sites in the south (up to 30 m AHD at Jaffray Fig 2.6) to the sites in the north (18-20 m AHD at Lesron Fig 2.6). Patterns of elevation across sites differed between sites (Fig 2.6). General patterns of vegetation composition were recorded along the transect as presence of species and *Melaleuca* health was recorded as apparently healthy (no apparent signs of stress), unhealthy (apparent signs of stress) or dead. Signs of canopy stress included leaf death and discolouration, epicormic growth, and numerous dead branches.

Duck Island was characterised as an ephemeral saline swamp as it is sometimes wet, sometimes dry and has very high soil salinities during the dry times of the year. The vegetation consisted of both the salt tolerant *M. halmaturorum* and the less salt tolerant *M. brevifolia* (Fig 2.6 a). Elevation increased from the *M. halmaturorum* flats to the *M. uncinata* and *M. brevifolia* dunes. Samphire was the ground cover under the *M. halmaturorum* flats and *Gania phylum* was the ground cover under the dunes. *G.phylum* also occurred on the flats but health was poor. The health of *M. brevifolia* was poor on the low lying flats, maybe from rising saline groundwater, but good on the dunes. This site was therefore characterised as highly saline with low waterlogging (Table 2.1).

Hansons Swamp was characterised as an ephemeral swamp and had very flat topography. This site frequently showed large surface flows during winter which was considered to be primarily a result of groundwater rising to the surface. Vegetation health was good at this site and vegetation composition was reasonably diverse, dominated by *M. brevifolia* shrubs. Melaleuca species were mainly *M. brevifolia*, with a line of *M. halmaturorum* through the centre of the study site, and groups of *M.uncinata* trees (Fig 2.6 b). The distribution of *M. halmaturorum* did not seem to be associated with elevation but may have been associated with soil characteristics such as calcrete depth. This site was therefore characterised as having medium waterlogging with moderately saline water (Table 2.1).

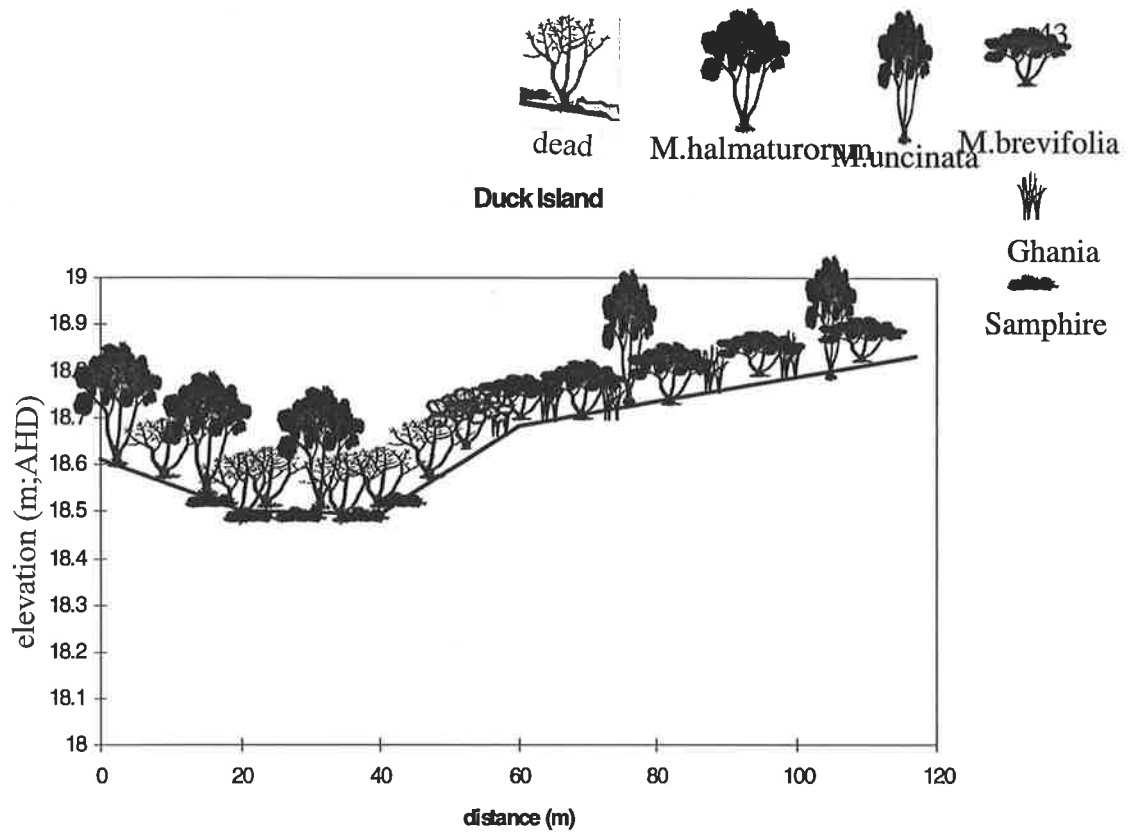
Lesron was characterised as an ephemeral, saline swamp and a terminal groundwater discharge area. Lesron had undulating topography with a slope towards a low lying basin and the topography was generally very low (Fig 2.6 c). Health of *M. halmaturorum*, which occurred over most of the low lying area, was generally poor and was dead in the lowest parts. The vegetation in the study area was dominated by *M. halmaturorum*, while the less

salt and waterlogging tolerant *Melaleuca* species were found outside of the study area on the higher dunes. Species diversity was low with the more salt and flooding tolerant species becoming dominant. This site was therefore characterised as highly saline and highly waterlogged (Table 2.1).

Jaffray Swamp can be characterised as a seasonal permanent wetland, consisting of a wetland basin which is currently filled seasonally, and a fringing vegetation which is thought to be flooded infrequently. Jaffray swamp species distribution was investigated by McGibbon (unpublished data, 1996). *M. halmaturorum* lines the edges of the basin. There is also a peninsula at a higher elevation (30 m ADH; Fig 2.6) where the vegetation includes *Melaleuca halmaturorum*, *M. brevifolia*, *Eucalyptus camaldulensis*, *Hakea rostrata* and numerous ground-covers and shrubs such as *Mimilus repens* and *Atriplex* species (McGibbon, unpublished data). The *Melaleuca* vegetation at this site is less frequently flooded than at the other sites, the vegetation health is very good, and the species composition is very diverse (37 plant species; McGibbon, 1996). This site has been characterised as low salinity and low waterlogging (Table 2.1).

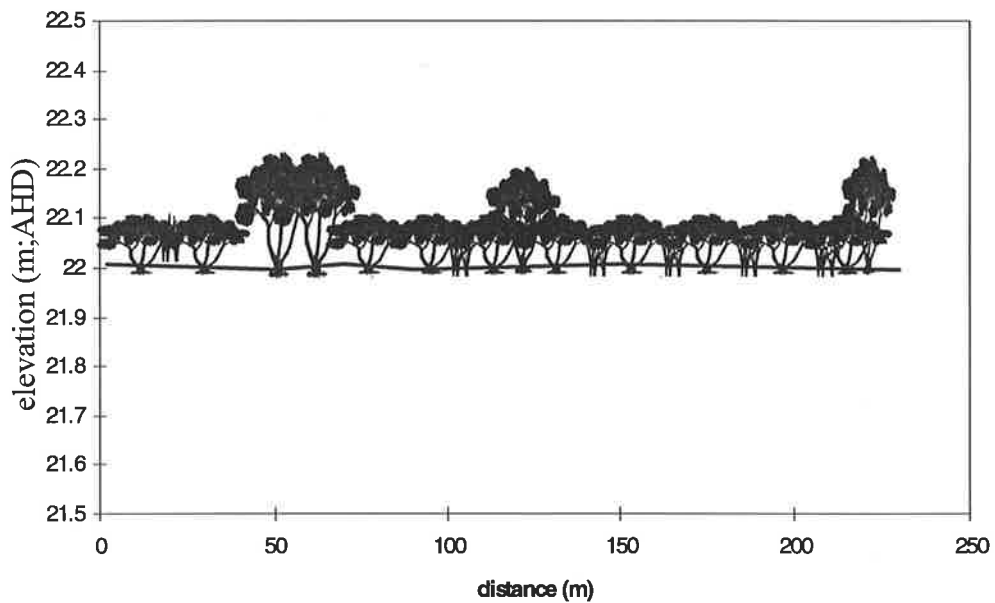
Table 2.1: Site characterisation, indicated as predicted degree of salinity and waterlogging, for all sites.

Site	Salinity	Waterlogging
Duck Island	High	Low-Medium
Lesron CP	High	High
Hansons Swamp	Medium-Low	Medium-High
Jaffray Swamp	Low	Low



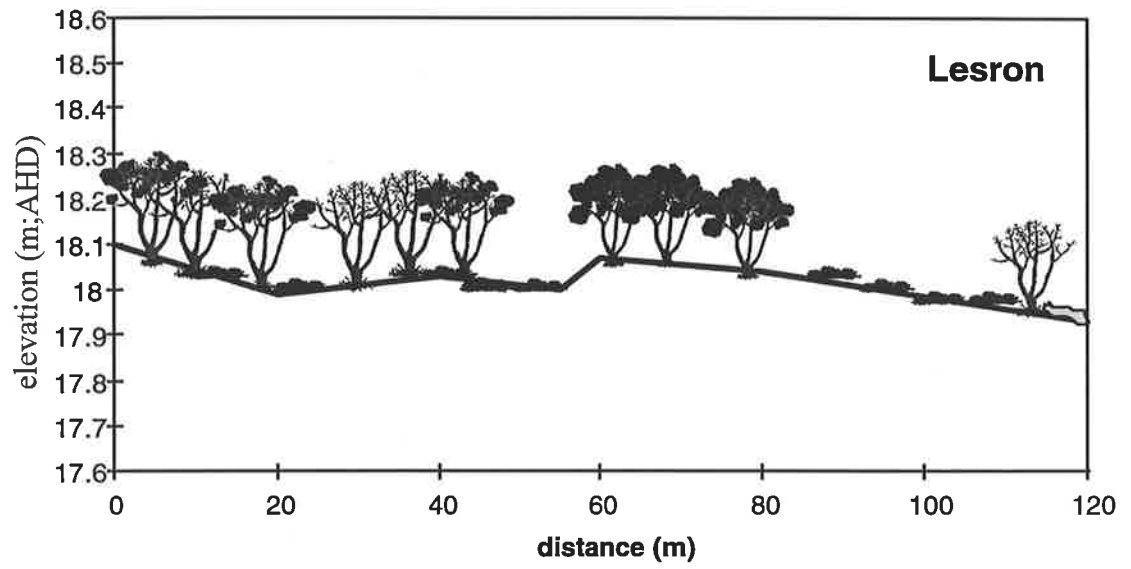
(a)

Hansons



(b)

Figure 2.6: Topographical cross section of the Duck Island (a), Hansons Swamp (b), and Lesron (c) showing vegetation type, tree health and position on the elevation gradient (m; ADH). Vegetation (top right corner) was a composition of *Melaleuca* species, *Ghania* species (grasses) and *Salicornia* species (samphire). Poor tree health is indicated by a less dense canopy and dead trees are indicated by a canopy with branches only.



(c)

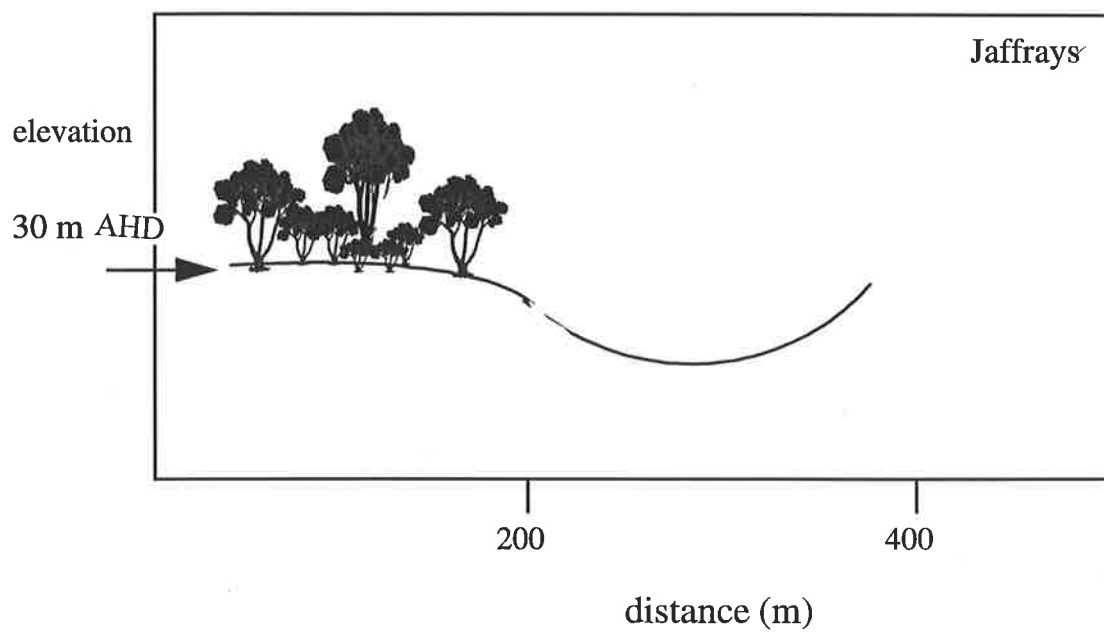


Figure 2.7: Schematic representation of Jaffray Swamp indicating general vegetation structure at the study site (see text) and surveyed elevation point (m; ADH).

Chapter 3: Tree Water Use

3.1 Introduction

Melaleuca halmaturorum naturally occurs in swamps and wetlands which are often saline and waterlogged and so it appears to be able to tolerate these conditions (van der Moezel, 1991). However it is not known to what degree extended periods of these soil conditions influence transpiration of mature trees. This information would be useful when examining the water balance of wetlands and the groundwater balance in regions, such as the Upper South East region of South Australia. In these large areas, *M. halmaturorum* trees dominate the groundwater discharge areas, and so may be important in affecting groundwater discharge. If transpiration is limited by salinity and waterlogging it may not be predictable from potential evapotranspiration (PET). Salinity is commonly found to reduce water use of crop plants, through influences on both stomatal conductance and leaf area but the effect of salinity combined with waterlogging on water use has been investigated to a lesser extent (see section 1.2.2). In order to characterise water use strategies and quantify groundwater discharge, tree water use must be quantified. The aim of work outlined in this chapter was to quantify the water use of mature *M. halmaturorum* and to identify errors associated with the estimate. This necessitated an investigation of the issues of scaling from single tree estimates to whole forest estimates of water use.

3.1.1. Mechanisms of tree water use

Water is an important factor in determining both the distribution of plants over the earth's surface and the characteristics of the individual plant. Water is the most abundant compound in an active cell. It is required in the plant for the maintenance of turgidity so that photosynthesis can be maintained (Cowan, 1982). Water is a raw material in photosynthesis, a solvent for vital reactions, and a medium for solute movement (Oertli, 1966). The metabolism and growth of plants are influenced by even mild water deficits in plant tissues. These deficits occur when the plant can not obtain adequate water supplies to fulfill its requirements and will occur at different stages of water availability for different species, with many drought tolerant species able to obtain water from sources of extremely low water potential (Turner, 1986; Kozlowski, 1968).

The success and even survival of land plants depends on sufficient water moving upward from the roots to replace that lost from the shoot by transpiration, and this will be influenced

by the processes at the leaf, in the conducting system and at the root. Water loss from plants in the form of vapour is the dominant process in plant water relations providing the energy gradient that is the major control (aside from root pressure) on the absorption of water and ascent of sap in trees. Sap is pulled upwards to the transpiring surfaces under high tensions (Kramer and Boyer, 1995). This water tension is transferred to the roots where it causes an inflow of water from the soil, thus in moist soil water absorption is controlled by transpiration. However in soil of lower water status there will need to be a further drop in plant water potential to absorb water through roots and there may be further resistances to the uptake of water at the root/soil interface.

Water loss from plants involves water moving down a water potential gradient from the soil, through roots, stems, leaves, and boundary layer to the free air. At each step there is a gradient in water potential and some resistance to flow. The largest gradient occurs between the leaf and atmosphere where stomata also provide a large resistance. For water absorption to roots thus;

$$Absorption = \frac{\Psi_{soil} - \Psi_{rootsurface}}{r_{soil}} = \frac{\Psi_{rootsurface} - \Psi_{rootxylem}}{r_{root}}$$

Where Ψ is the water potential and r is the resistance to water movement. The resistance at the root soil interface may be the controlling resistances at times of water stress and many stresses have been found to decrease the permeability of roots to water (section 1.2.3). Virtually nothing is known about the extent to which the movement of the root system towards water and vis-versa, which determines the supply, is able to match the demand imposed by the atmospheric foliage (Monteith, 1995). During dry weather, the maximum rate of transpiration may be determined by the ability of roots to extend towards new sources of water rather than by rates of diffusion of soil water to roots (Monteith, 1995).

Transpiration is dependent on the effects of a number of variables, some of which are environmental and some of which are characteristics of the vegetation (Jarvis, 1981). The rate of transpiration depends on the supply of water at the evaporating surfaces, the supply of energy to vaporise water, the size of the driving forces and the resistances of the pathway thus;

$$T = \frac{C_{leaf} - C_{air}}{r_{leaf} + r_{air}}$$

where T is the transpiration rate ($\text{g m}^{-2} \text{sec}$), C are the vapour concentrations of air and the evaporating surface inside the leaf (g m^{-3}), and r are the diffusive resistances of the paths for vapour diffusion in the leaf and the through the air boundary layer (sec m^{-1}). The driving force for the transpiration flux is the difference between the vapour pressure of the evaporating surface in the leaf, which depends on the leaf temperature and water potential, and the humidity of the air, which depends on the water content and temperature. Two groups of resistances affect transpiration, the internal resistance in the plant (canopy) and the external or boundary layer resistance in the environment. Canopy resistance is dominated by stomatal resistance (Jarvis, 1981).

Stomatal resistance is affected by radiation, saturation deficit, temperature and the external concentration of CO_2 (McNaughton and Jarvis, 1983; Jarvis, 1976). Stomatal resistance is also affected indirectly by drought, salinity and flooding (see section 1.2.2). Stomatal closure has been observed at large saturation deficits as a feedback response to low leaf water potentials and low turgor, preventing further water loss and so leaf water stress (Farquar, 1978). However the controls on stomatal resistance are not clear. For example it has been recently suggested that the response of stomata to vapour pressure deficit (D) is really a response to transpiration rate (Mott and Parkhurst, 1991). Hormonal messages have also been shown to close stomata in response to root zone water deficits (Munns and Termaat, 1986; see section 1.2.2).

Boundary layer resistance is chiefly dominated by wind speed, leaf size and shape and the roughness of the canopy surface for a stand of plants (Stull, 1988). Boundary layer resistance is usually the dominant resistance for grassland and heathland while canopy resistance is usually dominant in forests (Jarvis, 1981). As boundary layer resistance is lower for tall plants such as trees there is the potential that they will be well coupled to the air around them (Jarvis, 1985; Montieth, 1981). The boundary layer resistance becomes less important for transpiration as water stress increases and the stomatal resistance becomes dominant.

The energy required to evaporate water from plants comes from direct solar radiation, from radiation reflected or re-radiated from the soil and surrounding objects. When transpiration occurs, energy changes water from the liquid state to the vapour state. The energy budget for a leaf can therefore be partitioned as;

$$R_n + H + \lambda E = 0$$

Where R_n (net radiation), H is the sensible heat flux and λE is the latent heat flux and if any two of these fluxes are quantified the third can be estimated. This energy budget can also be used to estimate transpiration and is incorporated into the, equilibrium evaporation equation to estimate potential evapotranspiration (section 3.2.1), the Penman Monteith equation to estimate transpiration (section 3.2.4) and the Bowen ratio methods (Appendix 5).

Leaf and canopy characteristics (including leaf area) can influence the absorption and emission of energy and this will influence leaf temperature, vapour pressure and the rate of transpiration. The degree of coupling between boundary layer and the leaf surface will also influence transpiration and recent work has concentrated on the feedback mechanisms involved in this relationship (Monteith, 1995). For example the closure of stomata may result in a reduction in energy used for transpiration, increasing the transfer of sensible heat which will increase the temperature of the boundary layer, making it warmer and drier and increasing the evaporative demand (McNaughton and Jarvis, 1991; Monteith, 1995). In addition, if the influence of radiation or vapour pressure deficit is to reduce stomatal conductance then transpiration will not increase as anticipated, resulting in a positive feedback (Jarvis, 1981). As soil dries, transpiration (E) will not only be sensitive to changes in stomatal conductance (g) but also to the changes in vapour pressure deficit (D) and temperature (T) that are associated with this (Jarvis and McNaughton, 1986). If plants are well coupled to the atmosphere g and D will have a greater effect than R_n which will dominate transpiration if the plants are not well coupled (McNaughton and Jarvis, 1991).

This response of stomata to D has recently been interpreted as a response of stomata to transpiration rate (Mott and Parkhurst, 1991) with g reaching a maximum value when E is zero and g being minimal at a maximum rate of E (Monteith, 1995). The limiting rate of E is thought to be related to the soil water content and the extension of the root system. When equations relating the physiological dependence of g on E are combined with equations relating the thermodynamic dependence of E on g it can be seen that g initially increases in the morning in response to increasing irradiance partly offset by the increase in transpiration rate and when a maximum irradiance is reached in the middle of the day g declines with increasing E . As irradiance and D declines in the afternoon stomata continue to decrease (Monteith, 1995).

3.1.1. Measurement of transpiration and problems of scale

It can be seen from the previous discussion that the study of evaporation from vegetation is an inter-disciplinary field of research encompassing meteorology and physiology, with physiologists usually concentrating on processes at the leaf level, while meteorologists have concentrated on measurement of the driving forces and so are most focussed on processes at the boundary layer. The water use of vegetation is often considered at many different spatial and temporal scales, from the leaf level to the catchment scale. Tree water use can be measured at a number of scales, the leaf, the whole tree and the stand and then converted to other scales by using scaling techniques (Fig 3.1). The objectives of the study will determine the scale and so the methodology that is used to measure water use.

Leaf gas exchange measurements use the diffusion equation to calculate transpiration in terms of a water vapour concentration difference and resistances across the stomata and leaf boundary layer. The leaf to air concentration gradient is determined from the humidity of the air and the vapour concentration of the intercellular spaces, which is assumed to be the saturated vapour concentration at the measured leaf temperature. Leaf conductance, as measured with a porometer, is defined as the transpiration rate divided by the leaf to air vapour concentration gradient. Boundary layer resistance can also be estimated by taking into account the leaf size and shape and the wind speed. Leaf measurements of conductance can also be scaled up to tree water use by means of the Penman Monteith equation and this methodology will be discussed further in response to scaling to canopy fluxes. At the leaf scale, the significance of stomatal control of transpiration will depend on how well the saturation deficit at the leaf surface is coupled to that of the ambient air (Jarvis and McNaughton, 1986). However, leaf level estimates of transpiration may not be readily scaled to a whole tree or canopy scale if aerodynamic resistances are different to that measured in the porometer chamber (Pearcy et al, 1992).

The water use of a whole tree can be estimated in a number of ways (Pearcy et al, 1992) including gravimetric and phytometric methods such as lysimeters (Dunin and O'Loughlin, 1988), cut shoots (Roberts, 1977), ventilated chambers (Greenwood and Beresford, 1980; Dunin and Greenwood, 1986; Farrington et al, 1989), and sap flow velocity units (Marshall, 1958). All of these techniques measure water use that is a composite of leaf water loss from the entire canopy of a tree. The heat pulse technique which predicts single tree water use from heat pulse velocity will be discussed in section 3.2.2. If stand transpiration is required these estimates of single tree water use need to be scaled to the stand level (Denmead, 1984). This has been attempted by a number of workers chiefly by

the comparison of results from measurements at a number of scales (Hatton and Vertessy, 1990; Walker et al, 1989; Ham et al, 1990; Dawson, 1996; Kostner et al, 1992; Goulden and Field, 1994; Dugas et al, 1993; Werk et al, 1988; Steinberg et al, 1990; Kelliher et al, 1992; Schulze et al, 1985; Diawara et al, 1991; Edwards and Warwick, 1984; Cermak et al, 1976; Rychnovska et al, 1980) but also by examination of the errors involved in using a number of scalars (Cermak and Kucera, 1990; Hatton and Wu, 1995). Where communities are heterogeneous and it is not practical to measure water use from every tree scaling errors may occur (Hatton and Wu, 1995). Leaf area has been shown to be the most precise and physiologically meaningful scalar to use in extrapolating from tree to stand (Cermak and Kucera, 1990; Hatton et al, 1995).

Evapotranspiration can also be measured from a stand of plants from energy balance or water balance methods. Water balance methods are reviewed by Holmes (1984). These methods are based on the hydrological equation to estimate evapotranspiration (ET)

$$ET = P - RO - UD - \Delta S$$

Where P is precipitation, RO is surface runoff, UD is underground drainage and ΔS is the change in water content of the soil (Moran and O'Shaughnessy, 1984; Sharma, 1984). Water balance methods have also been used to estimate groundwater use by vegetation using hydrograph techniques (e.g. Salama et al, 1994).

Energy balance methods (Garratt, 1984; Majek and Bingham, 1993) depend on the fact that the amount of water lost from an area of land is by evaporation depends chiefly on the energy available to evaporate water and the net radiation. An example of this approach is the Bowen Ratio (Appendix 5). Energy entering the system as net radiation (R_n) is dissipated as sensible (convective) heat and latent (evaporative) heat. The Bowen Ratio is the ratio of sensible heat to latent heat (Appendix 5).

Transpiration can also be estimated from a stand of plants by incorporating information of leaf conductance into models of evaporation such as the Penman Monteith equation which incorporates the concepts discussed in the preceding section. A major issue that has arisen from attempts to use the Penman Monteith equation to predict evaporation has been the identification of an appropriate resistance factor (Denmead, 1984). Measurements of stomatal resistance at various parts of a tree canopy need to be aggregated in a meaningful way to produce a canopy surface resistance factor (Baldocchi et al, 1991). However, if plant stands are closely coupled to atmospheric conditions, porometer data on stomatal

conductance can be used to make reliable estimates of transpiration rates (Jarvis and McNaughton, 1986). All of the concepts discussed in this section were used in the work outlined in this chapter and will be discussed in the next section.

3.2 Methodology

Rationale for methodology

Transpiration rates were estimated and compared to potential evapotranspiration estimates to identify limits to transpiration. Sap flow techniques were used to obtain a continuous record of single tree flux that could then be scaled to obtain areal fluxes. A methodology was therefore established that allowed estimates of areal fluxes from single tree estimates (Fig 3.1).

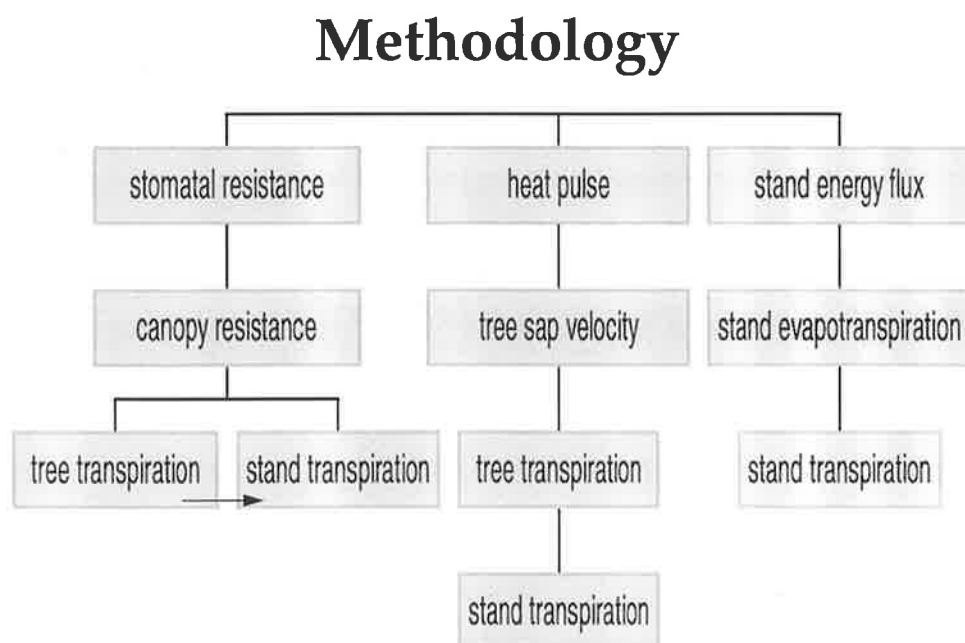


Figure 3.1: Rationale of methodology; Methods of estimating transpiration at different scales.

Transpiration was estimated from the 4 sites described in chapter 2. Heat pulse velocity was measured on 1-2 trees at the 4 sites and daily single tree sap flux (L) was estimated from this. The first tree was used to obtain the baseline data and the second tree was measured whenever equipment became available to check that the first tree was not behaving abnormally and was fairly representative for the site. In addition, at Duck Island there were consecutive measurements of flux taken from 8 trees during the scaling experiment. The flux estimated by the heat pulse was compared to the amount of water taken up by a cut tree to identify the error involved in the single tree flux measurement.

These measurements were scaled up to a forest estimate of water use based on tree parameters. Duck Island was the major site and a longer term record of single tree sap flux was obtained at Duck Island. A more intensive investigation was conducted at this site of various scalars and the errors that are involved when using these different scalars. This was done by measuring sap flux of a larger number of trees of varying sizes for a shorter period of time during the study period. The best way to scale was identified by comparing relationships between the different scalars and tree flux. The scaled estimate of transpiration obtained from these trees during the intensive experimental period was then compared to an estimate of evapotranspiration obtained with the Bowen ratio technique at this site at the same time (Hatton and Vertessy, 1990). This allowed the examination of potential errors in scaling with different tree parameters.

For the long term heat pulse measurements at the other sites (Lesron, Jaffray and Hansons) and for the data obtained outside of the intensive sampling time at Duck Island, scaling measurements were less intensive with the partial intention of relying on scaling relationships obtained during the intensive measurements at Duck Island. The flux / tree parameter relationship obtained for the individual study trees was used in combination with the scalar information for the site to scale up to areal fluxes (see later). These measurements were compared to Penman Monteith calculations of transpiration using leaf resistance measurements.

3.2.1 Potential Evapotranspiration

Potential Evapotranspiration (PET) is an estimation of the maximum amount of water that can be transpired by trees under well watered conditions. Potential evapotranspiration was estimated with the equilibrium evaporation equation (Slatyer and McIlroy, 1961);

$$\lambda E = \left(\frac{s}{s + \gamma} \right) * (R_n - G)$$

Where E is the potential evapotranspiration (mm/day), λ is the latent heat of vaporisation (KJ/kg), R_n (KJ/m²/day) is the net radiation (shortwave + longwave), G (KJ/m²/day) is the ground heat flux, s is the slope of the saturation vapour pressure curve at temperature T (C) and γ is the psychrometric constant. E was calculated on a daily time step with daily averages used for all parameters. Temperature data was collected from the weather station and used to calculate the slope of the saturation vapour pressure curve (the difference between $e_s(T+0.5)$ and $e_s(T-0.5)$), λ and γ (Murray, 1967) where;

$$e_s = 6.1078 \exp\left(\frac{17.269T}{237.16 + T}\right)$$

$$\lambda = 2.501 - 0.0024 * T$$

$$\gamma = 0.646 + 0.0006 * T$$

Ground heat flux was considered to be negligible. Net shortwave radiation intercepted by the canopy was estimated by;

$$Rsn = Rsd(1 - \alpha)$$

Where Rsd is the downward radiant flux at the surface of the canopy (KJ/m²/day) and α is the albedo coefficient (0.3; Stewart, 1984).

Net longwave radiation was estimated as;

$$Rln = (Rld - Rlu) * dayl / 1000$$

Where Rld is the incoming long wave radiation (Wm²) estimated according to Brustaert (1982) as;

$$Rld = \epsilon_a \sigma T_a^4$$

Where ϵ_a is the atmospheric emissivity for clear skies, σ is the Stefan- Boltzmann constant (5.6697E-8 W m⁻² K⁻⁴) and T_a is the air temperature (K) Where;

$$\epsilon_a = 1.24 \left(\frac{e}{T_a} \right)^{1/7}$$

Where e is the vapour pressure (mbar) and Rld is the incoming long wave radiation (Wm²) and is estimated according to Brustaert (1982) as;

$$Rlu = \epsilon_s \sigma T_a^4$$

Where ϵ_s is the surface emissivity and is assumed 1.0.

Rainfall data was also collected during this time and is presented in Appendix 2.

3.2.2 Heat pulse: estimated single tree flux

(a) Sap velocity

Sap velocity (cm/day) was measured (Greenspan Technology units) on 2 trees at each of the sites over a 12 month period and 8 trees over an intensive 2 week period at Duck Island. The Greenspan heat pulse instruments (Greenspan, 1996) use the compensation method (Huber and Schmidt, 1937) to calculate heat pulse velocity. A pulse of heat is sent from the probes into the stems. The time it takes for the temperature above and below the source of heat to equilibrate is used to compensate for the effect of heat diffusion and identify heat

convection. A maximum time of equilibration is set which represents no flow (set at 250 sec in this study).

The sap flow velocity is then estimated from the heat pulse velocity by making corrections for sapwood water content and wood density (Marshall, 1958; Edwards and Warwick, 1984) and the wound caused when probes are inserted in the sapwood (Swanson and Whitfield, 1981). Standard probes were inserted at 4 separate depths on two sides of the tree or the branch if multiple stems existed. The insertion depths and depths to sapwood and heartwood are shown in Appendix 3. Heat pulse velocity was then corrected to sap flow velocity using parameters of wood density, water content and wound size which are shown in Appendix 3.

(b) Sap flux

The resulting velocity estimates were used to estimate sap flux (L/day) using the method of Hatton et al (1990) (Appendix 3). The weighted average technique (Hatton et al, 1990) was used to estimate flux from these velocities which are obtained at more than one depth in the sapwood to allow for differences in sap velocity radially with depth (Appendix 3). Given a set of sapflow velocity estimates from n sensors placed at different depths between the radius at the cambium and the heartwood, the annular cross section of the tree is divided into n concentric annuli (Appendix 3). The flow within each annuli is calculated from velocities measured within that annuli and weighted according to the fractional area of sapwood that each sensor most closely represents (Hatton et al, 1990).

Sensors should be placed at a variety of depths to identify velocities at high and low velocity parts of the sapwood. In the current study the tree sapwood were generally not very extensive (1-2 cm thick) because of the nature of the environment and so the placement of 4 sensors usually covered the entire sapwood. Tree sapwood area was estimated from holes drilled at four compass points around the tree, with the change in colour of wood from light to dark indicating the change from sapwood to heartwood.

The validation of flux estimates was tested through a cut tree experiment (Roberts, 1977). A small (42 mm diameter) tree was cut at the base, re-cut under water in a bucket, and covered in plastic to prevent evaporation. The cumulative volume of water taken up by the tree was measured every 20 minutes over a 9 hour period (830 to 1730 hrs) by measuring the decline in the water level and was compared to that estimated by the heat pulse technique.

3.2.3 *Stand Transpiration: Scaling single tree heat pulse estimates*

To scale single tree estimates of transpiration in natural communities where tree spacings are irregular it is necessary to find relationships between the flux of individual trees and some easily defined parameter, which can then be related to ground area. The errors involved in using different parameters to scale the flux were investigated in the following section.

(a) Scaling experiment: Duck Island

Estimated fluxes from single trees (L/day) were scaled up to areal fluxes (L/m²/day or mm/day) based on the relationships between individual tree parameters and associated tree flux. This was achieved by conducting measurements similar to those outlined in Hatton et al (1995). Single tree fluxes were estimated as described above on 8 trees of various sizes. The following parameters were measured on these trees along with the 15 additional trees in the plot of 232 m²; leaf area, canopy projected area, sapwood area, trunk diameter, and tessellated ground area (Appendix 4.).

Leaf area was measured using the Adelaide technique (Andrew et al, 1979). A hand held module branch was identified and used to estimate by eye the number of such modules in the canopy. Leaves were then removed from the module and weighed. A relationship between leaf dry weight and leaf area was used to calculate leaf area of the module and hence the tree leaf area was found by multiplying module leaf area by the estimated number of modules making up the tree canopy.

Sapwood area was estimated by drilling holes at four compass points around the trunk (30 cm above the ground or the base depending on the length of the main stem). The apparent boundaries of sapwood and heartwood were determined by colour change and the area of sapwood was calculated from this and the mean diameter of the trunk at this point assuming a circular cross-section.

Projected canopy area was determined by measuring the length and width of the canopy. The projected area was treated as a rectangle and the area calculated in the normal way. The location of each tree in the plot was recorded and ground area was apportioned to each tree through a tessellation technique as outlined in Hatton and Vertessy (1990).

Analysis of variance was calculated to identify the major factors influencing tree flux. The regression equation for each tree parameter and flux relationship was used to calculate total plot fluxes with the knowledge of the total sum of the tree parameter in the plot (Appendix 4). Regression analysis was conducted to determine relationships between single tree fluxes and these parameters and these relationships were used to scale single tree fluxes to whole plot fluxes using information of the tree parameters for each tree in the plot. The relationship between the flux and the tree parameter was considered to be constant and was multiplied by the relationship between the tree parameter and the ground area. Standard deviation on these plot flux estimates were determined by the ratio method as was the variance (Cochran, 1953). Actual evapotranspiration (AET) was measured with the Bowen Ratio technique by Frank Dunin and Wybe Ryenga (CSIRO Division of Plant Industry) and details of the method and results are outlined in Appendix 5. The proximity of the resulting flux estimate to the actual evapotranspiration, along with magnitude of the error and the r^2 of the relationship was used to determine the best scalar. The regression relationships calculated during the time of intensive sampling were used to estimate transpiration rates which were then compared to known evapotranspiration estimates at the time. This information was used to investigate the differences between various scalars and which were the most reliable scalars.

(b) Seasonal transpiration and other sites

The relationship between tree parameters and flux may differ for different times of the year. Therefore the regression relationships obtained using this technique could not be used to determine transpiration rates at other times unless this intensive information relating sap flux to tree parameter was collected at all other times and regression relationships determined at these other times. As this was not possible at each time, the relationship between flux and sapwood area (sap flux density) was calculated for the single tree at each site and for each sampling date and multiplied by the total sapwood area for the site (the scalar).

$$\text{ie. } T \text{ (mm/day)} = \frac{F}{S} * \frac{S}{G}$$

where F is single tree flux (L/day), S is the sapwood area (cm^2) and G is ground area (m^2). The relationship between S and G was considered to be constant while the relationship between F and S was thought to be variable, driving the seasonal variability in the transpiration rate. This assumption is based on the fact that transpiration rate is limited by the tree parameter at times (ie tree size) but at other times is limited by other factors such as potential evapotranspiration therefore changing the relationship of F and S.

At Duck Island, the scalar was as estimated during the intensive experiment (a) while at the other sites the scalar was estimated by measuring tree circumference (or diameter), then estimating sapwood area from this. It was assumed that the relationship between sapwood area and circumference was the same for trees at other sites as at Duck Island. These two parameters were measured on only a few trees at the other sites (heat pulse trees) but were plotted along with the Duck Island data to test the assumption. These various relationships were used to estimate sapwood area for each of the trial plots at each of the sites and so sapwood density for each of the sites.

3.2.4 Leaf resistance: Null balance porometer

Leaf resistance to water vapour loss was measured on leaves of 3 trees from Duck Island and Hansons at sampling times from Nov 1993 to October 1994. This was done (1) to investigate stomatal closure and patterns of resistance and the control of stomata on transpiration. (2) to provide another estimate of transpiration. (3) to obtain information on minimum stomatal resistance for Penman Monteith PET calculations.

(a) Leaf resistance

Leaf resistance was measured with a null balance diffusion porometer (Licor 1600). Null balance porometers are based on the solution for the following equation

$$F = g\Delta q\rho$$

Where F is the flux of water in transpiration, Δq is the difference in specific humidity between leaf and air, g is the leaf conductance and ρ is the density of air. In the null balance type of diffusion porometer the transpiration rate is determined from the rate of inflow of dry air necessary to maintain the humidity in the chamber constant (Percy et al, 1992).

Measurements were made in sec/cm and then converted to sec/m and also to conductance values in mmol/m²/sec based on relationships with temperature and pressure (e.g. Percy et al, 1992). Three trees were measured ($n = 5$ leaves on each tree) at regular (60 - 90 minute intervals) throughout the day. Measurement branchlets (containing 6 - 10 leaves) were marked and the resistance was followed throughout the day. Leaves were then removed at the end of the day, dried at 90 degrees for 24 hours and then weighed. A linear regression

was developed through weighing and measuring the leaf area (using a Licor leaf area meter) of 30 leaves.

$$A = 3.59 * W + 4.7099$$

Where A is the leaf area (mm²) and W is the dry weight of the leaves (mg). This was used to calculate the leaf area of the measurement branchlets from leaf dry weights. Original field resistance readings were then adjusted with the new leaf area to produce the final resistance reading.

Canopy resistances (r_s) were estimated from these leaf resistances (see 3.1.2) by simply treating the canopy as one stratum and dividing the mean resistance (of replicate leaf measurements; r_i) for every time interval by the leaf area index as the canopy resistance is reasonably approximated by the parallel sum of the individual leaf resistances (L_i) (Jones, 1983).

$$r_s = \frac{r_i}{L_i}$$

Where r_{i} is the mean leaf resistance per unit projected area in a given stratum and L_i is the leaf area per unit ground area or in a stratum of the canopy. Canopy resistances were also estimated from the stand T and ET estimates (Bowen ratio and scaled heat pulse) using the Penman Monteith equation with climatic data obtained from the weather station (see next section).

(b) Estimated transpiration rates

These canopy resistance estimates (sec/m) from each time interval were used to estimate areal transpiration rates for the day using the Penman Monteith equation. The Penman Monteith calculation (Montieth, 1973) takes into account the specific aerodynamic effects of tree canopies on resistance to water flux along with the energy balance (see PET 3.2.1) as follows;

$$\lambda E = \frac{S R_n + \rho C_p (e_s - e) / r_a}{S + \gamma(1 + r_s / r_a)}$$

Where E is the evaporation rate, λ is the latent heat of vaporisation of water, R_n is available radiant energy, $e_s - e$ is vapour pressure deficit of the atmosphere, ρ is air density, C_p is specific heat of air at constant pressure, S is the slope of the saturation vapour pressure curve, γ is the psychrometric constant and r_s and r_a are resistances to vapour transport from within the plants to the bulk leaf surface and from the leaf surface into the atmosphere respectively. S , γ and λ are estimated as described in section 3.2.1. ρ is obtained from temperature (Murray, 1967);

$$\rho = 1.292 - 0.00428 * T$$

The net radiation intercepting the canopy is obtained empirically by using an exponential function of the leaf area index, analogous to the Beer-Lambert Law (Monteith, 1965a) thus;

$$R_n = R_d(1 - \alpha) * \exp(k * LAI)$$

Where k is the light extinction coefficient (used -0.4), LAI is the leaf area index (as per table 3.2), and α is the albedo coefficient (0.1; Stewart, 1984).

The aerodynamic resistance (r_a) is a function of the canopy roughness and height and wind speed (Monteith, 1965b; Stewart, 1984; Abteu et al, 1995);

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_0}\right) * \ln\left(\frac{z_h - d}{z_0 h}\right)}{k^2 U}$$

Where z_m is the wind speed measurement height (m), d is the zero displacement height (m), z_0 is the aerodynamic roughness (m), z_h is the air temperature and humidity measurement height (m), $z_0 h$ is the roughness length for heat and vapour transfer ($0.1 Z_0$), k is the Von Karman constant for turbulent diffusion (0.41) and U is the wind speed at height z (ms^{-1}) measured over the study site (Abteu et al, 1995).

Data on leaf temperature, relative humidity, and radiation were collected with the porometer on a hourly basis, averaged for the canopy and for the measurement period and used to calculate the Penman Monteith predicted evapotranspiration for every time interval (1-2 hrs). Data was also collected from the nearby weather station on a daily basis and was used to calculate some of the parameters (ie r_a).

3.2.5 Water Use Efficiency: $\delta^{13}\text{C}$

The ratio of the carbon isotopes $^{13}\text{C} / ^{12}\text{C}$ in leaf material can be used to examine the water use efficiency of C_3 plants. There is a relationship between $\delta^{13}\text{C}$ and intercellular CO_2 concentration and water use efficiency (Farquar et al, 1982) with a more negative $\delta^{13}\text{C}$ indicating a higher water use efficiency (molar ratio of photosynthesis to transpiration). Leaves were removed from the ends of branches (young leaves which should reflect the water use efficiency at that point in time) and the middle of the branches (old leaves which should reflect the integrated water use efficiency over the long term) from 3 trees at each of the sites. Leaves were sampled on 3/2/94 (summer) and 6/7/94 (winter) to examine the water use efficiency when there were potential extremes in soil water availability. Leaves were dried at $\sim 70^\circ\text{C}$ for 48 hrs, combined, and ground finely. Subsamples of ~ 5 mg were then analysed for $\delta^{13}\text{C}$ with a continuous flow IRMS (Barrie, 1990).

3.3 Results

3.3.1 Potential Evapotranspiration (PET)

Average daily equilibrium evaporation peaked in summer ~ 6 mm/day and was lowest in winter ~ 1.5 mm/day (Fig 3.2 a). This pattern was in response to changes in net short-wave (Fig 3.2 b) and long-wave radiation, VPD and temperature (Fig 3.2 c).

3.3.2 Heat pulse: estimated single tree flux

(a) Sap velocity

Estimated sap velocities ranged from 3 - 46 cm/hr depending on season, tree variability and site (Fig 3.3). Sap velocities were lowest at Lesron (Fig 3.3 b; 2-8 cm/hr), intermediate at Duck Island and Hanson where they were similar (Fig 3.3 a and c 3-18 cm/hr) and then highest at Jaffray (Fig 3.3 d; 5-45 cm/hr; \bullet). The highest sap velocities were measured in January at all of the sites (Fig 3.3). The daily pattern usually showed a high sap velocity early in the morning, followed by a decline mid-morning and then an increase in sap velocity towards the middle of the day (Figure 3.4 a-d).

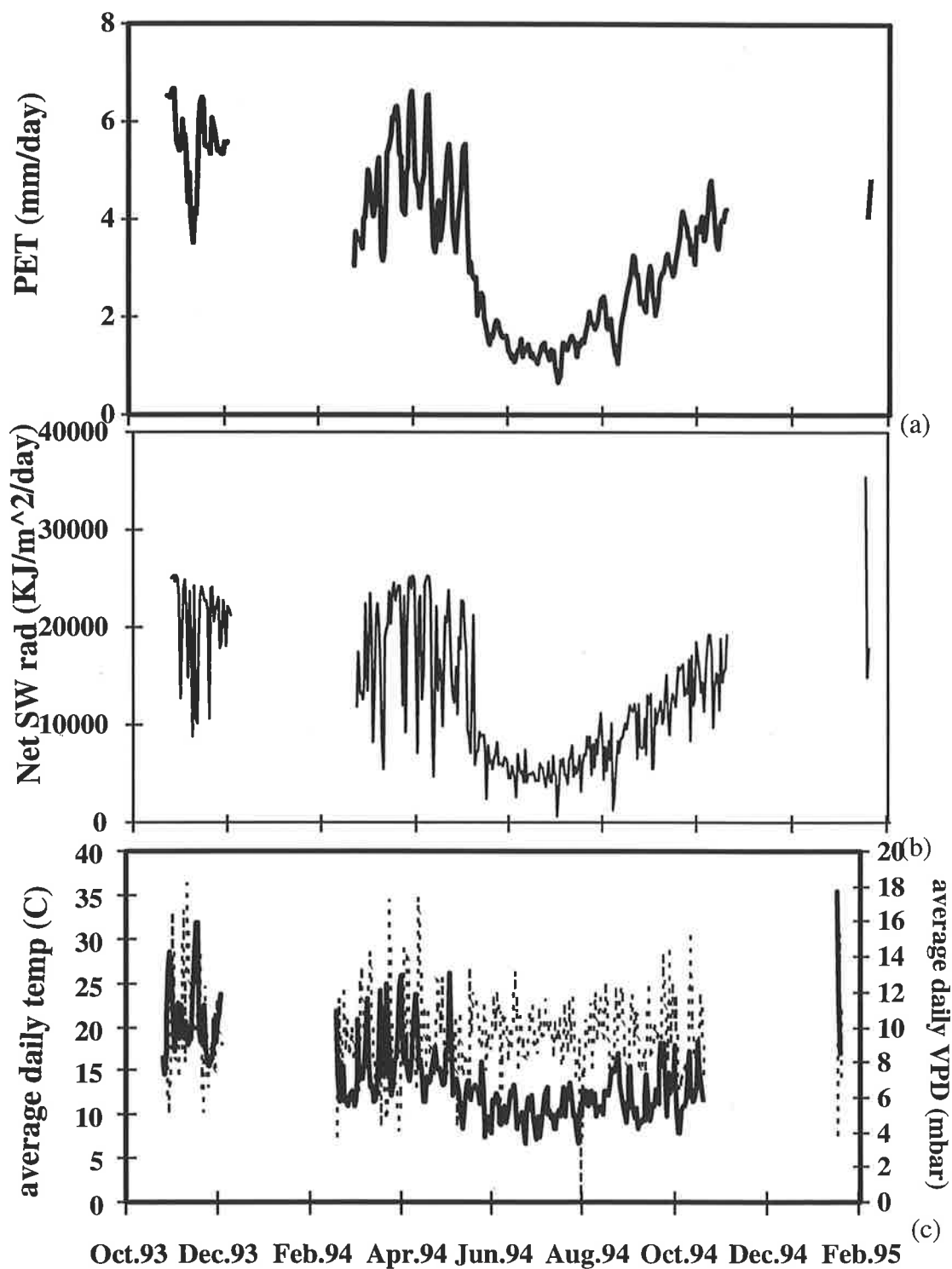


Figure 3.2: Estimated potential evapotranspiration (equilibrium evaporation; (a)) from climatic data collected at the Duck Island site. Also shown is net radiation ($\text{KJ}/\text{m}^2/\text{day}$; (b)), average daily temperature ($^{\circ}\text{C}$; dotted line) and VPD (mb; solid line). Results are shown from October 1993 to February 1995.

(b) Sap flux

Single tree fluxes were estimated from these velocities, and adjusted for the wound diameter and water content (as described in methodology). The diameter of the wound arising from insertion of the probes was measured on some trees and averaged 3 mm (Appendix 3). This was larger than expected based on the diameter of the drill bit (1.8 mm), but not unreasonable (see discussion). The sapwood volume fraction of water averaged 0.4 (Appendix 3) but was higher at Jaffray and lower at Lesron.

The daily pattern of flux (L/hr) was the same as sap velocity (Fig 3.4) with a maximum of 0.2 to 1.1 L/hr usually in the middle of the day depending on tree size, site and season (Fig 3.4 a-d). The cumulative flux for the day ranged from 1.2 to 10 L/tree depending on tree size, site and season (Fig 3.5 b). The mean daily fluxes for each month were highest at Jaffray (4 - 10 L/tree/day) as the sapwood area of the trees here were large as well as the sap velocities. The mean daily tree flux was lower at Duck Island (1.8- 3 L/day) and at Hansons (1.2 - 2.8 L/day) and lowest at Lesron (1.2 - 1.5 L/day) (Fig 3.5 b). The comparison of water taken up by the cut tree and the heat pulse estimate indicated that the volume of water removed from the bucket by the cut tree (1700 ml) was 37% higher than that estimated by the heat pulse technique (1100 ml), when using a wound diameter of 3 mm (as indicated by discolouration around the drill holes).

When these individual tree fluxes were normalised on the basis of sapwood area, differences between the measurement trees at each of the sites were reduced (Fig 3.5 c). Sap flux density ranged from an average daily winter flux of 0.09 to 0.12 L/cm²/day to an average daily summer flux of 0.1 to 0.27 L/cm²/day (Fig 3.5 c). High sap flux density was estimated at Jaffray (Fig 3.7 d) with an average of 0.13 L/cm²/day in winter and 0.27 L/cm²/day in summer. Smallest sap flux density was estimated at Lesron (Fig 3.6 b) with an average daily flux of ~0.1 L/cm²/day. Intermediate estimates of sap flux density were found at Duck Island and Hansons (Fig 3.6 a and c) of 0.12-0.18 L/cm²/day. In addition the second tree measured at Duck Island, Hansons and Jaffray showed similar sap flux densities to the long term trees (Fig 3.6) and at Duck Island during the intensive measurement period sap flux densities averaged 0.06 to 0.14 L/cm²/hr between the 6 trees (Fig 3.7 b). The second tree measured at Lesron showed sap flux densities that were initially similar to the long term measurement tree but after June the flux became erratic which may have been associated with a decline in tree health which was observed during this time.

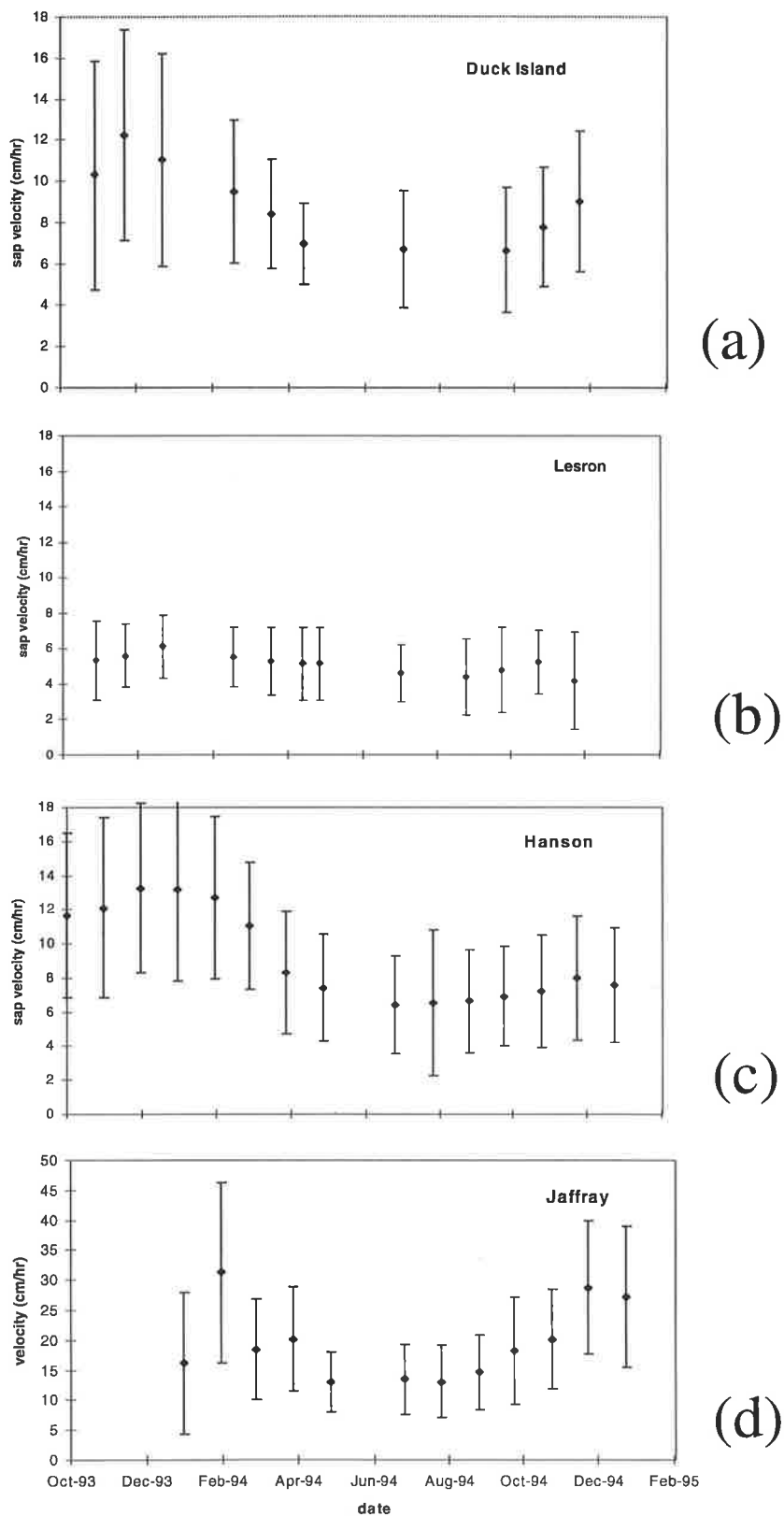


Figure 3.3: Monthly sap velocity (cm/hr) at Duck Island (a), Lesron (b), Hansons (c) and Jaffray (d) from October 1993 to February 1995; error bars are standard deviations.

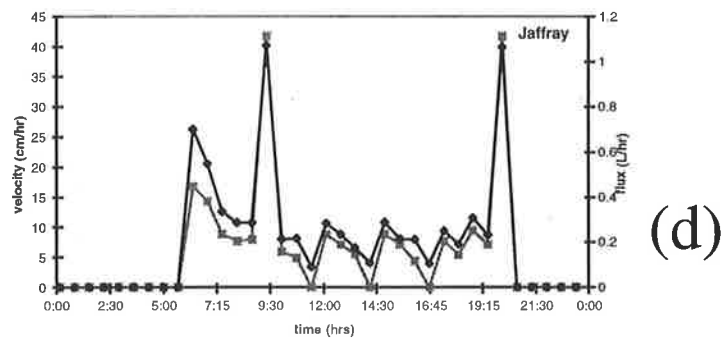
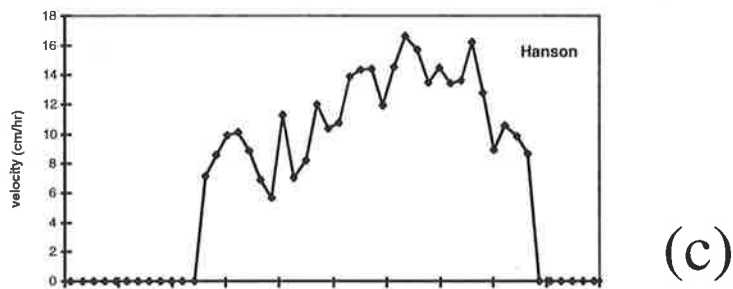
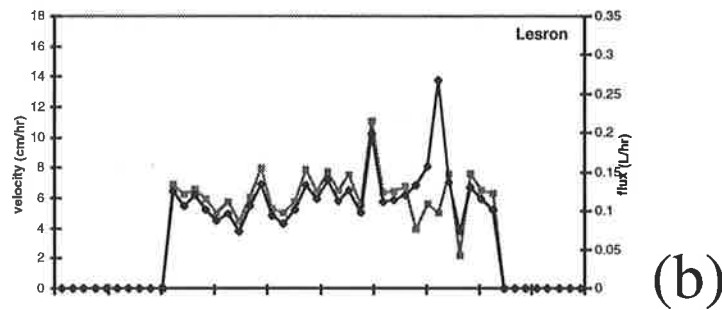
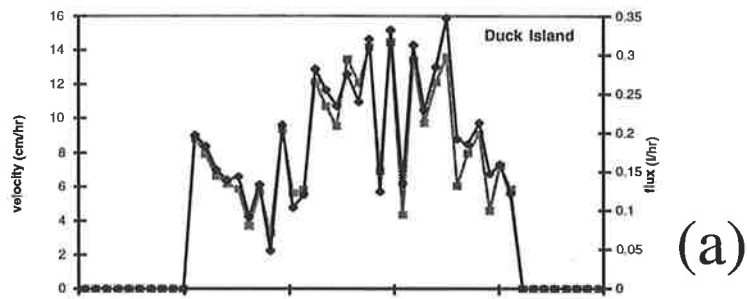


Figure 3.4: Hourly sap velocity (\blacklozenge ; cm/hr) on 2/3/94 for sampling tree at Duck Island (a), Lesron (b), Hansons (d) and Jaffray (d). Associated estimated flux (L/hr) is also shown (\blacksquare) for all sites except Hansons.

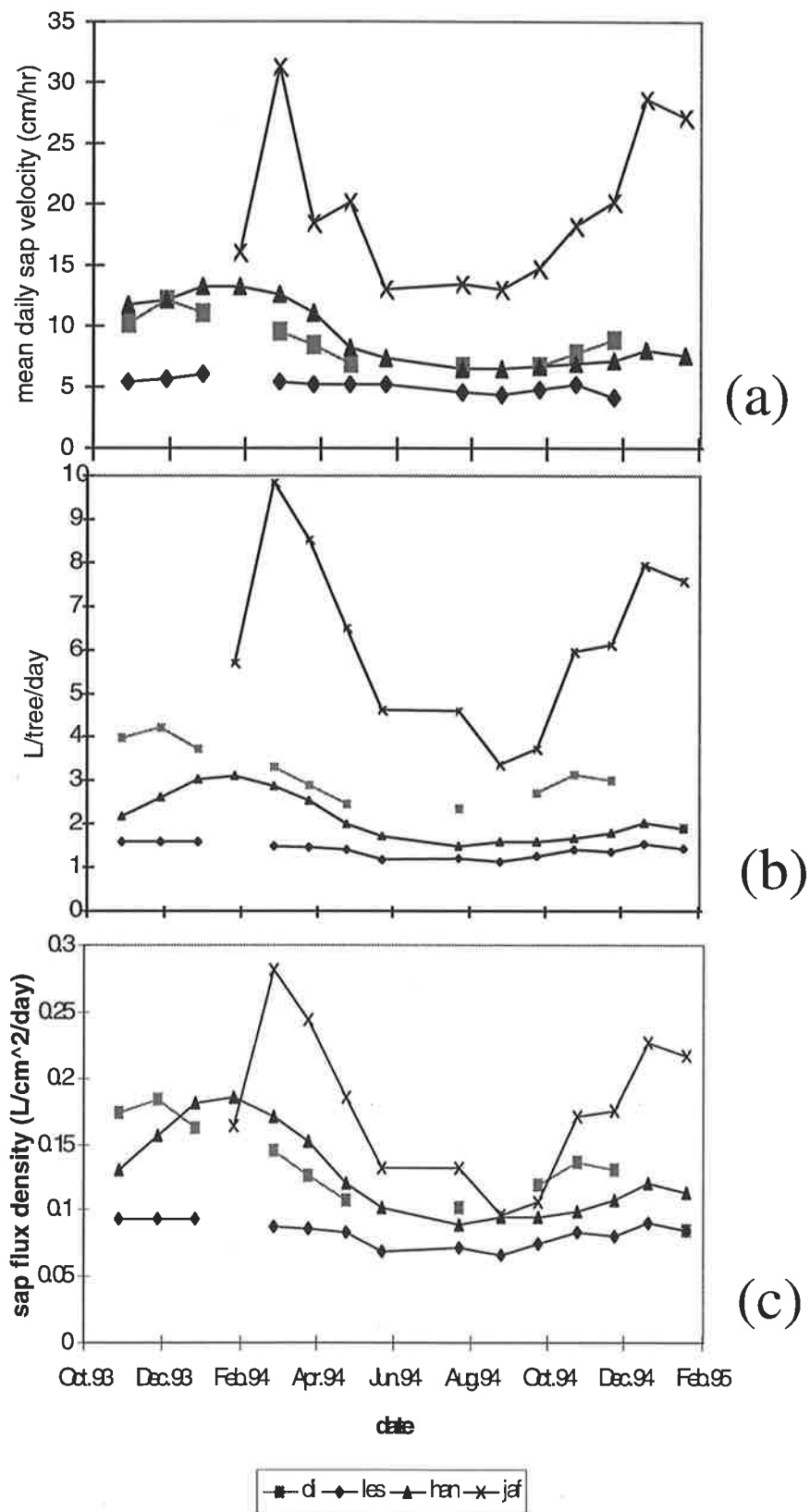


Figure 3.5: Single tree velocity (cm/hr; (a)), single tree flux (L / tree/ day; (b)), and sap flux density (L/cm²/day; (c)) averaged for the month for each site (see legend) from October 1993 to February 1995.

3.3.3 Stand Transpiration: Scaling single tree sap flux estimates

(a) Scaling experiment: Duck Island

Sapwood area for trees in the investigation plot at Duck Island ranged from 3.5 - 153 cm² and trunk diameter ranged from 2.4 cm to 55 cm (Appendix 4). Leaf area ranged from 0.4 m² to 29.2 m² per tree and the projected canopy area ranged from 0.3 m² to 18.9 m². Tessellated ground area ranged from 7.7 to 18.4 m² (Appendix 4).

The estimated total averaged for the five sampling days ranged from 0.5 to 0.9 mm/day according to the variable used to estimate flux (Table 3.1). The relationship between canopy area and tree flux (Figure 3.8 a) gave the highest estimate of total flux and the closest estimate to AET which averaged 1.5 mm/day (Table 3.1 and Appendix 5). This relationship also had the best coefficient of determination (r^2 ; 81%) and the lowest standard deviation (30%; Table 3.1). The relationship between flux and leaf area had the next best r^2 (64%) but the estimated transpiration was low. The relationship between flux and sapwood area (Fig 3.8 b) had a low r^2 (41%) but a reasonable estimate of transpiration (Table 3.1). Tessellated ground area has the worst relationship with flux ($r^2 = 21\%$).

Table 3.1: Regression relationships between scalars and flux for each tree parameter and estimated flux indicating the slope and r^2 of the relationship, the estimated total flux from the plot (L/day), the estimated areal flux from the plot (mm/day), and the standard deviation and standard error on this estimate. The mean actual evapotranspiration from the Bowen ratio is also shown.

Independent Variables	slope	R ² as %	Total (L/day)	Flux Total (mm/day)	Flux Stdev (mm/day)	SE (mm/day)
Sapwood Area (cm ²)	0.095	42.55	186.68	0.80	0.19	0.03
Mean Diameter (cm)	0.024	40.71	126.73	0.54	0.11	0.03
Leaf Area (m ²)	0.417	64.14	122.47	0.52	0.18	0.05
Tess Ground Area (m ²)	0.537	20.65	132.67	0.57	0.24	0.06
Canopy Area (m ²)	0.630	81.43	214.23	0.92	0.28	0.04
Actual ET (Bowen Ratio)				1.5	0.1	

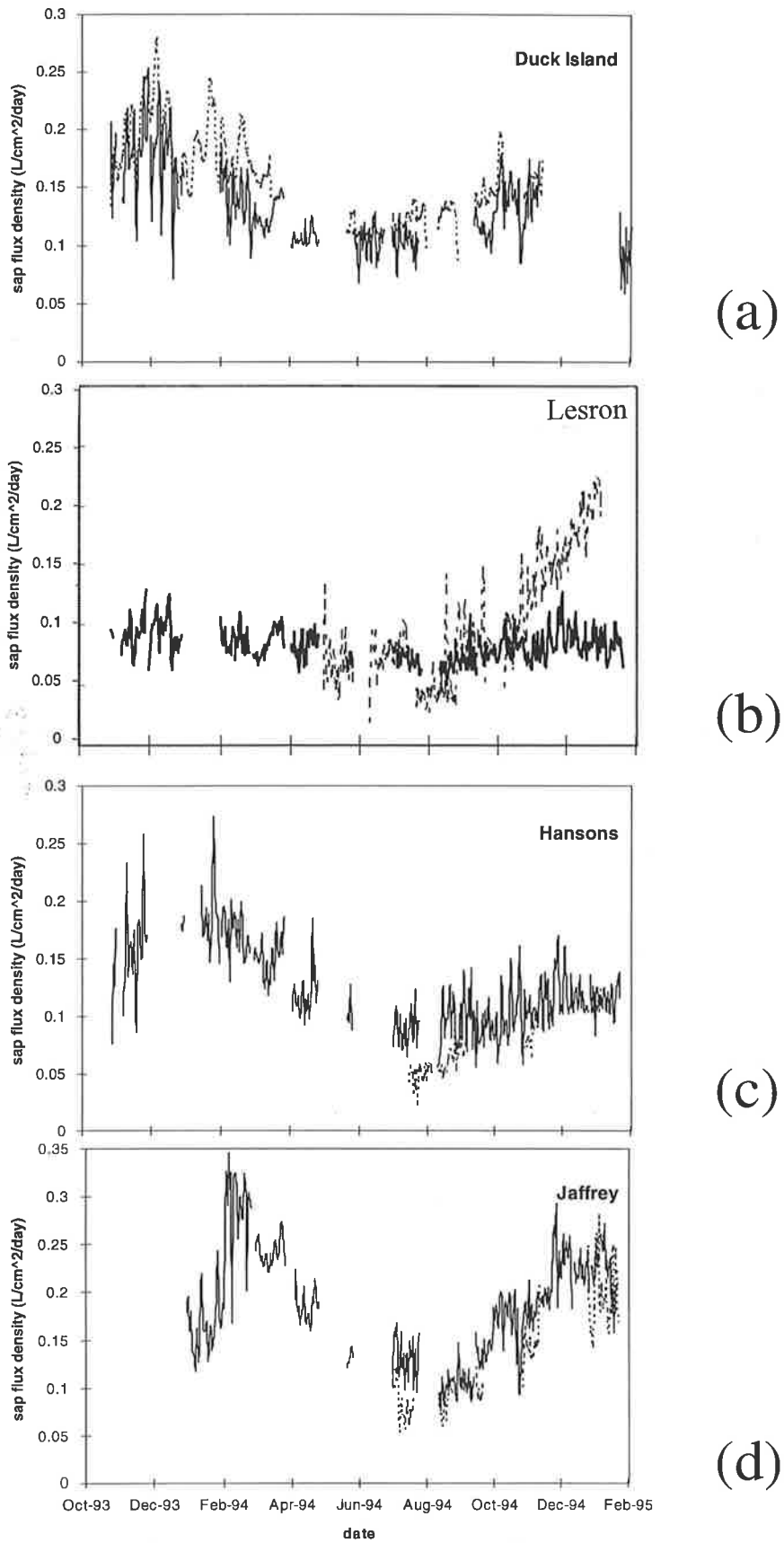


Figure 3.6: Daily single tree sap flux density ($L/cm^2/day$) for trees at Duck Island (a), Lesron (b), Hansons (c), and Jaffrey (d). The solid line is the primary measurement tree and the dotted line is the second sampling tree that was measured periodically.

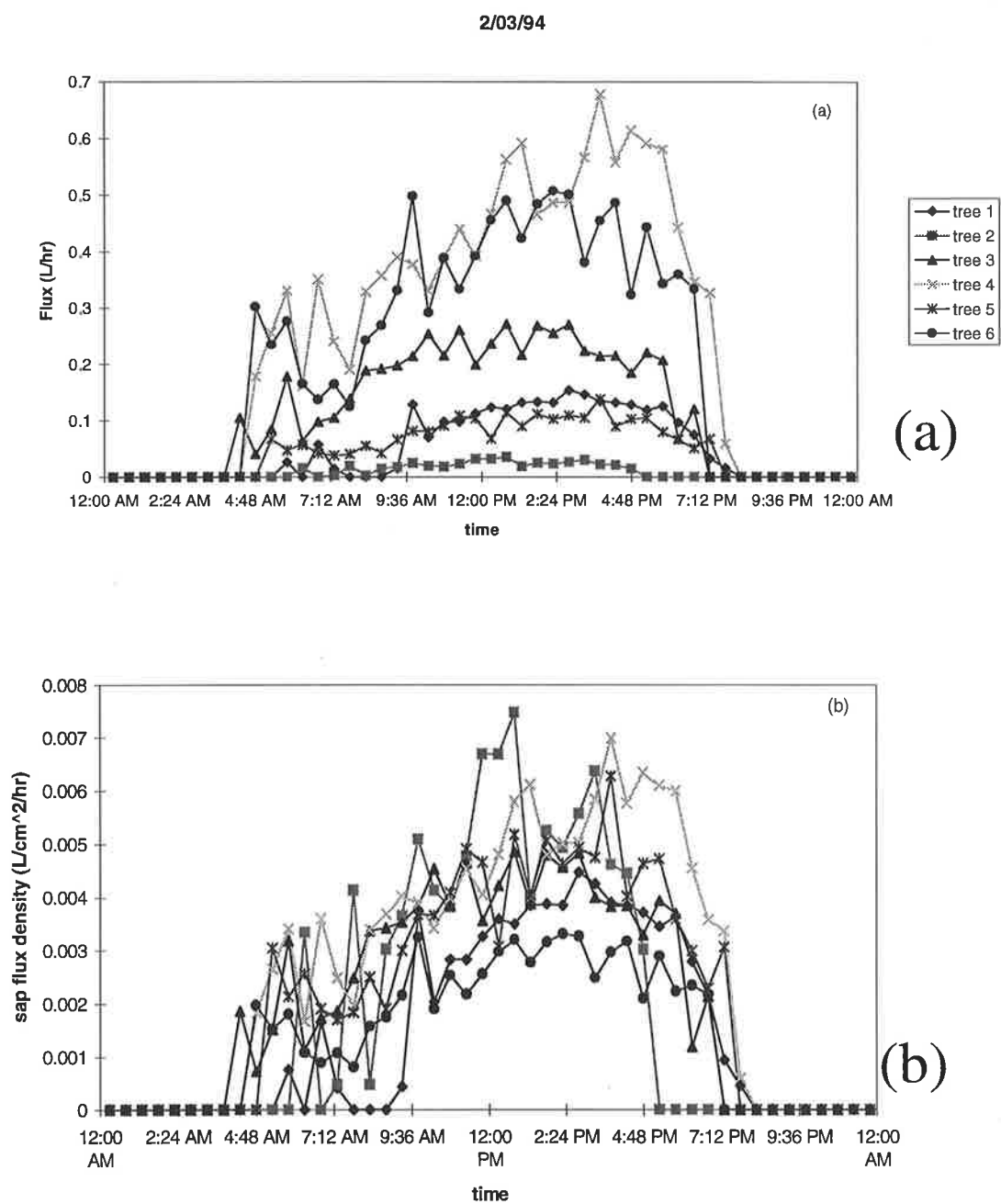


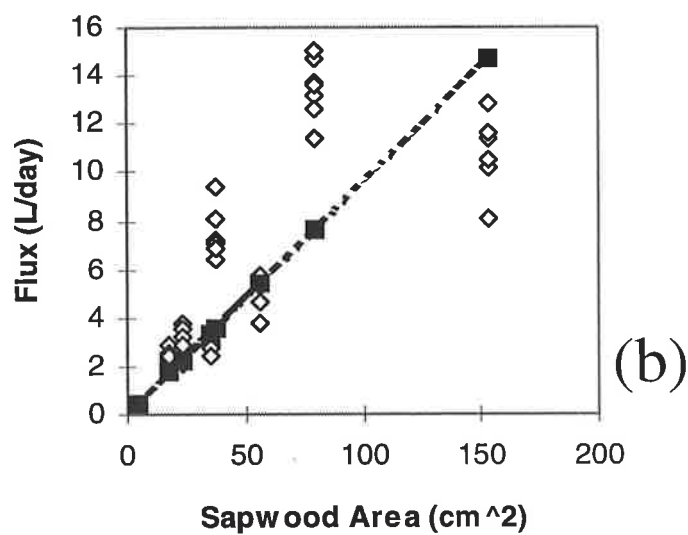
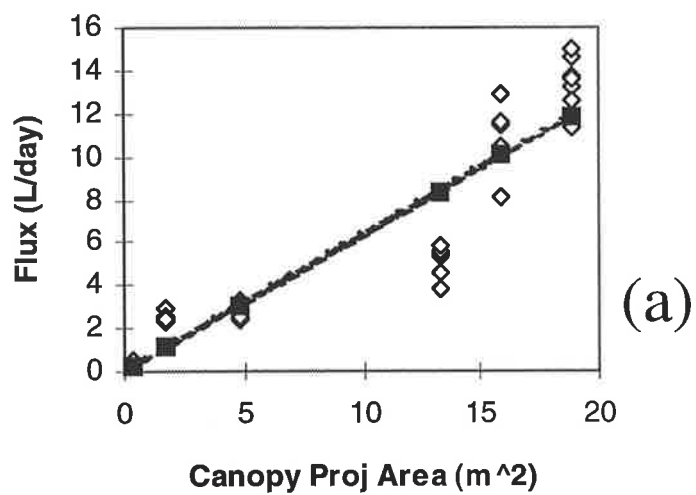
Figure 3.7: Hourly flux (L/hr; (a)) and sap flux density (L/cm²/hr; (b)) of sampling trees 1-6 that were measured during the intensive scaling experiment at Duck Island.

Actual evapotranspiration as measured by the Bowen Ratio method (AET) on 25/2 to 3/3/94 (see Appendix 5) was highest mid-morning (up to 0.23 mm/hr) and then fell to 0.1 mm/hr in the mid-afternoon (Fig 3.9). These estimates of AET could be compared to hourly estimates of T with the heat pulse (scaled with sapwood area; Fig 3.9). It can be seen that values for T (mm/hr) were similar to AET (0.03 to 0.16 mm/hr) but peaked in the afternoon after low fluxes in the morning often in a reverse pattern to that that found for ET (Fig 3.9).

(b) Seasonal transpiration and other sites

Average tree sap velocity and sap flux density was negatively correlated with groundwater salinity (Fig 3.10 a) and positively correlated with tree size (sapwood area) across sites (Fig 3.10 b). Therefore the relationships between tree parameters (ie canopy area, sapwood area) and flux at Duck Island (Fig 3.8) could not be extended to the trees at the other sites, even during the intensive scaling time. Additionally the relationships between flux and sapwood area during the intensive scaling time at Duck Island could not be extended to other measurement times because the sap flux density also changed at other times of the year (Fig 3.7 a). It was therefore concluded that the sap flux density (as established in the previous section) was variable and should be multiplied by one of the above scalars which were considered to be independent and unchanging (ie the sapwood density of the plot) to give the transpiration rate.

The different sites had different tree densities (Table 3.2), with the highest densities at Hansons and Jaffray and the lowest at Lesron and Duck Island. Tree size was variable within the plots and trees of different sizes had different sapwood areas (ie Appendix 4). The sapwood area was measured directly at Duck Island and was well correlated with tree circumference (Figure 3.11 a). It was therefore considered that the circumference of the trees at other sites could be measured and related to this sapwood area / circumference relationship from Duck Island to estimate the total sapwood area in the plot and so the sapwood density. The total circumference per unit ground area differed across sites, being highest at Lesron and lowest at Duck Island (Table 3.2). However when the circumference/ sapwood area relationship from the test trees from other sites were related to the Duck Island trees it was concluded that trees at Lesron tended to have less sapwood area per given tree circumference, the trees at Jaffray tended to have more sapwood area per given tree circumference and the trees at Hansons tended to have similar relationships to the Duck Island trees (Fig 3.11 a).



◇ Flux (L/day) - - - ■ - - - Predicted Flux (L/day)

Figure 3.8: Relationship between the scalars sapwood area (cm²; (a)) and canopy projected area (m²; (b)) and flux (L/day) for Duck Island, indicating the real values (open symbols), predicted values (closed symbols) and associated regression lines.

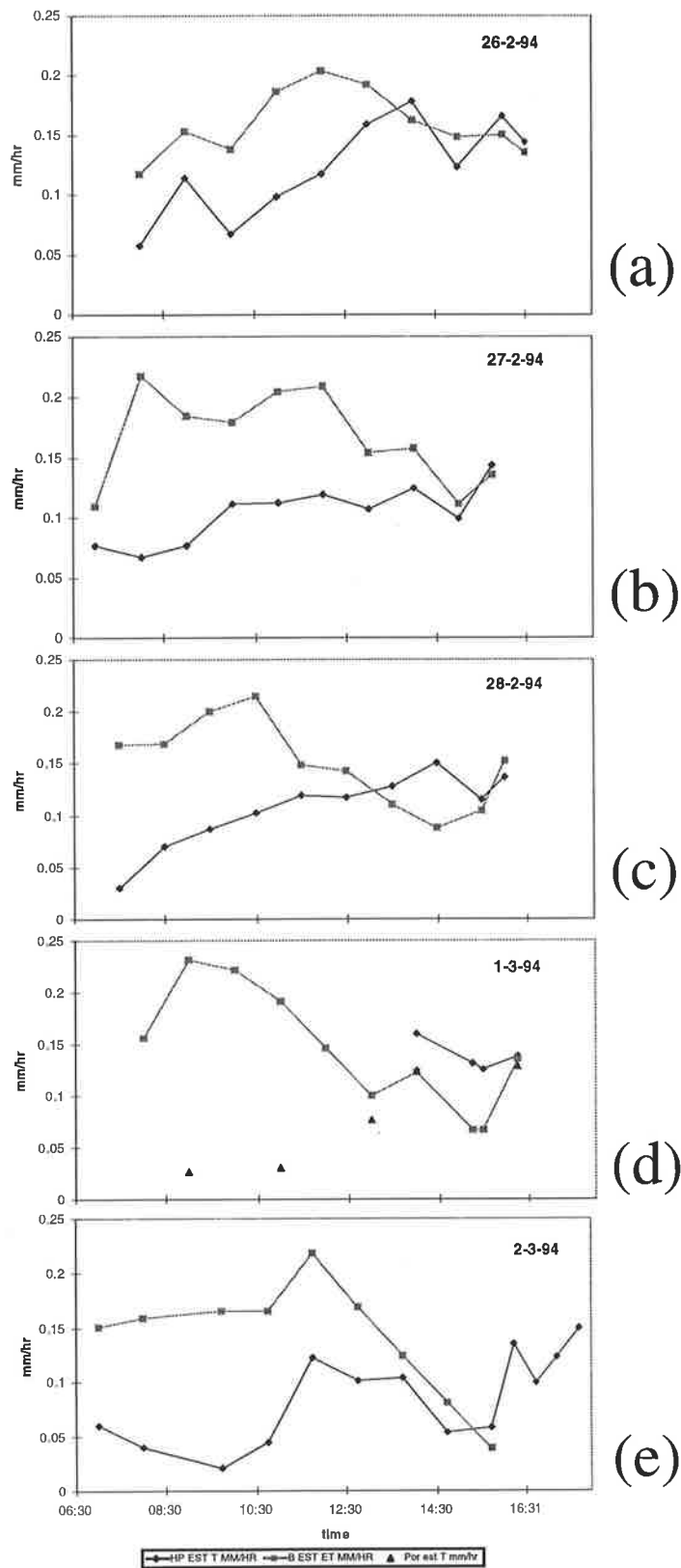


Figure 3.9: Estimated hourly transpiration (mm/hr) from the heat pulse (HP) and hourly evapotranspiration with the Bowen ratio (B) during the scaling experiment at Duck Island. Transpiration estimates with the porometer (Por) were obtained on 1/3/94.

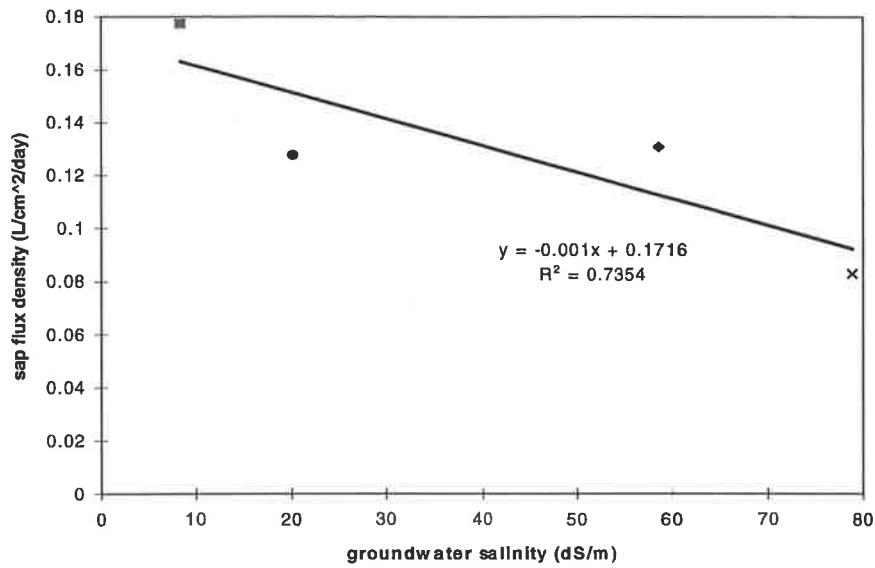
Therefore this methodology may have resulted in an over-estimation of total sapwood area at Lesron and an underestimation at Jaffray. These various relationships between circumference and sapwood area were used to estimate sapwood at each of the sites. This resulted in the following site sapwood density estimates (Table 3.2) with the highest sapwood area densities at Hansons and the lowest at Lesron.

Table 3.2: Estimated tree density (tree/ m²), circumference density (per ground area; mm/m²), sapwood density (area per ground area; cm²/m²), leaf area per ground area (leaf area index; m²/m²), and canopy projection (m²/m²).

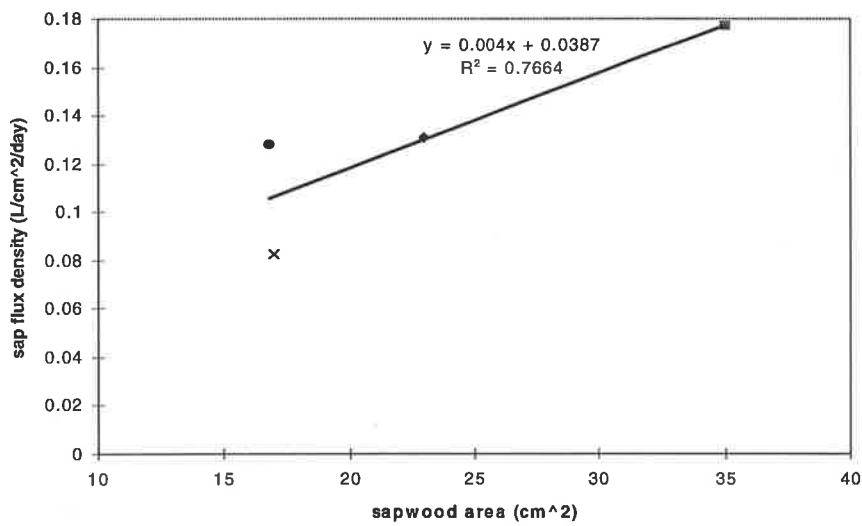
	plot size (m ²)	tree density (tree/m ²)	circ density (mm/ m ²)	est.sapwood area density (cm ² / m ²)	est. area index (m ² / m ²)	est. canopy density (m ² /m ²)
Duck Island	232	8.8	91.1	10	1.2	1.8
Lesron	30	10	202.5	8.6	1.1 ^A	1.5
Hanson	70	18	181	21	2.4	3.7
Jaffray	26	13.4	119	15.5	1.7 ^B	2.7

The leaf area in the plot and hence the leaf area index was also estimated for all of the sites based on the sapwood area / leaf area relationship established for trees at Duck Island but using the sapwood area estimated above (Fig 3.11 b). However the relationships between leaf area and sapwood area used to calculate the leaf area index may not have held for the other sites (Fig 3.11 b). The tree at Jaffray appeared to have a higher leaf area / sapwood area ratio and so would have had a higher leaf area index than calculated at Lesron.

It was concluded that sapwood was the most reliable estimated scalar from the data available and it was multiplied by each sap flux density to get a transpiration rate (Fig 3.12 a-d). The resulting transpiration estimates followed the same seasonal trend as sap velocity. For trees at Duck Island, transpiration rates reached an average daily rate of 1.4 mm/day (stdev 0.3) in summer and autumn and an average daily rate of approximately 1.2 mm/day (stdev 0.2) in winter and spring (June - Nov) (Table 3.3). Transpiration rates at Hansons averaged 3 mm/day in summer (stdev 0.7) and 2 mm /day in winter (stdev 0.4; Table 3.3).

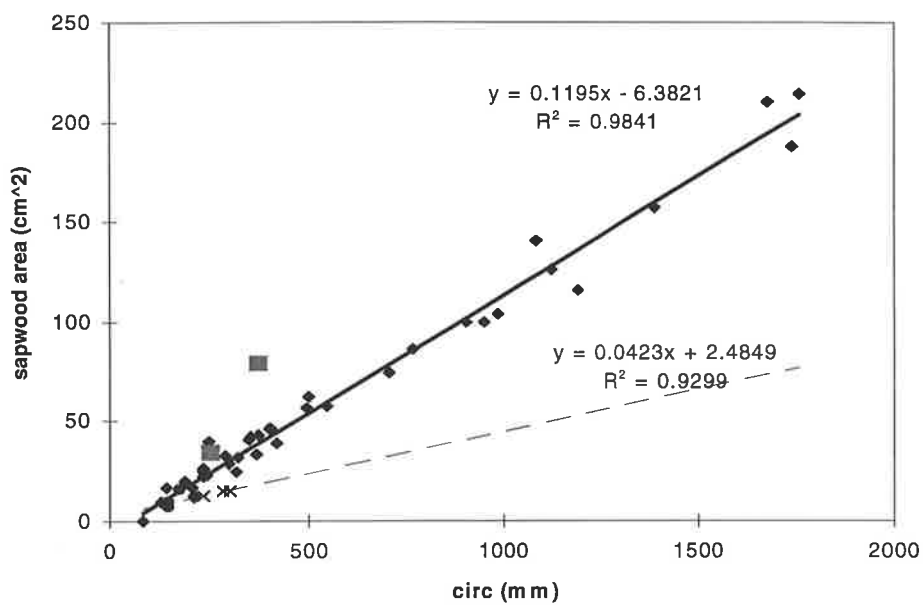


(a)

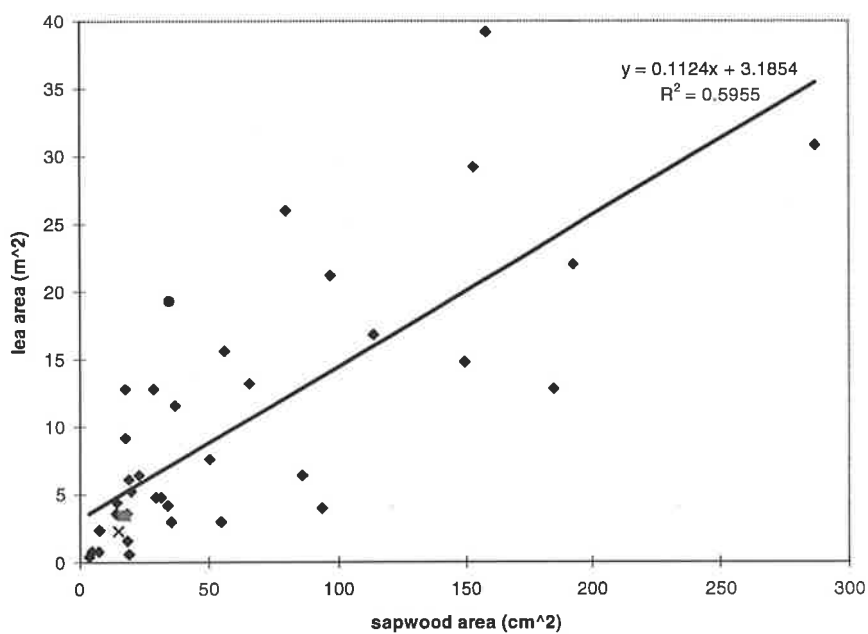


(b)

Figure 3.10: Relationship between mean sap flux density (L/cm²/day) and (a) mean groundwater salinity (dS/m) and (b) mean tree sapwood area (cm²) for trees at Duck Island (◆), Lesron (⊗), Hansons (●) and Jaffrey (■).



(a)



(b)

Figure 3.11: Relationship between sapwood area (cm²) and tree circumference (mm; (a)), and relationship between leaf area (m²) and sapwood area (b) for trees at Duck Island (◆), Lesron (◻), Hansons (●) and Jaffrey (✕). The solid line indicates the regression line for the relationship for all Duck Island trees and the dashed line for trees at Lesron.

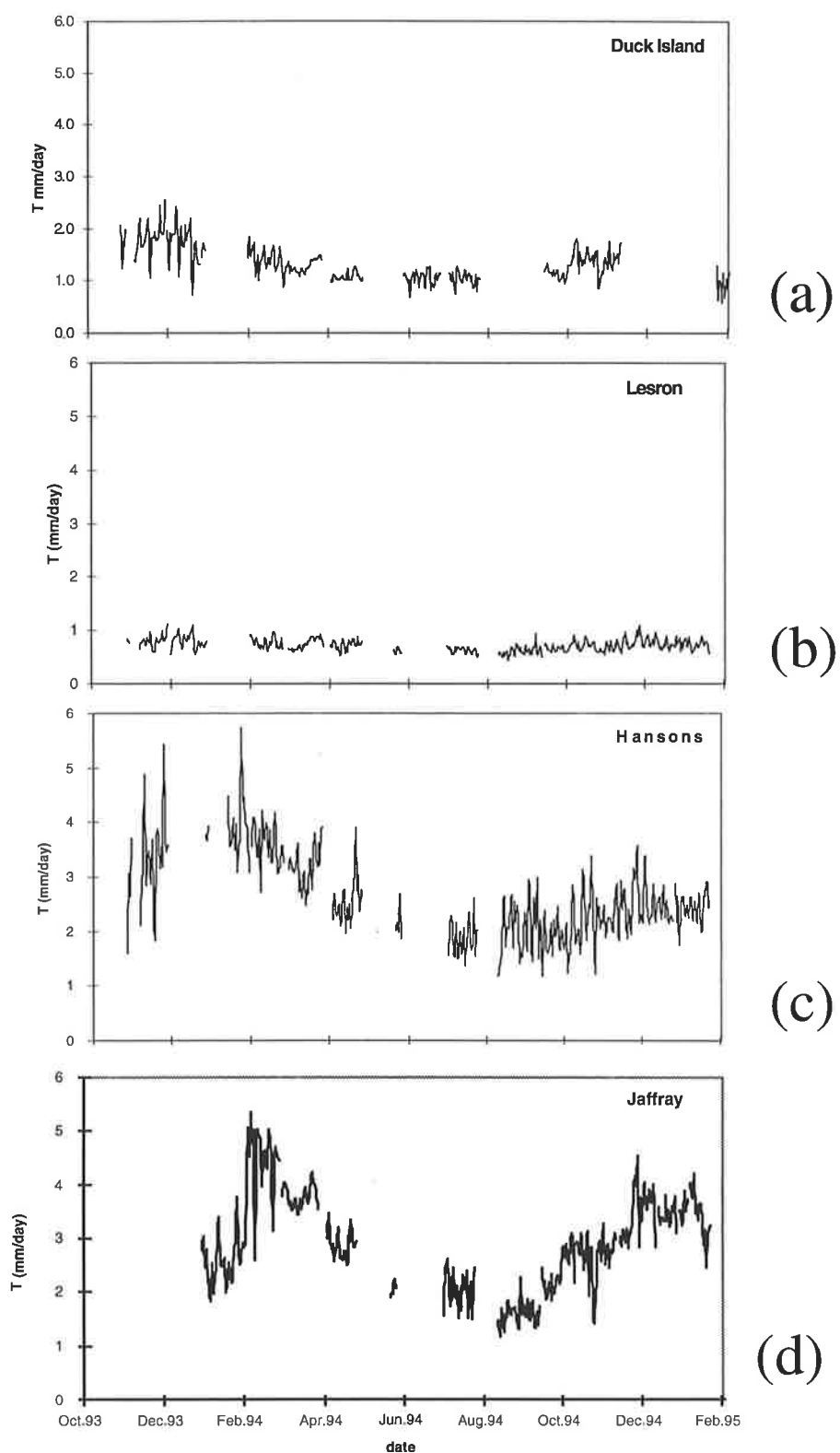


Figure 3.12: Estimated transpiration rates (mm/day) for Duck Island (a), Lesron (b), Hansons (c) and Jaffray (d) from October 1993 to February 1995.

At Lesron the transpiration rates averaged 0.7 mm/day at all times (stdev 0.1; Table 3.3). The estimated transpiration rates at Lesron were lower than at the other sites despite tree densities being similar and this site having the highest circumference density. This is because the plot sapwood areas were lower because of the different relationship between tree size and sapwood area. In addition the lower sap velocities of trees at Lesron resulted in lower single tree transpiration rates and also resulted in a lower total plot transpiration estimate. Transpiration rates at Jaffray averaged 3.4 mm/day in summer (stdev 0.8) and 2.2 mm/day during winter (stdev 0.6; Table 3.3). Jaffray Swamp transpiration rates were higher than transpiration rates from all other sites. Trees at Jaffray had much higher sapflux densities than the other sites. Therefore despite tree densities and sapwood densities not being significantly higher than the other sites the higher sap velocities resulted in higher transpiration rates for *M.halmaturorum* at this site.

Table 3.3: Average daily water use and standard deviation for summer and autumn (December to May) and winter and Spring (June to November) at each site.

SITE	Avg T Summer/Autumn (Dec - May) mm/day	Avg T Winter/ Spring (June - Nov) mm/day
DUCK ISLAND	1.4 ± 0.3	1.2 ± 0.2
LESRON	0.7 ± 0.1	0.7 ± 0.1
HANSONS	3 ± 0.7	2 ± 0.4
JAFFRAY	3.4 ± 0.8	2.2 ± 0.6

3.3.4 Stomatal resistance

(a) Single leaf resistances at all sites

Patterns of leaf resistance showed either a rising trend (Fig 13.13 a, d and g), a falling trend (eg Fig 13.13 e and h), and a more erratic pattern which included low resistances in the middle of the day and plateaus (eg Fig 13.13 c and Fig 13.14 b). Trees at Duck Island had minimum measured leaf resistances of ~150 sec/m (~200 mmol /m² /sec conductance) early in the morning in the middle of summer (Fig 3.13 d) and maximum leaf resistances of 4000 sec/m early in the morning in Autumn (Fig 3.13 h). Leaf resistances were mainly high early in the morning (Fig 3.13 e and h) or late in the afternoon (Fig 3.13 a and g) however there was never a decisive closure in the late afternoon.

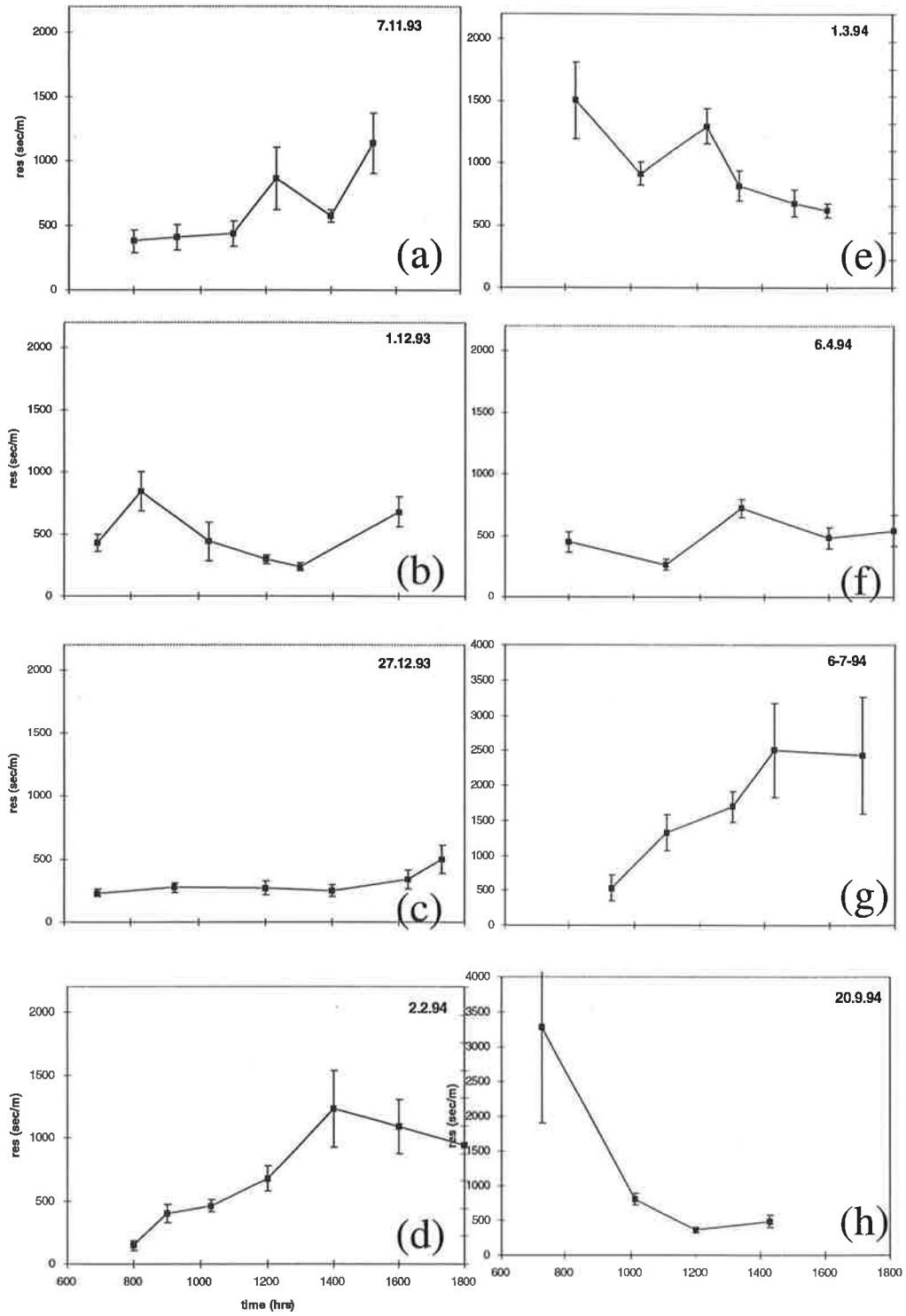


Figure 3.13: Hourly mean stomatal resistance (sec/m) for trees at Duck Island at each sampling time.

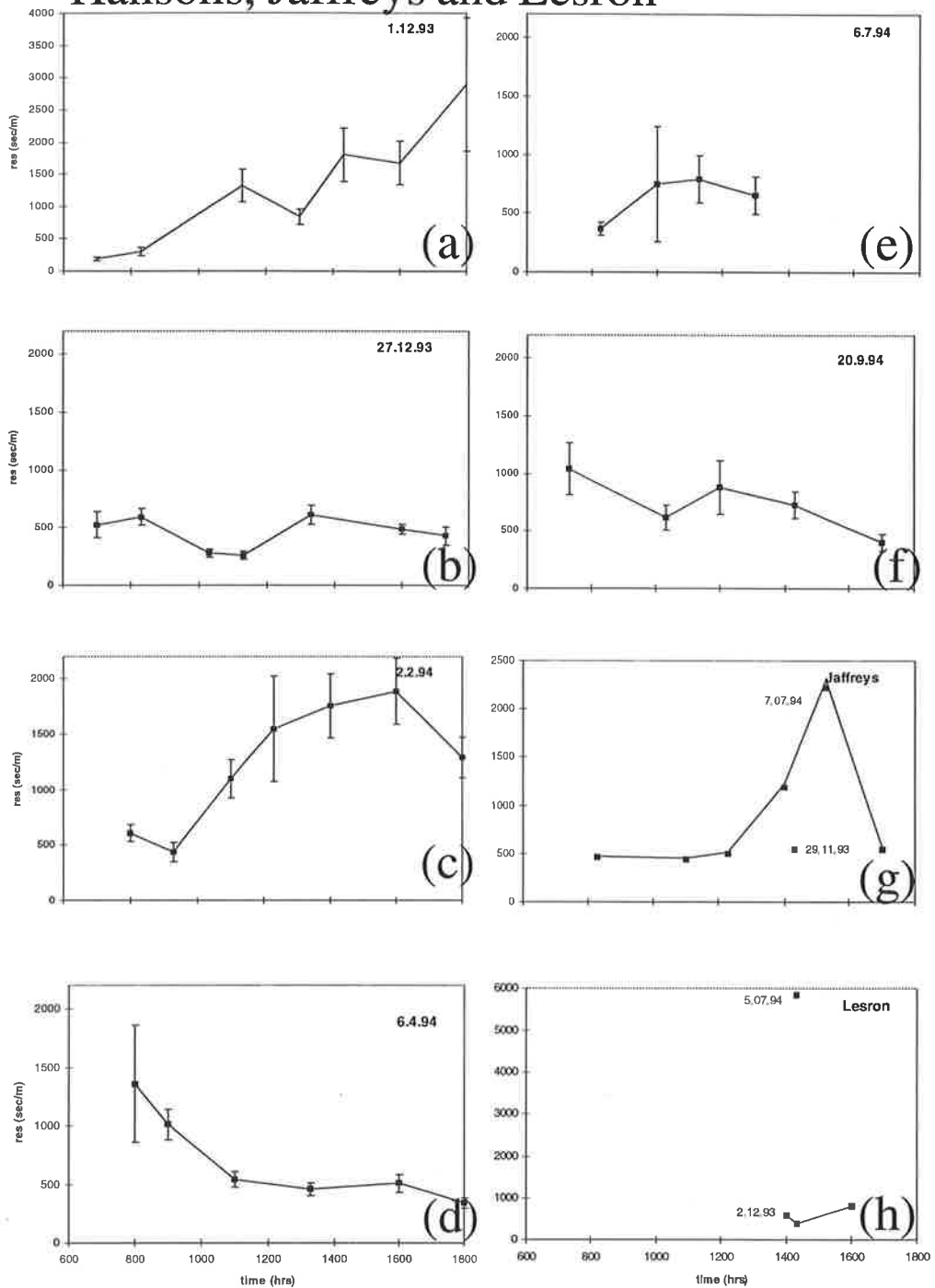


Figure 3.14: Hourly mean stomatal resistance and standard deviation (sec/m) for trees at Hansons at each sampling time (Fig a - f) and for trees at Jaffrey Swamp (g) and Lesron (h) at two sampling times (indicated on figures).

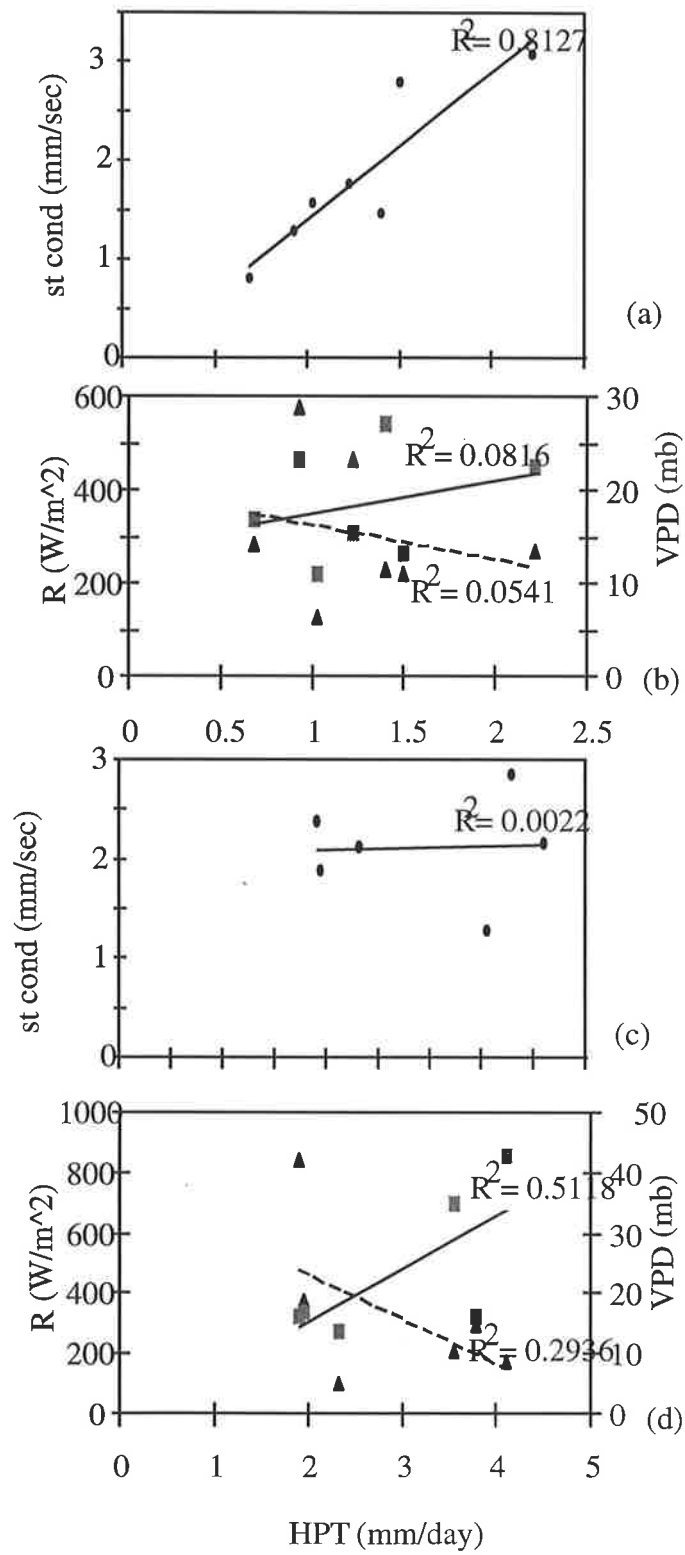


Figure 3.15: Regression relationships between heat pulse estimated transpiration (HPT; mm/day) and stomatal conductance (●; mmol/m²/sec) and VPD (■; mb) and net radiation (▲; W/m²) for Duck Island (a and b) and Hansons (c and d). There is a good relationship between transpiration and stomatal conductance at Duck Island and a poor relationship at Hansons.

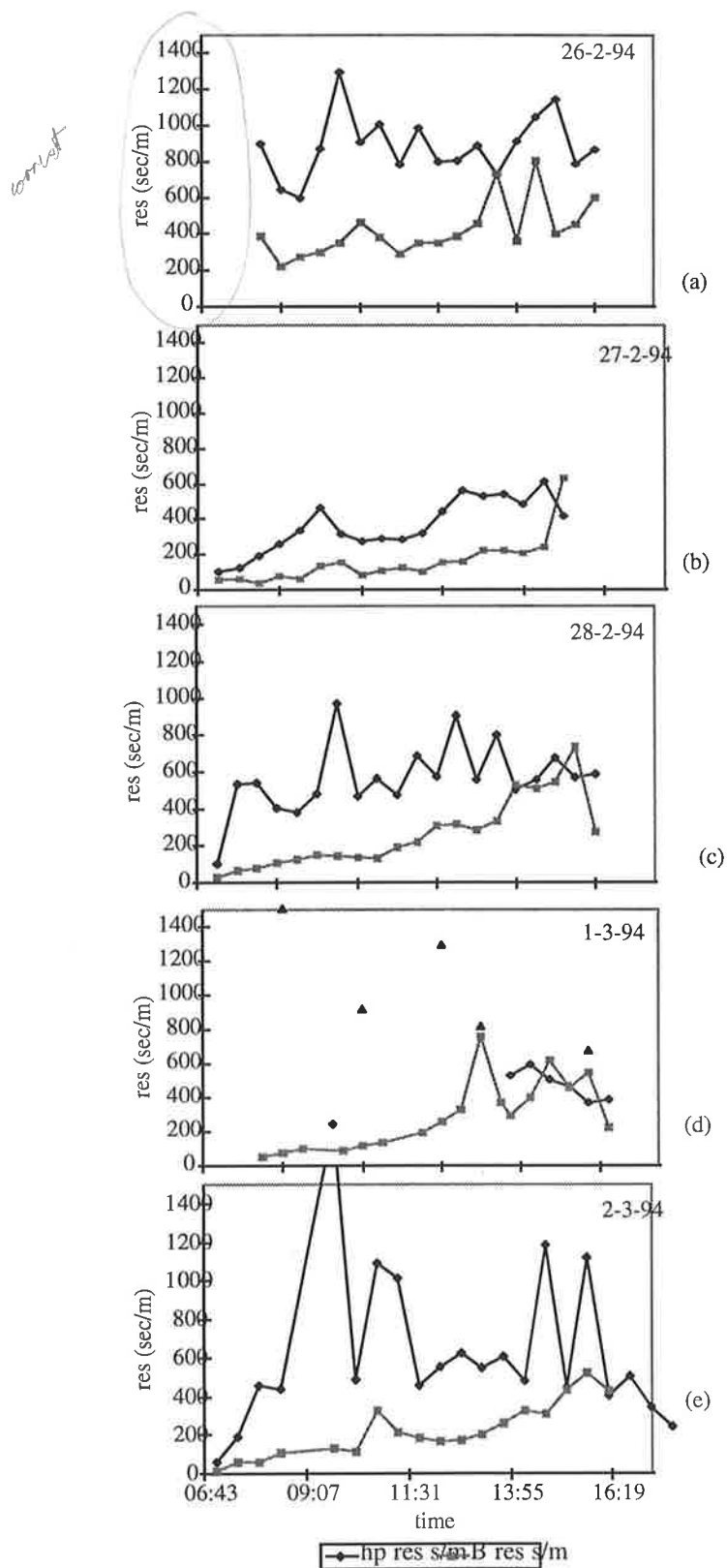


Figure 3.16: Estimated hourly canopy resistance from the Bowen ratio evapotranspiration measurements (B) and heat pulse areal estimates (hp) over the period of the scaling experiment at Duck Island. Canopy resistance was also estimated with the leaf estimates from the porometer (\blacktriangle ;(d)).

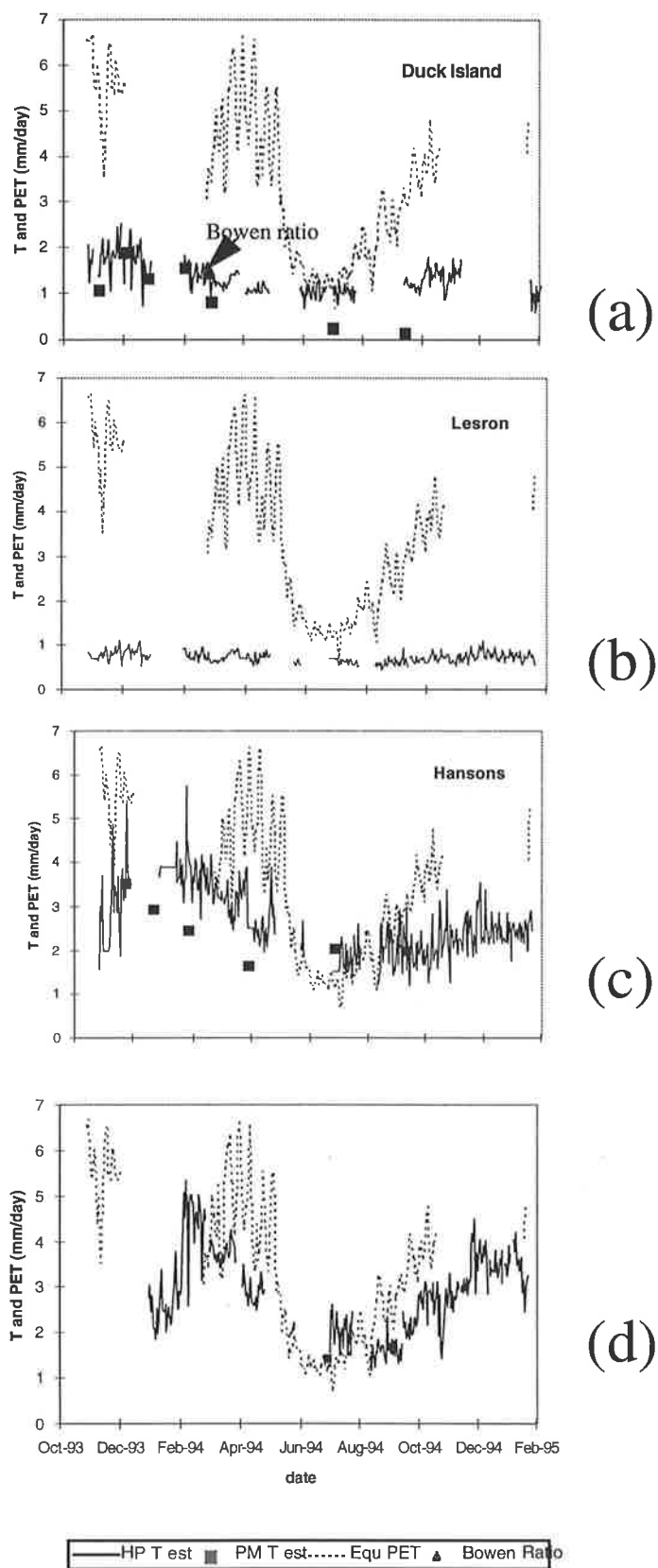


Figure 3.17: Estimated transpiration with the heat pulse technique (solid line) and equilibrium evaporation estimated PET (dotted line) for Duck Island (a), Hansons (b), Lesron (c) and Jaffray (d). Penman monteith estimated transpiration is also shown (■) as is the Bowen ratio actual evapotranspiration (▲).

(b) Estimated canopy resistances and areal transpiration rates.

Estimated canopy resistances were greater than 100 sec /m at Duck Island; estimates using the Bowen ratio were found to be lower than those obtained with the scaled heat pulse estimate (Fig 3.16). Canopy resistances obtained with the porometer were higher than either of the other estimates on 1/3/94 at Duck Island (Fig 3.16 d). Transpiration rates estimated with the Penman Monteith equation for Duck Island and Hansons were similar to that estimated with the heat pulse technique ($r^2 = 0.8$). Daily estimates of transpiration rates ranged from 2 mm/ day to 0.5 mm/ day at Duck Island (Fig 3.17 a) and from 4 mm/day to 2 mm/day at Hansons Swamp (Fig 3.17 b). The transpiration estimates were found to be slightly lower than the heat pulse estimates at Jaffray and slightly higher at Lesron (Fig 3.17 d and Fig 3.18).

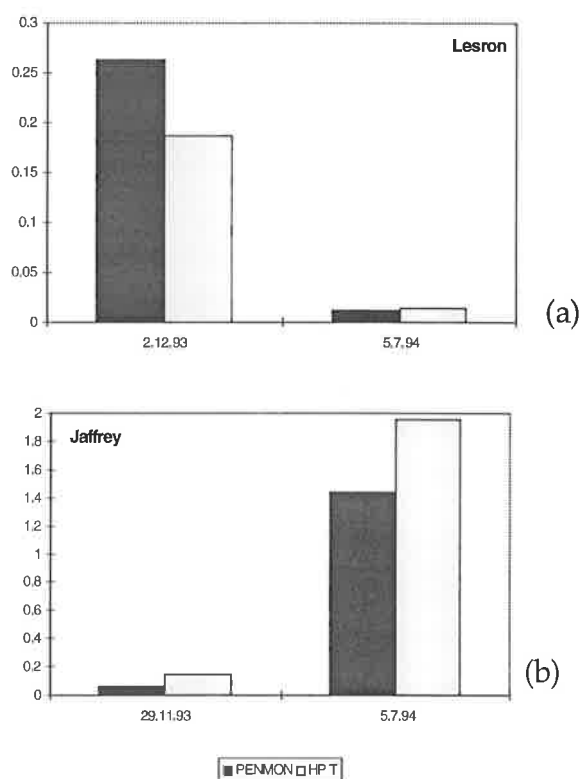


Figure 3.18: Estimated transpiration (L/m^2 / sampling time period) for trees at Lesron (a) and Jaffrey (b) at two times as estimated with heat pulse (HP) and the Penman monteith equation (Penmon).

3.3.5 Water Use Efficiency

$\delta^{13}C$ values ranged from -25 ‰ (Lesron new leaves in summer) to -31 ‰ (Jaffrey old leaves in summer) depending on site and season (Fig 3.19). New leaves in summer at all sites had higher (less negative) $\delta^{13}C$ than old leaves indicating higher water use efficiency. For new

leaves in summer (which should reflect the current conditions) $\delta^{13}\text{C}$ was highest for Lesron and lowest for Jaffray (Fig 3.19). Differences between $\delta^{13}\text{C}$ of leaves in winter were less pronounced between sites. For both young and old leaves, Lesron had the highest $\delta^{13}\text{C}$ followed by Duck Island and Hansons. However for the winter sampling leaves from Jaffray had higher $\delta^{13}\text{C}$ than leaves from Hansons (Fig 3.19).

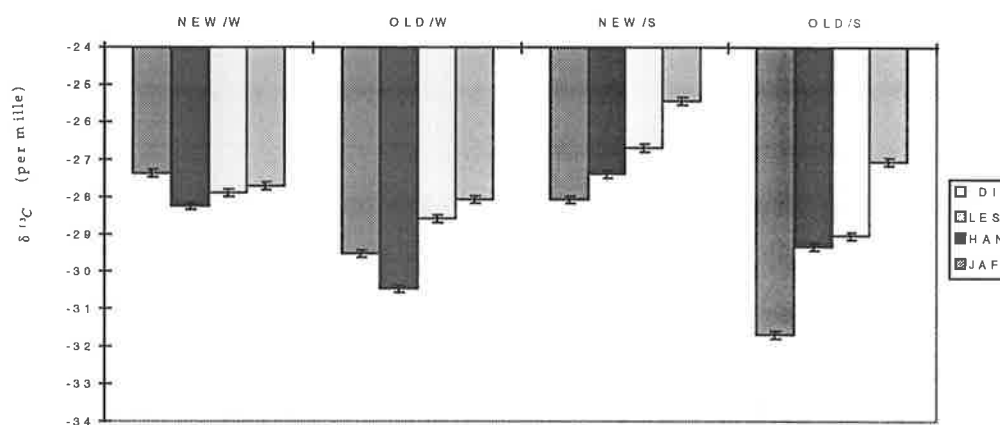


Figure 3.19: $\delta^{13}\text{C}$ (‰) of old and new leaf samples in summer (S; 3/2/94) and winter (W; 6/7/94).

3.4 Discussion

3.4.1 Using the heat pulse method to estimate transpiration in saline environments

The heat pulse technique has been and is currently being used in many different environments to gain an understanding of the hydrological role of trees. This study provides insights into the errors that may be encountered when using the technique in a very saline system where errors can occur at three scales; the single tree, the scaling to the test plot and the scaling to the whole forest (Denmead, 1984).

During spring, summer and autumn at Duck Island the heat pulse, leaf conductance measurements and canopy measurements of AET were all similar. However the independent ET estimate obtained with the Bowen ratio during the scaling experiment was ~ 0.3 mm / day higher than the other estimates. The difference between these could have

been a result of soil evaporation (Ham et al, 1990) or measurement errors in the Bowen ratio (Angus and Watts, 1984) or the transpiration estimates (Barrett et al, 1995). No measurements of soil evaporation were actually made in the current study however soil evaporation of 0.3 mm/day has been found for *Atriplex* plantations over shallow saline groundwater (Greenwood and Beresford, 1980). The difference between transpiration and evapotranspiration estimates could also be accounted for by errors in fetch for Bowen ratio measurements, or variability between trees. Hatton and Vertessy (1990) found evapotranspiration calculated from the Bowen ratio to be lower than estimated flux from test heat pulse trees and suggested that the test trees may not have represented the whole forest and may have overestimated the flux. Other studies have found lower estimates of transpiration with the heat pulse compared to energy balance approaches (Kelliher et al; 1992; Diawara et al, 1991; Walker et al, 1989) while others have shown good correlations between energy balance and sap flow measurements (Kostner et al 1992; Dawson, 1996).

Leaf resistance measurements when used to estimate transpiration of the stand, produced a similar result to the heat pulse estimated during summer and autumn. This is despite no separation of the canopy into separate functional layers (Jarvis and McNaughton, 1986) a process that is thought necessary for precise estimates of tree transpiration from leaf estimates for the Penman Monteith calculation (Green, 1993). It has been suggested (Barrett et al; 1995) that sap flux is overestimated at low sap flow velocities but this apparently did not occur at this site. The good comparison between the heat pulse estimates and Penman Monteith estimates of transpiration is probably a result of the limited transpiration rate (see next section) which results in a low response of transpiration to climatic factors and a high stomatal control. This is combined with a low leaf area index and a canopy structure that results in leaves being concentrated at the top of the canopy where most leaves are exposed to similar conditions and so may be expected to have a similar transpiration rate.

However discrepancies did occur in winter between heat pulse and Penman Monteith estimates of transpiration when low winter stomatal conductances combined with low temperatures, low VPD, and low R resulted in low estimates of transpiration with the Penman Monteith equation. During these times the heat pulse estimate of transpiration was higher than the Penman Monteith estimate. Similar results have been found by many workers (Cohen et al, 1985; Dawson, 1996; Dugas et al, 1993; Moreno et al, 1996). Moreno et al (1996) found an underestimation of transpiration by the Penman Monteith method as compared to a heat pulse estimate of transpiration when using a canopy

resistance from well watered plants but when they adjusted this value for a hypothetical value for stressed plants found a good match with heat pulse method. A good match has been found between heat pulse and Penman Monteith estimates in well watered irrigated tree plantations (Myers et al, 1996; Schulze et al; 1985; Steinberg et al, 1990; Golden and Field; 1994; Edwards and Warwick, 1984). Therefore the underestimation of transpiration with the Penman Monteith equation could have occurred through errors in estimation of the climatic variables, errors in the estimation of the average leaf resistance, or underestimation of functional leaf area when scaling leaf resistances to canopy resistances.

Errors with the heat pulse technique may have occurred at the single tree level or at the stand level. Single tree flux errors may occur through the misalignment of probes, and the conversion of heat pulse velocity to sap velocity (Hatton et al, 1995). For *M. halmaturorum* in the current study sap velocity was always low (5 to 18 cm/hr) and although above the threshold representing significant error (and therefore overestimation of flux) for rainforest tree species (Barrett et al, 1995) this range of velocities has been accepted to represent true velocity in many tree species (Swanson and Whitfield, 1981; Lassoie et al, 1977; Lopushinky, 1986). Errors in converting heat pulse velocity to sap velocity may occur in the estimation of the wound size. An overestimation of wound can result in a reduction in the velocity estimate (Swanson and Whitfield, 1981). The wounds estimated in this study were at the large end of the range observed in many trees species (Dye and Olbrich, 1993; Marshall et al, 1989; Barrett et al, 1995) and above those recorded for others (Dunn and Conner, 1993; Edwards and Warwick, 1984; Hatton et al, 1995). However the wound size has been found to be accurately represented by the colour change in other species and so the estimates are probably reasonable (Marshall et al, 1989; Barrett et al, 1995). Errors in single tree flux estimates are generally a result of incorrect estimation of functional sapwood area (Hatton et al, 1995), the volume fraction of water (especially in trees where seasonal water uptake is variable ie Caspari et al, 1993), and spatial variability in the sap flux density profile in the tree (the largest source of error according to Hatton et al, 1995) due to probe placement in non functional parts of the sapwood (62 %; Streeter, 1993). Sap flux density estimates for Eucalyptus trees have been shown to have errors of 13 % with additional errors involved in the calculation of single tree fluxes from these sap flux densities estimated at 25 % (Hatton et al, 1995). Cut tree experiments to estimate errors in single tree estimates of flux by heat pulse have underestimated flux by up to 15 % (Swanson and Whitfield, 1981; Green and Clothier, 1988; Olbrich, 1991; Dunn and Conner; 1993; Barrett et al, 1995; Hatton et al, 1995). The

cut tree experiment in the current study found a 38 % underestimation of single tree flux by the heat pulse estimate.

The second scale of errors occurs when scaling from single trees to plot fluxes. These have been estimated to be 5 % (in addition to the 38% error in single tree flux estimates) by Hatton et al (1995) assuming no bias, no errors on measurement of the scalar and no compensating errors. For *M. halmaturorum* relationships between single tree fluxes and the tree parameters (scalars) differed in their r^2 ranging from 21-81% with canopy projected area being the best fit and tessellated ground area being the worst fit. In the present study canopy area had the best relationship with flux ($r^2 = 0.81$) and also the best estimate of the total flux (stdev 30 %), indicating a good relationship between tree flux and canopy area. Good estimates of transpiration were found when using this scalar for Kiwi fruit vines (Edwards and Warwick, 1984). Leaf area had a reasonable and linear relationship with flux ($r^2 0.64$) but underestimated the total flux. Leaf area has been found to be a good scalar in many studies where the trees are in a state of equilibrium with the environment (Hatton et al, 1995; Angelocci and Valanogne, 1993; Ham et al, 1990; Cermak, 1989; Greenwood et al 1985; Werk et al, 1988). The linear relationship between leaf area and water use may indicate that the leaf area is in equilibrium with the environment and not dynamically changing in response to changing water availability as is assumed for many water stressed forests (Hatton and Wu, 1995) where a curvilinear relationship develops (Greenwood et al, 1982; Thorburn, 1993; Hatton and Wu, 1995).

The relationship between these scalars sapwood area and diameter and flux was not as good as the previously mentioned ones ($r^2 = 0.41$) indicating errors in the measurement of these scalars or else poor functional relationships. Any errors in measurement of sapwood area and diameter would have been propagated as these parameters were also used in scaling from velocity to flux of single trees. Sapwood area has been found to be a good scalar for eucalypts in a saline environment at most times, resulting in scaling errors of 8 to 26 % (Thorburn et al, 1993a), and for trees in other environments (Hatton et al, 1995; Granier et al, 1990; Diawara et al, 1991; Cermak and Kucera, 1987; Dunn and Conner, 1993). Despite the poor relationship in this study, it may be the case that sapwood area and diameter are more practical scalars to use because of the ease of measurement (as compared to leaf area). The worst scalar was tessellated ground area. Although this has been found to be a good scalar of transpiration in regularly spaced plantations (Hatton and Vertessy, 1990) it has been observed to be a bad scalar in other studies in natural communities (Ladefoged, 1963; Hatton et al, 1995).

Sap velocity of trees at Hansons was similar to Duck Island and differences in the areal transpiration rates arose as a result of differences in the leaf area index between sites. This was caused by higher tree densities at Hansons. Discrepancies between estimates obtained with the heat pulse and estimates obtained with the Penman Monteith (PM) occurred in summer, with PM estimates being lower than heat pulse estimates. These differences are probably not a result of overestimation by the heat pulse technique at low velocities as this would have also occurred in winter when velocities were lower. However errors may have occurred in scaling the single tree heat pulse estimates to areal transpiration, resulting in an overestimate of transpiration as discussed above. Conversely errors in the Penman Monteith calculations may have been greater at this site as a result of the higher leaf area index and greater variability in net radiation entering the canopy, VPD, and leaf resistance. As a result of these errors the actual transpiration rates at Hansons are probably somewhere between the two estimates of transpiration (Fig 3.17 b).

3.4.2 Ecophysiological response of M.halmaturorum to groundwater salinity and waterlogging

Estimated transpiration for *M.halmaturorum* ranged from 5 to 0.6 mm/day depending on site and season. *Melaleuca* species have been generally known to be high water users but up until now this has not been quantified for saline environments. *Melaleuca styphelioides* in fresh soil water was found to use up to 6 l/hr of water (Mishra and Sands, 1992). When this flux is scaled to account for sapwood area, the resulting sap flux density is similar to that found in the present study indicating that differences in fluxes between forests of *Melaleuca* may be controlled by differences in density of trees (and so sapwood area) rather than differences in flux capabilities of individual trees.

PET ranged from 6 mm/day in summer to 1.2 mm/day in winter. The water use of trees at Duck Island was limited to below PET during summer and was similar to PET in winter. Low stomatal conductances and therefore low transpiration was probably associated with salinity induced water stress during summer (Munns and Termaat, 1986) and transpiration was limited by energy availability in winter. At Lesron transpiration rates were estimated to be below PET in summer and winter, probably as a result of salinity and waterlogging which is known to reduce the growth of *M.halmaturorum* seedlings (van der Moezel et al, 1991; see next chapter). Transpiration was closer to PET at Hansons and Jaffray Swamp which are fresher sites although transpiration at Hansons still appeared to be limited below PET in summer.

The transpiration rates estimated in the present study (up to 5 mm/day) were larger than those found for other trees species in saline environments and are similar to trees overlying groundwater of much lower salinity (6 - 11 dS m⁻¹; Fraser et al, 1995; Greenwood et al, 1982; Van Hylckama, 1974). For groundwater of similar salinity (30 - 55 dSm¹) *Eucalyptus largiflorens* on the Chowilla floodplain had transpiration rates of 0.1 to 0.3 mm day⁻¹ and *Eucalyptus camaldulensis* had rates of 0.1 - 0.3 mm day⁻¹ (Thorburn et al, 1993a) *Atriplex* species have been found to use only 0.2 mm day⁻¹ of water over saline groundwater of 30 dS m⁻¹ (Slavich et al, 1996). However mangroves, a plant type that is probably most similar to *M.halmaturorum* in habitat type and salinity, are thought to use up to 1 mm/day of water, in response to sea water salinity (Passioura et al, 1992).

Differences between the water use of different forests and plantations may be attributed to differences in tree density (ie differences in sapwood area/ leaf area in a plot). For example *M.halmaturorum* had a leaf area index of 1.3 while *Atriplex* had only 0.34 (Slavich et al, 1996) and *E. largiflorens* 0.6 to 1.0, allowing greater water use by *M.halmaturorum* from a groundwater of high salinity. Differences amongst site transpiration rates in the present study were controlled by differences in tree densities and so leaf area between sites. Leaf conductance at the sites did not appear to differ significantly (being low at most times) however there would have been an effect of long term leaf conductance to water that resulted in differences in site leaf area. Water use efficiency was higher at the more saline sites. At Lesron, where the site was apparently saline and waterlogged, long term growth rates were low (Olga Barbourina; unpublished data). Where salinity was high, transpiration was usually well correlated with stomatal conductance and was poorly correlated with VPD and R indicating a stomatal control on transpiration. Good control of stomatal conductance may result in low water use, low growth rates and high water use efficiency in these swamps, contributing to the survival of *M.halmaturorum* (e.g. Golombek and Ludders, 1993; Flanagan and Jefferies, 1989a). Other factors (environmental and physiological) which may influence the water use strategy and so contribute to these differences in transpiration will be explored in the following chapters.

3.5 Summary and conclusion

Transpiration rates were high and consistent amongst the 3 different independent measurements with seasonal daily averages ranging from 0.7 mm/day to 3.4 mm/day (Table 3.3). Leaf area dominated the difference in transpiration rates between sites with stomatal conductance not appearing to be important in the short term in controlling transpiration. Transpiration decreased with groundwater salinity and may have been influenced by waterlogging when combined with high salinity.

Chapter 4: Soil and Plant Water Status

4.1 Introduction

It is widely recognised that soil water availability influences the ability of roots to take up water, and is a determinant of root density, distribution, and structure (Passioura, 1988; Bresler and Hoffman, 1986; Neumann et al, 1994). However, the manner in which different species respond to water availability differs. For example Thorburn et al (1993a), studying a *Eucalyptus* floodplain forest underlain by saline groundwater, found that some trees responded to rainfall by changing their sources of water from saline groundwater to low salinity surface soil water. Similarly Yakir and Yechiell (1995) recently provided evidence for the selective uptake of flood waters by some halophytic species occupying hypersaline environments. In contrast Lin and Sternberg (1994) studied the water sources of coastal red mangrove in response to changes in surface soil salinity induced by sea water intrusion and rainfall freshening of the surface soils. They found that mangrove roots were active in using surface soil water and that there was little change in uptake pattern with salinisation of the root zone or freshening of the groundwater.

It has been suggested that differences in response to soil salinity between species may be a result of differences in root system structure (shallow rooted as compared to deep rooted; Lin and Sternberg; 1994) and activity (Yakir and Yechiell, 1995). Differences between the same species on different sites may be explained by differences in environmental factors (e.g. soil waterlogging and presence of a permanent water source). It is apparent that the response of tree root systems to soil water availability can not be predicted based on current information and may be influenced by interacting plant and environment factors.

The previous chapter (Chapter 3) outlined the quantification of water use of *M.halmaturorum*. To understand what implications this has for groundwater use it is necessary to understand the sources of water. The aim of this chapter and Chapter 5 is to identify the water sources of *M.halmaturorum* in response to changes in soil water availability. This will be done by identifying the zones of water availability (Chapter 4) and then the water sources and root dynamics in response to these changing soil conditions (Chapter 5).

4.1.1 Soil and plant water potential

(a) Soil water potential

Soil water potential depends on four components of varying importance:

$$\Psi_{soil} = \Psi_m + \Psi_s + \Psi_g + \Psi_p$$

Where Ψ_m is the matric potential produced by capillary and surface binding properties, Ψ_s is the osmotic potential produced by solutes in the soil water, Ψ_g is the gravitational potential due to the force of gravity operating on soil water and Ψ_p is the pressure potential due to external pressure, but can often be disregarded because the pressure is near atmospheric in the root zone. The availability of water to plants decreases as the potential of the soil water decreases (Marshall and Holmes, 1988).

The matric potential is influenced by the structure of the soil and the water content. The structure of the soil also influences the level of contact of soil with the plant root (Passioura, 1988). Furthermore, it has been found that as plant roots are exposed to greater water potential gradients in drying soil, the resistances of the roots to water uptake also increases (Blizzard and Boyer, 1980). Water movement occurs by capillary flow in response to drying by evaporation at the soil surface and drying of the profile by roots. The matric potential and gravitational potential are instrumental in determining water movement within the soil profile and from the groundwater into the unsaturated zone above it. The matric potential is either measured directly or indirectly from water content/ water potential relationships.

The soil osmotic potential is lowered by the presence of solutes in the soil solution. As discussed in chapter 1 (1.2.1), salinity results in a reduction of soil water availability and possible ion toxicity effects. The osmotic soil potential effect on the movement of water into plant roots from soil arises because of the differentially permeable membranes that occur at this interface (Kramer and Boyer, 1995). The osmotic potential is measured directly using psychrometers or indirectly through established relationships between salt concentration in the soil solution and water potential.

The effect of osmotic potential on water uptake by plants is generally thought to be additive to matric potential (Marshall and Holmes, 1988). However it has also been suggested that as the soil dries the matric potential will become the dominant force because of the effect of soil drying on root contact and also because plants may be able to respond to osmotic potential by osmotic adjustment, by using the solutes available to them (Shalhevet and Hsiao, 1986). In some environments, osmotic potentials may dominate some parts of the profile (ie deeper

where there is a saline groundwater) and matric potentials may dominate other parts (ie surface where there is soil drying) (Thorburn et al, 1993a). When this occurs water extraction has been assumed to respond to the part of the profile where water is preferentially available (Thorburn et al, 1993a).

(b) Plant water potential

The availability of soil water to plants (as influenced by soil water potential) is determined by the ability of plants to lower plant water potential. In order to absorb water roots must generate water potentials low enough to create a water potential gradient from soil to root. The lower limit for water availability (called permanent wilting point) is determined by the minimum possible plant water potential at which plants are able maintain turgor. This is widely variable amongst species (see chapter 1.2.1) and will be determined by a combination of plant characteristics including ability to osmotically adjust and to withstand xylem cavitation. The plant water potential is composed of:

$$\Psi_w = \Psi_s + \Psi_p + \Psi_m + \Psi_g$$

Where the subscripts s, p, m, and g refer to the effects of solute, pressure, porous matrices and gravity respectively (Kramer and Boyer, 1995). Gravitational potentials can usually be ignored except in tall trees (>1 m). The water potential components in the different compartments of the cell differ. Solute potentials will occur in both cell components although will be more significant in the interior of the cell (symplast). The cell symplast has a dominating solute potential, pressure potential (at full turgor) and the matric potential can be ignored. In the cell wall (apoplast) the matric forces can be important and the pressure potential can be ignored. Pressure potentials are positive and solute potentials are negative and so they often compensate for each other, except at full turgor. Water moves from the outside of the cell to the inside in response to water potential gradients and a local equilibrium is formed where:

$$\Psi_{s(a)} + \Psi_{m(a)} = \Psi_{s(sy)} + \Psi_{p(sy)}$$

Where sy is the symplast (internal cell), a is the apoplast (outside cell), and s, m and p are as previously outlined. If the water components of the plant equilibrates overnight (when transpiration has ceased), the cell water potential should be reflected in the leaf water potential (Fig 4.1). The xylem water potential should also equilibrate with the leaf water potential when transpiration has ceased. This is often measured to indicate the total cell water potential. The pre-dawn leaf water potential gives an indication of the soil water potential in the area from which the tree is taking water.

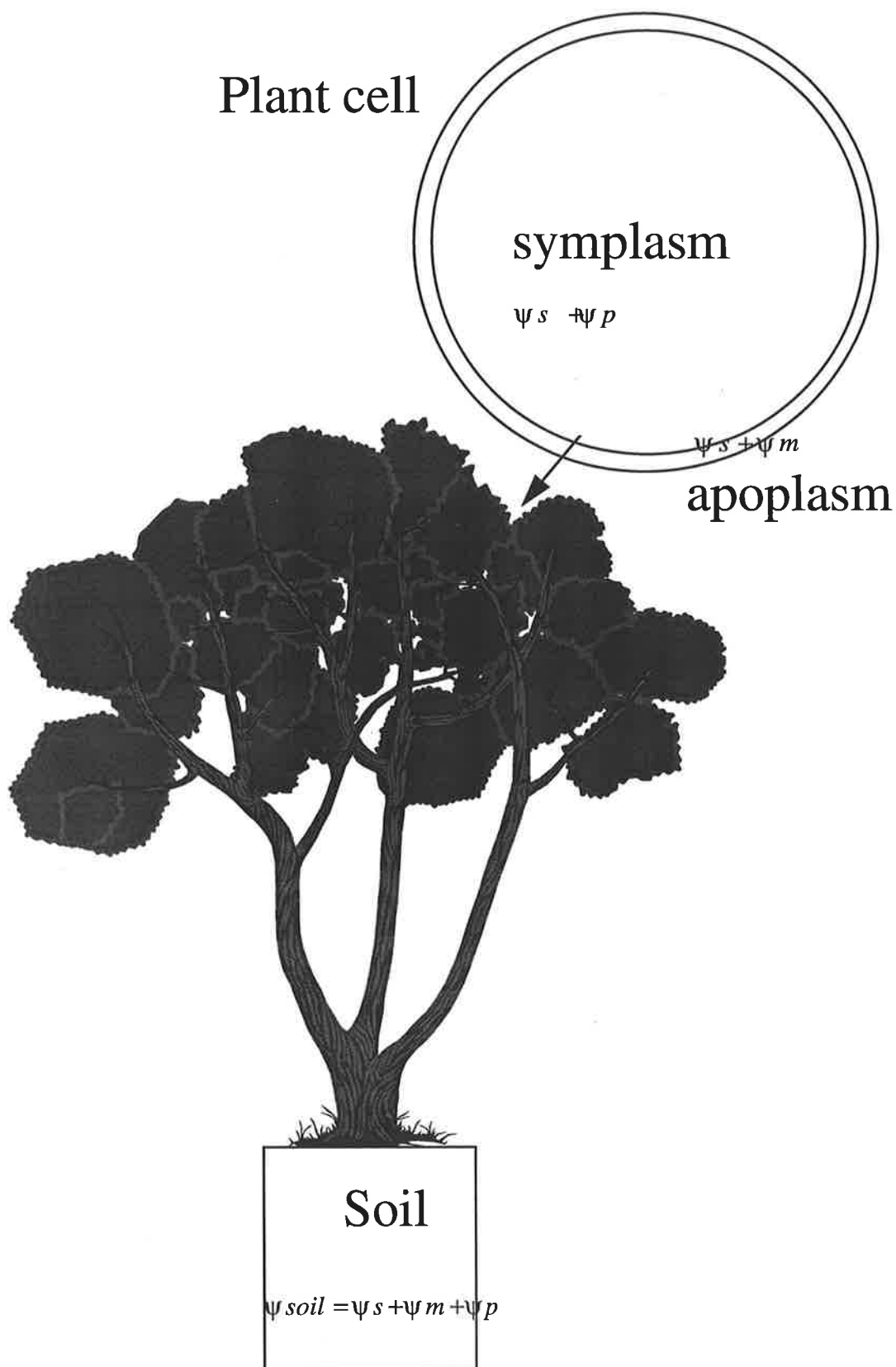


Figure 4.1: Summary of the dominant components of water potential in the plant cell wall (apoplast), cell interior (symplast) and the soil. Water potential in the cell wall is dominated by solute (s) and matric potential (m) while the interior of the cell is dominated by (s), which is compartmentalised, and pressure potential (p), at full cell turgor. The soil water potential is dominated by solute (s) and matric (m) components.

The difference between the pre-dawn and the mid-day water potential gives an indication of the extent to which the tree can lower its potential so as to extract water from the soil (Boyer, 1969) and the threshold to water uptake.

As a plant dehydrates, the plant water potential is altered by the reduction of the pressure potential inside the cell (a decrease of cell turgor) and this also concentrates the solutes and alters the osmotic potential (usually inside the cell). Osmotic adjustment has been suggested to occur in some plants in response to drought and salinity whereby a lower (more negative) osmotic potential is generated by the introduction of solutes (from internal or external sources) into the cells (see chapter 1.2.2). This will maintain turgor at a lower plant water potentials. Changes in cell elasticity in response to drought will also result in a maintenance of cell turgor at a lower plant water content (Tyree and Jarvis, 1982). The change in the components of cell water potential in response to drought can be investigated through pressure-volume curve analysis (see Fig 4.2 and section 4.2.3 b).

4.1.2 Other factors affecting water availability to roots

Other factors that influence the activity of roots in various parts of the profile will also influence soil water extraction. In environments which are waterlogged or are inundated for long periods, low oxygen availability can effect plant roots (Chapter 1.2). While some plants have the ability to use water from waterlogged parts of the soil profile (chapter 1.2.3), most plants do not have the physiological characteristics to do this and so waterlogging will result in a reduction in soil water availability. Waterlogging can be indicated by low redox potential (indicating the prevalence of reduced ions and low oxygen concentration) and by the presence of the reduced form of a number of ions. Both of these indicators can be used to determine the parts of the profile that are unavailable for root water uptake because of waterlogging. Soil waterlogging may also interact with soil salinity to make parts of the profile unavailable for water uptake.

Other factors which may influence extraction of soil water include root system structure (Fitter, 1991), the presence of soil layers that are difficult to penetrate (e.g., Misra and Gibbons, 1996), nutrient concentration, heavy metal availability (Davies, 1991; Fitter, 1991), and low temperatures (Callaghan et al, 1991). These factors may influence the permeability of roots to water uptake or the ability of roots to grow in particular parts of the soil profile. These other issues are not investigated in this study as it was considered that they would be

dominated by the soil water potential and soil waterlogging. However it is recognised that other factors may be involved in determining the availability of water sources for *M. halmaturorum*.

4.2 Methodology

Rationale for methodology

Soil water potential was measured. It is expected that plants will extract water from areas with a relatively low water potential. The water potential will also indicate the areas in the profile from where the plant can not extract water, based on minimum (threshold) plant water potential for plant water uptake. This technique has been validated for mallee species in a semi-arid environment in Australia (Brunel et al, 1990). Soil waterlogging and groundwater depth were also measured to identify parts of the soil and groundwater system that were unavailable for plant water uptake.

4.2.1 Groundwater depth and salinity

A piezometer was installed at each of the sites and groundwater depth (m below ground) was measured at each sampling interval (Appendix 1). Groundwater samples were taken from the bores after purging the bore and allowing it to refill. These samples were analysed for Cl concentration. An electrical conductivity (EC) reading was also taken from each bore using a EC meter.

4.2.2 Soil water potential

Soil and groundwater samples were taken 10 times from October 1993 to January 1995. Soil was sampled from under the trees at 0-10 cm incremental depths to the water table (or to the calcrete hard layer if it was impenetrable). Groundwater was sampled at the depth of the watertable. The soil samples were collected in jars and then sealed with electrical tape to prevent water loss. The total soil water potential was estimated by measuring and summing the components of the soil water potential; the matric potential, osmotic potential, and gravitational potential (0.01 MPa/m).

(a) Matric Potential

The matric potential arises from the interaction of water with the matrix of solid particles surrounding it. The matric potential was measured on the soil samples collected using the filter paper technique (Greacen et al, 1989). The water content of three filter papers per sample was brought to equilibrium potential with the soil water over a period of 6 days, and

matric suction was determined from the water content of the paper and a moisture characteristic curve of the filter paper (Greacen et al, 1989).

(b) Osmotic potential

The osmotic potential arises from the presence of solutes in the soil water (Marshall and Holmes, 1988). The osmotic potential was estimated from the chloride content of the soil. Soil chloride concentrations were measured on sub-samples of the soil sample taken in the field. The subsamples were oven dried at 105°C. To this soil 50 mL of 0.1 M Ba(NO₃) was added to 1 g of soil and shaken for 2 hours to extract the chloride. The extract was then diluted and analysed colorimetrically (Taras et al, 1975). Total chloride in the soil sample (grams of chloride per kilogram of dry soil) was converted to the concentration in the soil solution using the gravimetric water content. The osmotic potential (MPa) was then estimated from the concentration of Cl⁻ per unit volume of moisture in the soil (assuming the Cl⁻ was present as NaCl) by taking into account the osmotic potential of a 1 M NaCl solution, 4.5 MPa, and the molar mass of chloride, 35.5 g. From this a conversion factor of 0.127 was calculated and was multiplied by the concentration of chloride to give the osmotic potential. Cumulative Cl content in the top 40 cm (mg/cm²) was calculated from the mass of Cl and the water content of soil intervals to 40 cm and this was used to characterise the soil salinity at the sites.

4.2.3 Leaf water potential

(a) Pressure bomb

Leaf water potential was measured with a Scholander pressure bomb (Scholander et al, 1965; Ritchley and Hinckley, 1975). The apparatus consists of a pressure chamber in which a leaf is placed, with its petiole protruding through an aperture in the chamber lid, sealed with a rubber washer. Pressure is added to the chamber from a nitrogen gas source, until water in the xylem first appears at the cut surface of the petiole. This point represents the pressure which is needed to balance the tension that was originally in the xylem vessels. It is assumed that the symplastic water potential is in equilibrium with the apoplastic pressure potential (i.e. apoplastic pressure; Scholander et al, 1965; see section 4.1). It must also be assumed that osmotic potential of the apoplastic water is negligible (Ritchley and Hinckley, 1975). This should occur after overnight equilibration within the plant (Passioura, 1982). Branches were sampled for leaf water potential 1 hr to 30 min before sunrise (0300 to 0500 hrs) and at midday at each sampling time (Appendix 1). Branches (10cm long) were removed from 3

trees ($n=9$) and were stored in a plastic bag in the dark until measurement. The mean of all measurements per site was calculated and a 95% confidence interval of the mean was calculated using a t-test. It was assumed that the trees had equilibrated overnight with the soil or groundwater. This assumption was tested by taking measurements every 90 to 120 minutes from 1600 to 900 hrs during February of 1995. Providing equilibrium is achieved xylem water potential will be equal to the water potential of the source water at the depth of plant water uptake.

(b) Pressure-Volume Curves

Pressure-volume curve analysis (Tyree and Jarvis, 1982) was used to examine the symplastic osmotic (s) and pressure (p) potential of leaf water potential at times of high water stress (end of summer) and lower water stress (end of winter). The curve that arises from plotting inverse leaf water potential against RWC during the dehydration process can be used to identify the turgor loss point, estimate s at full hydration and estimate the cell elasticity. (Tyree and Jarvis, 1982; Fig 4.1). As a fully hydrated leaf is allowed to dehydrate the symplasmic p decreases and eventually reaches 0 (at turgor loss point). After this point all values of leaf water potential will be equal to s and decline linearly as relative water content (RWC) declines (Tyree and Jarvis, 1982). Extrapolation of this line (Fig 4.2) back to the y axis provides an estimate of the saturated osmotic potential. The slope of the initial part of the pressure volume curve is an indicator of the cell elasticity and the point at which the slope of the curve changes is the turgor loss point (Fig 4.2).

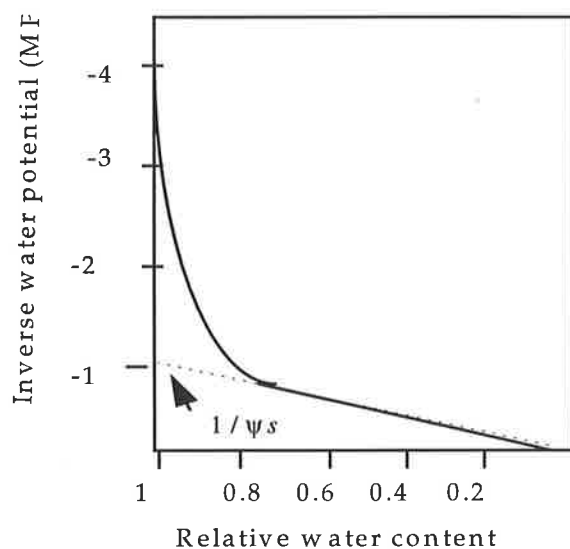


Figure 4.2: Pressure volume curve analysis; Relationship (solid line) between the reciprocal of tissue water potential ($1/\Psi$) and tissue relative water content (RWC). The dashed line defines the calculated relationship between the reciprocal of tissue osmotic potential ($1/s$) and RWC. The intercept of the dashed line with the y-axis yields the reciprocal of tissue osmotic potential at full hydration ($1/\Psi_s$). The intercept of the dashed line with the x-axis yields the RWC of the tissue apoplast (Koide et al, 1992).

Shoots were removed for pressure volume curve analysis from trees at Duck Island 30 min before dawn on 31/10/95 and 8/3/96. Total leaf water potential on adjacent shoots was also measured at this time with the pressure bomb. Shoots harvested for Pressure-Volume curve analysis were rehydrated for 24 hrs (Parker and Pallardy, 1987) before drying on the bench. A series of relative water contents and shoot water potentials were obtained as the shoots dried. The shoot water content was obtained by taking a weight-average (Robichaux, 1984) (a pre- and post- bombing weight) of water content with each water potential reading. At least 5 points were obtained before turgor loss point and then water potential readings continued to be taken until at least a 50% loss of water content from the initial hydration. The shoot water potential and shoot relative water content data were used to construct a curve (Schulte and Hinckley, 1985) from which the various shoot water relations parameters were obtained according to the method of Dawson (1988).

4.2.4 Soil waterlogging

(a) Ferrous iron indicator

Soil waterlogging was predicted in two ways. Firstly from March 1994, a field indicator of soil waterlogging was measured (Appendix 1). The presence of ferrous ions (the reduced form of Fe) indicated the presence of reducing conditions. The presence or absence of the ferrous ion was tested at each of the sampling times and at each of the soil intervals for all sites. The test solutions were made of 0.2 g α, α' -dipyridyl in 25 ml of 10% (v/v) acetic acid with 77 g of ammonium acetate and made up to 1 L with distilled water (Childs, 1981). 3 ml aliquots of solution were placed in small plastic vials, a small amount of soil from the field sub-samples was added to the vials and they were swirled gently until a colour developed. After 1-2 min a deep orange colour indicated the presence of abundant soluble ferrous ion, and a light orange indicated a small amount of ferrous ion. No orange colour to the otherwise colourless solution indicated the absence of ferrous ion.

(b) Redox (Eh) and pH

Cores were obtained from the field sites for redox and pH analysis in September 1994 and February 1996 to encompass the extremes in possible soil waterlogging. Soil redox potential relates to the activity of electrons and is a mixed potential which is a weighted average of the electron exchange currents between all the redox couples in the system and is dependent on the pH of the system as well as the concentrations of the redox couples. Oxygen serves as an electron acceptor and dominates the redox potential in well aerated

soils which may have a high Eh (400 mV at pH 5). In natural systems, the potential does not reach equilibrium because there is a constant input of electron donors and acceptors. Therefore the relationships between the Nernst equation, equilibrium potentials, and redox potentials is not rigorously defined even in simple systems (Bohn, 1971).

Pieces of PVC piping were forced into the ground as deep as possible (40 - 60 cm) and then were extracted with the soil intact. The cores were then sealed with rubber stoppers, silicone and plastic and brought back to the laboratory for redox analysis. A Freon chamber was used to prevent oxidation of the cores once they were unsealed. The cores were cut with a pipe cutter in the chamber at 5 cm intervals. Redox and pH potentials were measured potentiometrically with platinum electrodes inserted at each 5 cm intervals.

4.3 Results

4.3.1 Groundwater depth and salinity

At Lesron, Hansons and Duck Island, groundwater rose to the surface at the end of winter (0.15 - 0.3 m) and then fell to 1 - 1.5 m depending on the site (Fig 4.2 a). Groundwater was deeper at Jaffray Swamp (to 2.3 m) and did not rise to the soil surface as at the other sites, having a minimum depth below the ground of 1.2 m (Fig 4.2 a). The fluctuations in groundwater depth at Jaffray were associated with fluctuations in surface water depth in the adjacent water body.

Groundwater salinity ranged across sites with the highest average groundwater salinity occurring at Lesron (85 dS/m) and then in decreasing order Duck Island, Hansons and Jaffray (Fig 4.2 b). At Lesron, Duck Island and Hansons groundwater salinity was higher at the beginning of the sampling time (spring and summer), decreased over the autumn and winter, and then increased at the end of winter. At Jaffray groundwater salinity was constant at ~8 dS m⁻¹ (Fig 4.2 b).

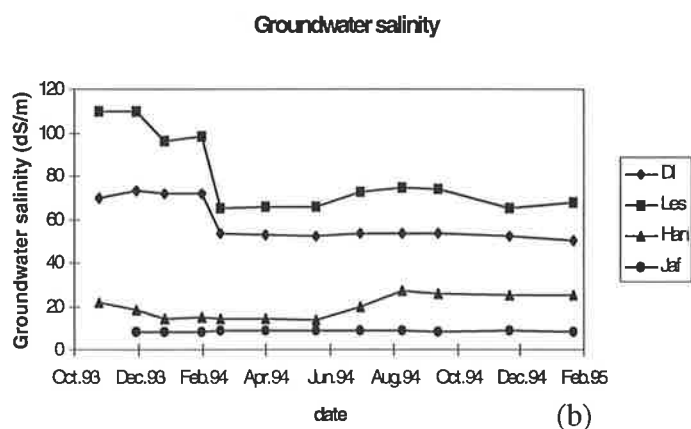
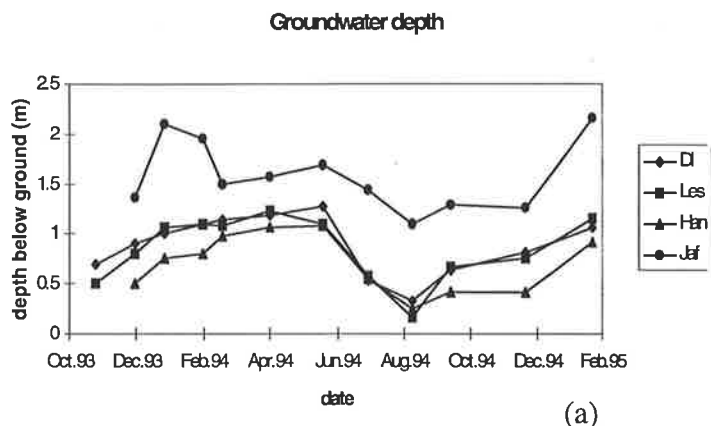


Figure 4.3; Groundwater depth (m; (a)) and groundwater salinity (dS/m; (b)) over time for the 4 sites (see legend) indicating the shallower groundwater during winter and the freshening of the groundwater at some sites after winter rains.

4.3.2 Soil water potential

At all sites soil water potential was dominated by osmotic soil water potential with the matric potential component generally being very small (Appendix 6). At Duck Island, Lesron and Hansons osmotic soil water potential was often 2 or more orders of magnitude larger than matric soil water potential while at Jaffray often under dry conditions osmotic soil water potential was only double matric potential (Appendix 6).

In summer at Duck Island, Hansons and to a lesser extent at Lesron osmotic potential was usually most negative at the surface and then reached a constant value towards the groundwater (Appendix 6). The matric potential, although generally high, was also generally lower at the surface, although sometimes more negative values were found in the deeper parts of the profile, indicating possible root activity (Appendix 6). In winter the osmotic soil water potential was either constant throughout the profile or else slightly higher at the surface after periods of rain. Matric potentials were always high. At Jaffray Swamp soils showed profiles

that often indicated accumulation of salt, above the groundwater (-2 MPa), rather than at the surface (> -0.5 MPa). Only in summer were more negative osmotic potentials reached in the soil surface (-3 to -4 MPa) compared to the subsoils (-2 MPa). Matric potential and osmotic potential were often more negative at depths of 50 cm to the groundwater indicating possible withdrawal of water from these depths and the resulting soil drying and salt accumulation.

Fluctuations in total soil water potential throughout the year were therefore often a reflection of seasonal changes in osmotic soil water potential. At Duck Island soil water potential was lowest (-12 MPa) in the surface soil at the end of summer (Fig. 4.3 a) as a result of high salt contents. Soil water potential then increased (i.e. became closer to 0) through the autumn and winter (-1.9 MPa; Fig. 4.3a) as a result of leaching and dilution of soil water from rainfall and groundwater rise. After periods of rainfall these surface soils often had higher soil water potentials than the groundwater. Deeper soil (0.3 - 1 m) remained similar to the groundwater water potential which remained between -2.8 and -3.8 MPa (Fig 4.3 a).

At Lesron, the seasonal pattern of soil water potential was similar with surface soil values reaching a minimum of -14.8 MPa at the end of summer and a maximum of -1.8 MPa at the end of winter (Fig 4.3 b). However because of the more negative groundwater values (-6.5 MPa) there were more periods when the surface soil values had a higher water potential (winter and spring) than the groundwater. At Hansons, the seasonal pattern was also similar to Duck Island but water potential values in the surface (0-10cm) were often very negative (minimum was -32 MPa) because of high salt contents and very low water contents (Fig 4.3 c). Water potentials of the 0-20 cm depth interval were similar to those found at Duck Island.

At Jaffray Swamp, matric potential often made a significant contribution to total soil water potential, especially during the summer (Appendix 6). The soil water potential in the surface soil reached a minimum in summer of -9 MPa (-1.5 MPa matric and -7.5 osmotic) and a maximum in winter of -0.5 MPa (-0.001 MPa matric; Fig 4.3 d). Water potential of soil from lower down in the profile (ie 40 cm to the groundwater) was more constant throughout the year at around -1.5 to -2 MPa. Soil water potential here was less responsive to seasonal variability and so was sometimes lower than the surface soil (in winter) and sometimes higher than surface soil values (in summer). Groundwater water potential was always high at around -0.5 MPa.

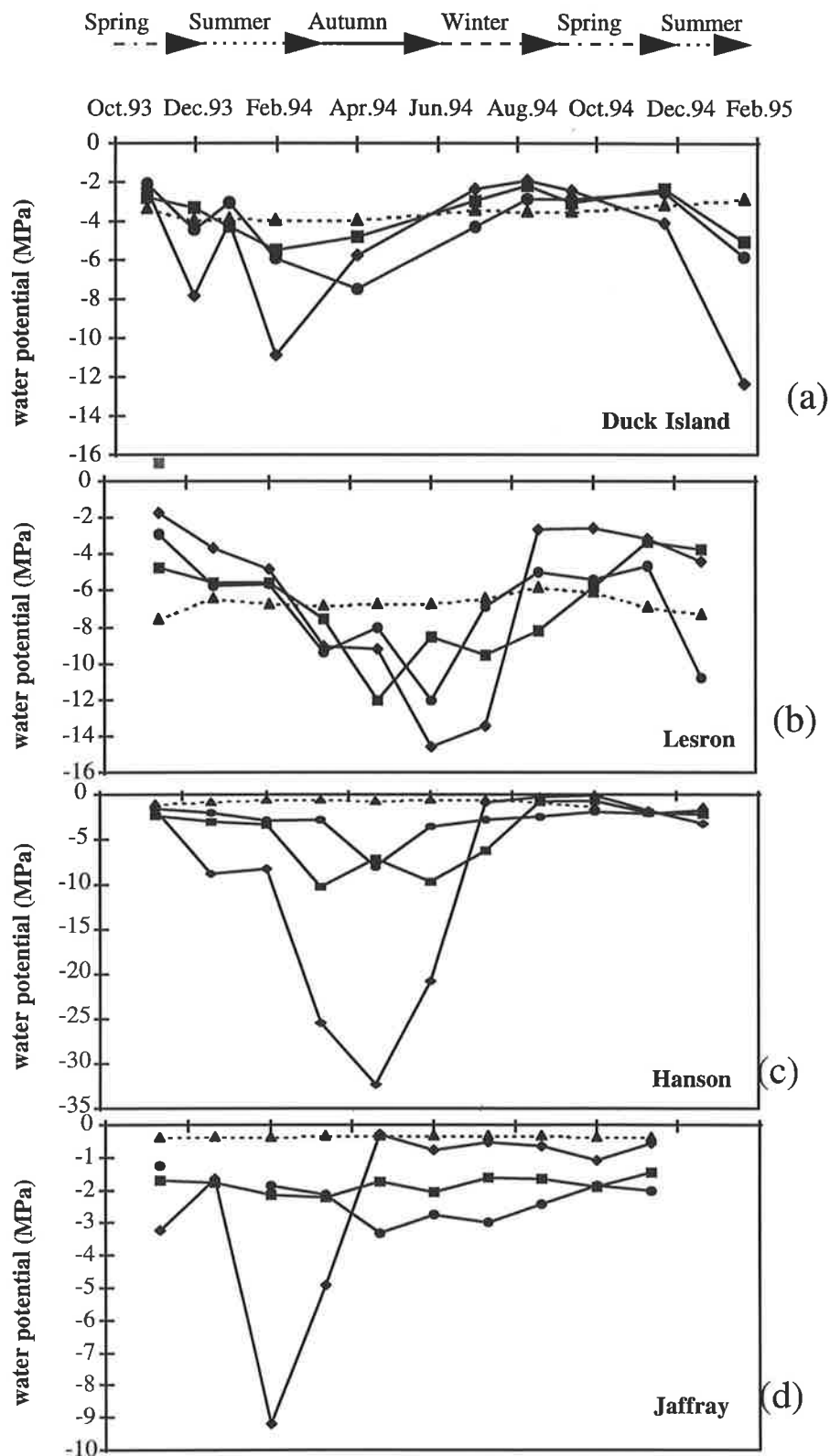


Figure 4.4: Total soil water potential (MPa) at 0-0.1 m (◆) and 0.1-0.2 m depth (■), or 0.4 - 0.5 m depth at Jaffray (■; (d)), groundwater osmotic potential (▲) and leaf pre dawn water potential from October 1993 to January 1995 for Duck Island (a), Lesron (b), Hansons (c) and Jaffray (d). Seasons are indicated at the top of the figure. Note the y axis scale is smaller for Jaffray and larger for Hansons.

Changes in osmotic potential in the soil profile over the sampling period can also be shown as the changes in the mass and the concentration of chloride in the soil surface. Soil salinity (cumulative in the top 40 cm) is represented in Fig 4.4 as Cl concentration and Cl mass (which is also shown as equivalent soil water potential). The mass of Cl was always highest at Lesron (up to 1300 mg cm²) and was usually next highest at Duck Island except at two sampling times in winter, and one in April 1994, when it was higher at Hansons than at Duck Island (Fig 4.4a). Next highest was Hansons and then Jaffray. At the end of summer when Hansons had very low water contents and so very high Cl concentrations. However Hansons dropped to very low Cl masses during winter when groundwater had risen and rainfall (Fig 4.2a) would have freshened the surface soils, and during this time Jaffray had higher Cl masses than Hansons (Fig 4.4a).

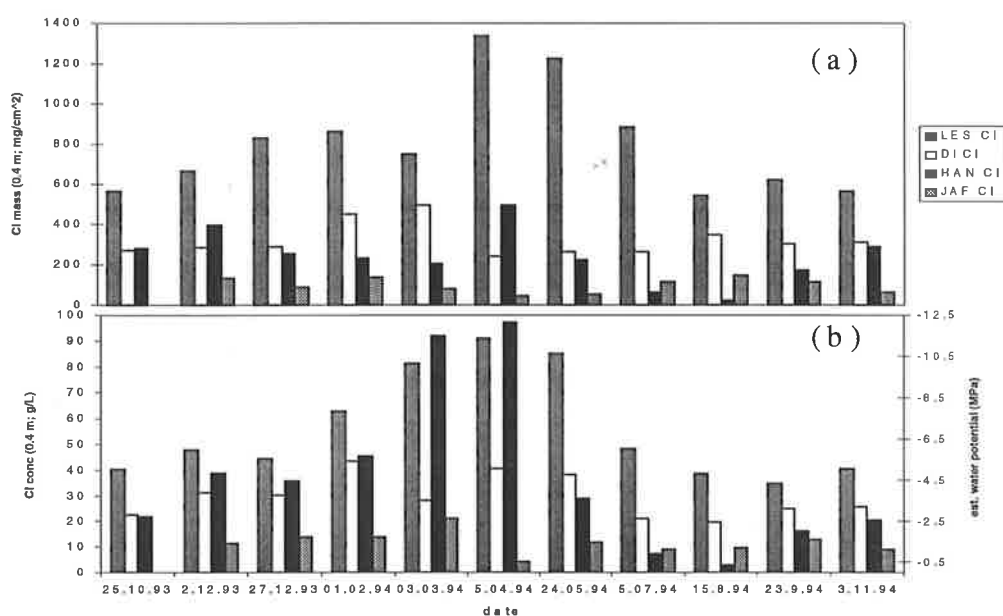


Figure 4.5: Cumulative Cl mass (a) and Cl conc (soil salinity; mg/L) (b) in the top 40 cm for each site over time. The estimated soil water potential from the Cl conc is shown on the second y axis of figure (b).

4.3.3 Leaf water potential

Leaf water potential ranged from -1 MPa to -12 MPa depending on site and season (Fig 4.5), being highest at the end of winter and lowest at the end of summer. Leaf water potential measured before dawn in winter was lowest (more negative) at Lesron (-5 MPa) and highest at Jaffray (-1 MPa) with Duck Island and Hansons having intermediate values (-1.8 to -2.5) (Fig 4.5). In summer the same pattern occurred with leaf water potential measured before dawn being lowest (more negative) at Lesron (-12 MPa) and highest at Jaffray (-3 MPa) with Duck Island and Hansons having intermediate values (-7 to -8) (Fig 4.5). Leaf water potential measured at mid-day did not alter much from that observed before dawn at all sites (Fig. 4.5). At sites where leaf water potential was the highest (ie Hansons and Jaffray) this difference was greatest (Fig 4.5).

Pressure -volume curves, were measured on leaves in spring when total pre-dawn leaf water potentials were -1.8 MPa and at the end of summer when total leaf water potentials were -6 MPa. Significant differences were found in turgor loss point (TLP), tissue elastic modulus from changes in the slope of the initial part of the curve, and saturated osmotic potential (Table 4.1). TLP during winter was -2.83 MPa and during summer was -4.79 MPa. Therefore the pre-dawn leaf water potential at Duck Island was above the TLP during winter and below the TLP during summer. The osmotic potential at full hydration was more negative in summer than in winter. The relative water content at TLP was also not significantly different between seasons although it also tended towards a lower water content in summer. The modulus of elasticity was lower in summer than in winter indicating that cells may have become more elastic in response to water stress, allowing more water to enter cells and so maintain turgor (Table 4.1).

Table 4.1: Pressure Volume (PV) curve analysis data for shoots taken on 8.3.96 (summer) and 31.10.95 (winter) at Duck Island and rehydrated. Pre dawn leaf water potential (MPa) was also taken on this day and is shown.

PV curve analysis	31.10.95	8.3.96
Pre-dawn leaf potential (MPa)	-1.8 ± 0.2	-6.1 ± 0.4
Saturated osmotic potential at full turgor (MPa)	-2.17 ± 0.12	-2.86 ± 0.28
Turgor loss point (MPa)	-2.83 ± 0.22	-4.79 ± 0.88
Bulk tissue elastic modulus (ε)	-9.87 ± 1.0	-6.66 ± 1.1
Relative water content at full turgor (%)	80.8 ± 2.3	76.8 ± 5.9

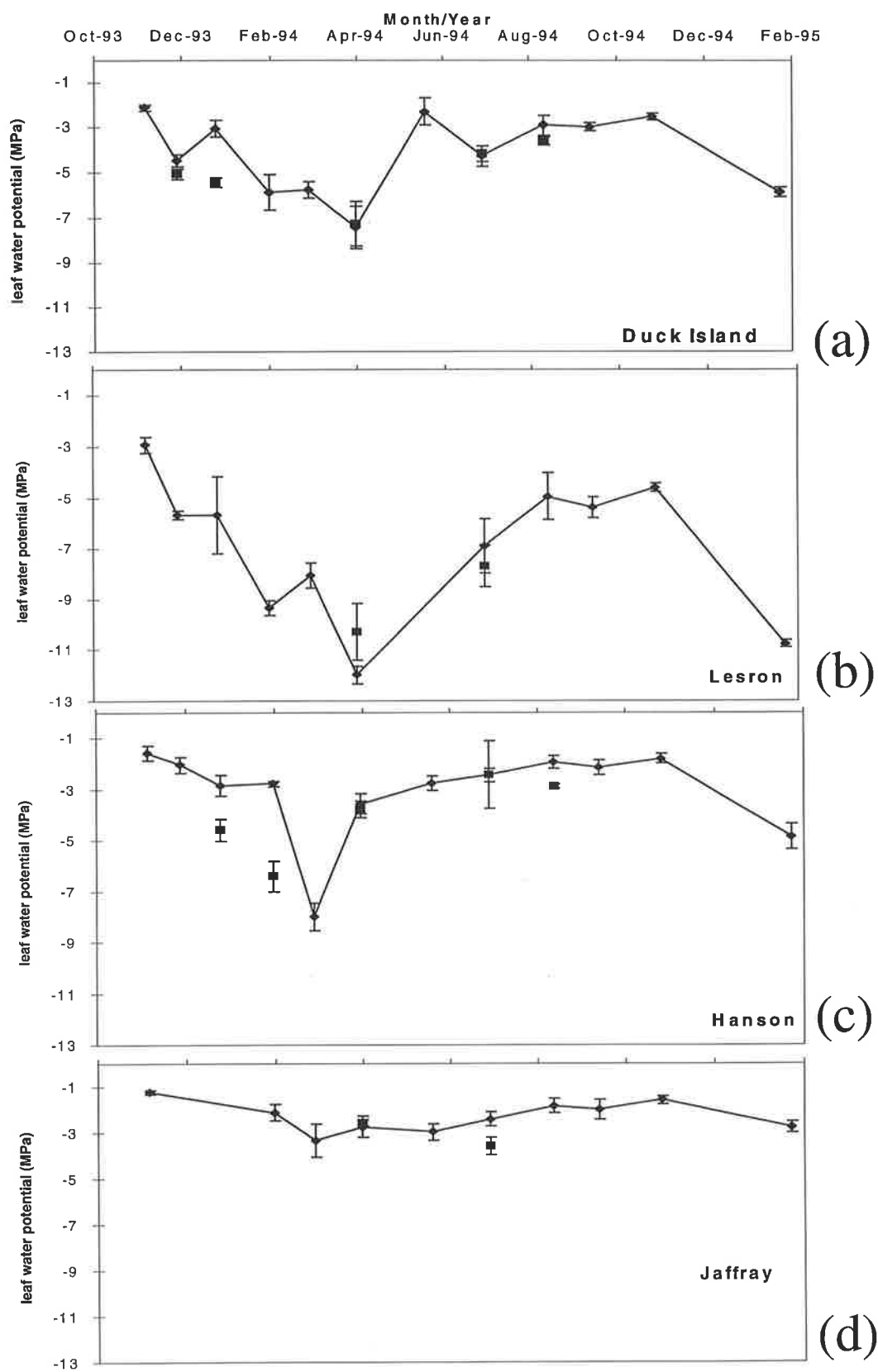


Figure 4.6: Leaf water potential (MPa) at pre-dawn (◆) and mid-day (■) for Duck Island (a), Lesron (b), Hansons (c) and Jaffray (d). Error bars indicate 95% confidence interval of mean.

At Duck Island leaf water potential, measured from sunset to sunrise on 11/2/95 was found to reach a maximum mean value at 0230 hrs (-6.1 MPa) which remained constant until sunrise, indicating pre-dawn equilibration with the soil profile (Fig. 4.6). Hence the pre-dawn leaf water potentials were used to indicate water potential at the rooting depth. At all sites pre-dawn plant water potential followed a seasonal trend, similar to the 0-0.20 m soil pattern (Fig. 4.3). This trend was most exaggerated at the most saline sites (Lesron and Duck Island). At Duck Island, Hansons and Lesron pre-dawn water potential matched surface soils at the end of winter (Fig. 4.3a-c). At the end of summer pre-dawn water potential was between surface soil and groundwater values at Hansons and at Duck Island (Fig. 4.3 a and c). However, at Duck Island, pre-dawn leaf water potential values at the end of summer were more negative than any available water sources. Possible reasons for this discrepancy will be discussed in the following section. At Lesron Pre-dawn water potential followed the surface soil values at all times of the year (Fig 4.3 b).

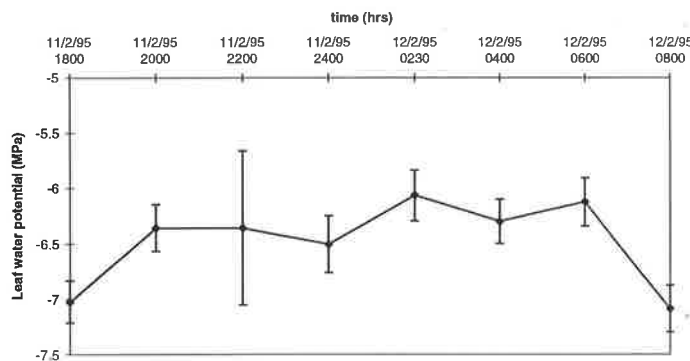


Figure 4.7: Leaf water potential (MPa; n=9) from 1800 hrs on 11.2.95 to 800 hrs on 12.2.95 indicating that the trees had equilibrated with the soil and reached a maximum water potential just after sunset on the 11.2.95. Error bars show the 95 % confidence interval.

4.3.4 Soil waterlogging

(a) Ferrous iron test

The results from the field ferrous ion test were either positive or negative. The negative test results are represented in figure 4.7 as nw (not waterlogged) and the positive test

results are represented as w (waterlogged). As samples were often not taken to the groundwater the test results in some instances have been extended to predict what the test result may have indicated at deeper depths. This is indicated as enw (estimated non waterlogged) and ew (estimated waterlogged). Soil at the Lesron site was waterlogged below 20 cm for most of the year (Fig 4.7 b). Soil was apparently waterlogged to the surface during winter. This was also the time of highest groundwater. Soils at Duck Island very rarely indicated waterlogging (Fig 4.7 a) although there were some sample intervals mid profile that showed evidence of ferrous iron (and so possible waterlogging). Similar patterns were found for soils at Jaffray Swamp and may be associated with the very heavy clays that were often found mid-profile at this site and were often discoloured indicating reduced conditions (Fig 4.7 d). Soil at Hansons Swamp could rarely be sampled below 40 cm because of very deep calcrete but waterlogging was often indicated in samples below 20 cm (Fig 4.7 c).

(b) Redox (Eh) and pH

Soil redox (Eh; mV) was averaged for the whole core (0-40 to 60 cm; Fig 4.8 a). Eh was usually positive except for Hansons Swamp during winter where values to -80 mV were measured. Redox was usually higher in summer than in winter indicating more oxidised conditions in summer although at Lesron and Jaffray this was not significant. At the end of winter, redox was lowest at Hansons, next highest at Duck Island (+100 mV) and then higher again at Lesron and Jaffray (Fig 4.8 a). At the end of summer, these differences between sites disappeared and redox was high and similar at all sites (+400 mV). Soil pH was also measured at these times and averaged 8 (Fig 4.8 b). There was no significant difference between sites or season.

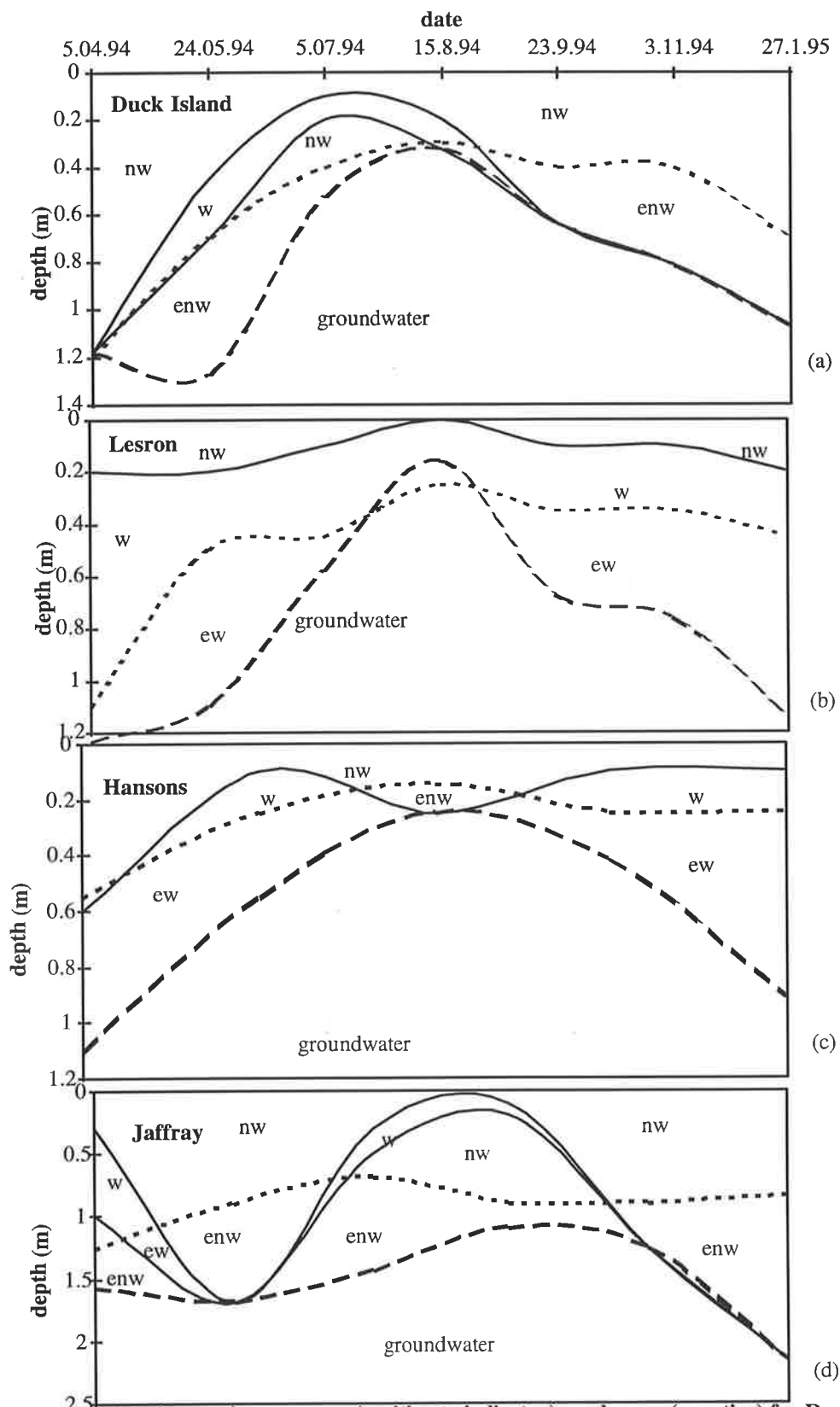


Figure 4.8: Soil ferrous ion presence (positive to indicator) or absence (negative) for Duck Island (a), Lesron (b), Hansons (c) and Jaffray (d) from April 1994 to January 1995. Results are shown from the soil surface to 40 or 60 cm depth, indicating the possible presence (w = +ve indicator) or absence (nw = -ve indicator) of waterlogging. Below the depth of soil sampling it was predicted that waterlogging may (ew) or may not (enw) have occurred based on results from the shallower soil samples.

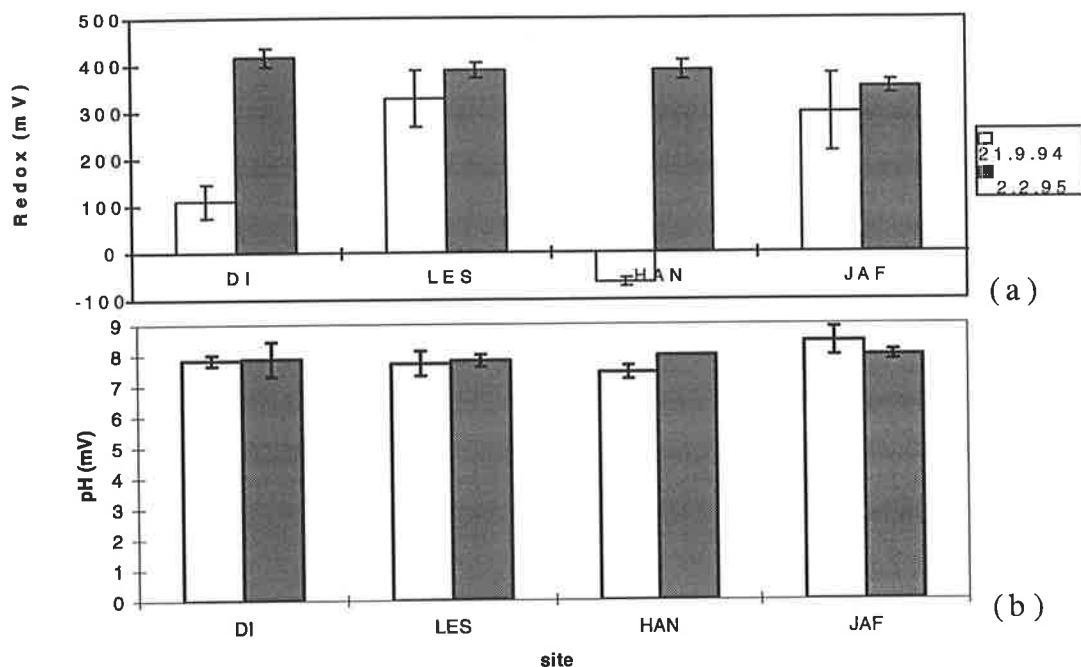


Figure 4.9: Redox potentials (mV; a) and pH (mV; b) for soil taken at on 21.9.94 (winter) and 2.2.95 (summer) at all sites to indicate possible waterlogging.

4.4 Discussion

4.4.1 Availability of water sources in a saline swamp

There were three lines of investigation followed when using the soil and plant water potential data to assist in identifying the sources of water. The first was to identify what parts of the soil profile were available for water uptake based on soil water potential information combined with leaf water potential which identified the threshold to plant water uptake (Table 4.2). The soil waterlogging data was also used to identify what parts of the soil profile were unavailable for plant water uptake, assuming that the plants can not extract water from waterlogged soil (Table 4.2). The second was to use pre-dawn plant water potential as an tracer of water sources. The third was to examine soil profiles for evidence of water extraction through the presence of salt accumulation and/or dry zones. These last two methods will be discussed with information in the next chapter to identify water sources. This section will focus on identifying parts of the root zone that were available for water uptake.

At Duck Island groundwater was very saline and shallow, rising close to the surface at the end of winter, in response to rainfall (Fig 4.2), and falling to 1.2 m over the summer. Despite groundwater rising through the soil profile, soil waterlogging did not appear to be prevalent at this site and was only indicated at the end of winter when groundwater was at its highest or in some mid profile points through the year. In particular, when groundwater was shallow, soil from the groundwater up to 10 cm below the surface appeared waterlogged, resulting in these parts of the soil profile being potentially unavailable for water uptake (Table 4.2 a). At this time waterlogging was indicated by the presence of ferrous ion and although Eh was still positive it had dropped from the summer values. Water availability in the surface soils at the end of summer when groundwater was deeper (1.2 m) was very low due to the high soil salinities caused by evaporative concentration of saline groundwater (Table 4.2 a). As it was often more negative than the plant water potential (threshold to water uptake) this water was therefore considered to be unavailable to plant use in the 0-0.1 m depth interval (Table 4.2a). Soil waterlogging was not apparent in the soil profile during summer.

During winter, surface soils often became freshened as a result of rainfall, and groundwater rising through the profile diluting and leaching accumulated salts. Therefore, based on soil water potential, all the profile was often available for water uptake (Table 4.2 a). At times, groundwater was more negative than plant water potentials and so was considered unavailable for water uptake.

At Hansons groundwater salinities were lower (medium salinity) than at Duck Island and Lesron (Fig 4.2) however high surface soil salinities were often recorded (Fig 4.4) probably because of higher water use (Chapter 3). Groundwater fluctuated from the surface to 1.4 m depth over the summer. Water availability in the surface soils (0-0.1 m) during the summer, late spring and autumn was also very low due to the high soil salinities caused by evaporative concentration of saline groundwater and low soil water content (Table 4.2 c). Water was therefore considered to be unavailable for plant use in the 0-0.1 m depth interval for much of the year and water in the 0-0.2 m soil interval was also unavailable during much of the summer. In addition, during summer there were apparent drying zones indicated in the matric potential profiles, along with gradual salt accumulation with depth (Appendix 6). Water in the surface soils did not become available until winter and early spring through the same processes of rainfall and groundwater rise as at Duck Island. Soil waterlogging was

indicated at some times below depths of 0.2 m at this site, usually in winter (Fig 4.7, Table 4.2 c).

Water availability in these ephemeral swamps was dominated by osmotic potential with matric potentials being very high (close to 0). The domination of soil water availability by osmotic potential has been observed in coastal wetlands such as mangrove fringe swamps (Lin and Sternberg, 1994) and marshes (De Jong and Drake, 1981). In these systems salt accumulates in the surface in response to sea water intrusion and evaporation with tidal events resulting in a removal of accumulated salt from the surface soils. In contrast, the pattern of salt accumulation in the surface soils in the *M.halmaturorum* sites is similar to that observed in other areas underlain by shallow saline groundwater and is caused by discharge of salt from shallow groundwater (Talsma, 1963; Smith et al, 1995; Huperman, 1995). Leaching of salt from the system through irrigation and rainfall has been considered to be necessary to maintain water uptake from these soils.

At Lesron, groundwater was ultra-saline, rising to the soil surface at the end of winter falling to 1.3 m over the summer (Fig 4.2). Soil water logging was indicated below 20 cm throughout most of the year and soil was apparently waterlogged to the surface during winter (Fig 4.7) making these zones unavailable for water uptake (Table 4.2b). Redox potentials were not low as was expected especially at the end of winter. This may be a result of (1) oxidation of the core during sampling and analysis (2) spatial variability in field sampling (3) oxidation of the soil profile with groundwater that contained a high oxygen content during the groundwater rise. At Lesron water availability in the surface soils at the end of summer when groundwater was deeper (1.2 m) was apparently also very low due to the high soil salinities caused by evaporative concentration of saline groundwater (Table 4.2 b). Plant water potential, however, was also very low (high salinity threshold) and tended to follow the 0-10 cm interval, or was often between the 0-10 and 10-20 cm soil interval (Fig 4.3). As a result, surface water sources may have in fact been suitable for water uptake. During much of these times the groundwater osmotic potential was more negative than plant water potentials and was assumed to be unavailable. An exception to this pattern was at the beginning of Autumn (3/3/94) when plant water potential was more positive than the 0-20 cm soil intervals and so these soils was considered to be unavailable to plant use and water may have been taken from deeper in the profile. There was evidence of drier soil at depth at this site (Appendix 6) during most times. However this was still classed as unavailable for water uptake because of waterlogging due to the calcrete layer which occurred

at 30- 60 cm depth. The limited extent of soil sampling at these three sites as a result of the calcrete layer makes it difficult to discriminate between the effects of soil type.

Soil waterlogging when combined with salinity in coastal swamps is considered to be responsible for the predominance of shallow roots of these plants. When surface soils have low permeability to infiltrating water, surface flooding will not always cause sub-soil waterlogging (i.e. Richter et al, 1996). In the current study, flooding of the soil profile from the bottom of the root zone to the surface was caused by groundwater rise, ensuring complete profile inundation if the groundwater rises completely to the surface. Therefore waterlogging occurred when groundwater inundated the soil profile for long periods. At Lesron, reduced conditions were apparent in the soil profile but the groundwater fluctuations were similar to the other sites. This may be because the waterlogging indicator was a result of long term waterlogging at this site although waterlogging was not observed during the study period because of drought conditions (Appendix 2). Long term surface inundation and shallow groundwater in this region is considered to be responsible for the decline in health of *M.halmaturorum* (Webb, 1993).

At Jaffray Swamp groundwater did not rise to the surface but fluctuated at depth and apparently in response to adjacent surface water fluctuations (Fig 4.2). Water availability in the surface soils (0-10 cm) during the late summer was very low due to the high soil salinities caused by evaporative concentration of saline groundwater and low soil water content (Fig 4.3). After autumn rainfall, soil water potential was higher and similar to groundwater values. Soil water potential in the deeper soils was more negative and relatively constant for much of the year. Water was therefore considered to be unavailable to plants in the 0-0.25 m depth interval for some of the summer but water in the deeper soil intervals was available during all of the year (Table 4.2 d). Groundwater always had a high water availability. Soil waterlogging was not very prevalent (Fig 4.7) and when it did occur was at depths in the mid-profile, which may be associated with heavy clays (Table 4.2 d). Pre-dawn plant water potentials followed the mid-profile soil values throughout the year, not responding to the surface soil fluctuations (Fig 4.3). Soil waterlogging was infrequent with some mid-profile soil samples showing indications of apparent reduced conditions. This may be associated with the very tight clays found in the subsoil at this site. The soil profiles at this site provided more information on the root activity than the other sites. A bulge of salt was often seen extending from 0.25 m to 1 m depth indicating water uptake and thus salt concentration at these depths. In addition there were often low matric potentials observed down to 1 m depth also suggesting water extraction at depth (e.g. Appendix 6.4 e, i, j).

Table 4.2: Summary on water availability (depth interval; m) of all water sources for each sampling time at Duck Island (a), Hansons (b), Lesron (c), and Jaffray (d).

(a) Duck Island

Season	Date	Unavailable (salinity)	Unavailable (waterlog)
Spring	26.10.93		-
Early Summer	1.12.93	0-0.2	-
Early Summer	28.12.93		-
Late Summer	2.2.94	0-0.1	-
Late Summer	21.2.94	0-0.1	-
Autumn	6.4.94	0-0.1	-
Late Autumn	24.5.94		0.4-0.7
Winter	6.7.94		0.1-0.3
Late Winter	16.8.94		0.2-gwater
Early Spring	20.9.94		

(b) Hansons

Season	Date	Unavailable (salinity)	Unavailable (waterlog)
Spring	27.10.93		-
Late Spring	30.11.93	0-0.1	-
Early Summer	29.12.93	0-0.1	-
Late Summer	3.2.94	0-0.2	-
Early Autumn	3.3.94	0-0.1	-
Autumn	7.4.94	0-0.2	0.6-gwater
Late Autumn	26.5.94	0.1-0.2	0.2-gwater
Winter	8.7.94		0.2-gwater
Late Winter	17.8.94		
Early Spring	20.9.94		0.2-gwater

(c) Lesron

Season	Date	Unavailable (salinity)	Unavailable (waterlog)
Late Summer	1.2.94	0.1-0.2	-
Early Autumn	3.3.94	0.1-0.2	-
Autumn	5.4.94	0-0.1	0.15-gwater
Late Autumn	24.5.94	0.1-0.2, gwater	0.15-gwater
Winter	5.7.94	0.1-0.2	0.05-gwater
Late Winter	15.8.94	0.1-0.2, gwater	0.05-gwater
Early Spring	23.9.94	gwater	0.15-gwater
Summer	27.1.95	gwater	0.15-gwater

(d) Jaffray

Season	date	Unavailable (salinity)	Unavailable (waterlog)
Spring	28.10.93	0-0.1	-
Late Spring	29.11.93		-
Late Summer	3.2.94	0.1-0.3	-
Early Autumn	3.3.94	0.1-0.3	-
Autumn	7.4.94		0.5-1
Late Autumn	25.5.94		1.3-1.5
Winter	7.7.94		0.8-0.9
Late Winter	17.8.94		0.1-0.2
Early Spring	22.9.94		-
Late Spring	4.11.93		-

The pattern of osmotic potential and matric potential is similar to that observed in soils on the Chowilla floodplain and has been associated with groundwater uptake from depth in the profile (Thorburn et al, 1993a). Investigations of this saline floodplain found that soil water availability was dominated by osmotic potential at depth and matric potentials near the surface. This pattern of salt accumulation is a function groundwater depth, groundwater salinity, and the hydrogeology of the site (to be discussed further in Chapter 7).

4.4.2 Ecophysiological implications for *M. halmaturorum*

Pre-dawn leaf water potential at Hansons and Duck Island during summer was generally between the surface soil and the groundwater as surface soil became more saline. At Hansons the pre-dawn leaf water potential was very close to the groundwater during late summer and early autumn when the 0-0.2 m soil interval were the most saline also indicating possible uptake from these zones. In winter pre-dawn leaf water potentials matched with the surface soil water potential at Duck Island and Hansons (Fig 4.4 a and c). At Lesron pre-dawn water potential usually matched with water potential of the surface soils, although when soil water potential increased at the end of winter pre-dawn leaf water potential did not usually follow. Pre-dawn water potentials at Jaffray were relatively constant compared to the other sites (Fig 4.4 d) and always matched with soil values at depth. There was a gradual increase in leaf pre-dawn water potential over winter which may be associated with a response to the sudden increase in water availability in the surface soils in response to rainfall. This information from all sites will be developed further in chapter 5 in conjunction with information on root activity in water uptake to identify water sources.

M.halmaturorum trees were able to reach much lower xylem water potentials (<-5 MPa) than many other plants and so could take up water unavailable to other plants. The ability to achieve low xylem water potentials has been found in various desert plants and coastal halophytes (Scholander, 1968; Galloway and Davidson, 1993). These very low leaf water potentials could have been underestimated by the pressure bomb (Ritchie and Hinckley, 1975). Evidence that errors in estimating leaf water potential were generally low is provided by the adequate match with soil water potential at most times. However at Duck Island in Autumn the plant water potential was lower (more negative) than all possible sources. This could possibly result from (1) plant equilibration with discrete sections of the soil profile that had a water potential different than measured (i.e. top 5 cm of the soil profile), (2) lack of equilibration with the soil overnight, or (3) errors or bias in both plant and soil measurement (Turner, 1981, 1987). This is in contrast to results for trees in drying soil where the depth of root equilibration overnight was found to be with the highest soil water potential (Breda et al,

1995) and may reflect the difference between the dry environment and the saline but relatively wet environment in the current study. It is interesting to note that this problem occurred only after *M.halmaturorum* had reached very low xylem water potentials (-6 MPa) and then seemed to disappear after winter rehydration indicating an apparent overestimation of plant water potentials after the plant had reached -6 MPa.

The maintenance of leaf turgor at these low water potentials at Duck Island may be result of osmotic adjustment or elastic adjustment. This is not unexpected based on the salinity of the environment where the abundance of solutes could be used by *M.halmaturorum* to decrease osmotic potentials (see chapter 1.2.1). In addition it has been shown that other *Melaleuca* species are able to produce nitrogenous compounds that assist in osmoregulation in response to drought stress (Naidu et al, 1987). However the long term benefits of osmotic adjustment are unclear, as growth may be affected as a result of the diversion of solutes for osmotic adjustment (Munns, 1988). Changes in cell elasticity may work in conjunction with this increase in solute potential to maintain turgor at lower leaf water contents. If osmotic adjustment occurs in roots it may allow water uptake from soil at lower water potential, but it is unclear what the magnitude of this advantage would be in the long term (Turner, 1986). It has been suggested (Shalhevet and Hsiao, 1986) that soil osmotic potentials may be weighted lower when combined with matric potentials, when examining the effect of total soil water potential on plant growth, because of the ability of plants to osmotically adjust against osmotic soil water potential gradients. In this system, where soil water potentials are very low but are dominated by osmotic potential, there is evidence that the ability of *M. halmaturorum* to osmotically adjust in response to low osmotic soil water potentials may contribute to the survival of trees. Other ecophysiological characteristics which result in water uptake in these systems will be examined in the following chapter.

4.5 Summary and Conclusions

Water availability in the *M.halmaturorum* ephemeral swamps is generally dominated by osmotic potential and is lowest in the surface soils in summer. Soil waterlogging is prevalent in winter and at Lesron is prevalent at most times below 20 cm. *M.halmaturorum* is able to lower leaf water potentials to low values (to -12 MPa) and so continue to take up water from saline soil.

Chapter 5: Root water uptake; Identification of water sources

5.1 Introduction

This chapter continues the investigation of water sources used by *M. halmaturorum* by examining the root system growth and activity in response to temporally varying concentrations of soil salinity and waterlogging. This was done by combining information of soil water availability from the previous chapter with information on root activity and growth at the four sites. Through this process the water sources were identified and the proportion of plant water that was groundwater was also identified. The hypothesis was that *M. halmaturorum* adjusts root growth and water uptake to all parts of the profile where the soil water is readily available and in this way maintains transpiration rates at levels required for continued growth.

5.1.1 Tree water sources

Plant roots will continuously penetrate new soil where there is available water as changing environmental conditions alter the moisture status of different areas of the soil profile. The water sources of a particular plant will also depend on the type of root system. Root systems of trees consist of large perennial roots and fine laterals which are usually ephemeral. The fine ephemeral roots will generally be in the soil surface horizons, and the sinker roots, which arise from large laterals, will generally be found in the subsoil or groundwater (Heinrich, 1990; Crombie et al, 1988). These trees have the ability to take advantage of water from a number of different sources. Some plants which are adapted to waterlogged conditions will have specialised root structures and in saline environments root system distribution may be influenced by root zone conditions (Chapter 1.2.3).

Possible tree water sources generally include precipitation, soil water, groundwater and surface waters. Precipitation for most plants will be available in the upper surface soils. Evaporation may remove most of this water before it able to be used by plants (Passioura, 1988). Soil water may therefore be divided into that which is in the surface soils and that which is in the sub-surface soil with the area of soil between the surface soils and the groundwater called the unsaturated zone. The water in this zone is often derived from groundwater.

The water sources used by plants have been investigated by observing the physiological behaviour of trees, through the conventional analysis of water relations such as stomatal conductance and water potential (Crombie et al, 1988; Sinclair, 1980). Root excavations have also been used to examine the sources of water used by trees. This however is a destructive method, and does not assess the uptake rates or patterns of use, only providing information for one moment in time. The existence of roots also may not reflect the activity of roots (Ehleringer and Dawson, 1992). Water budget data have also been used to make estimates of soil water removal (Garnier et al, 1986), as have measurements of the changes in water content of the soil surrounding roots, to indicate where roots are most active in removing water from the soil profile. However where the soil profile lacks homogeneity it is difficult to estimate accurately the uptake of water from a particular depth. This is particularly exacerbated in the unsaturated zone, where changes in soil moisture contents throughout the profile are slight and so not easily delineated, and the amounts of water participating in the water budget are small.

5.1.2 Stable isotopes to identify water sources

One technique that has recently been used to determine the sources of water being used by plants has involved the use of naturally occurring stable isotopes of water (^2H and ^{18}O) (Ehleringer and Osmond, 1991; Rundel et al, 1988). ^2H and ^{18}O in water have been used in the past for various hydrological studies of the saturated and the unsaturated zone of soils (Allison and Barnes, 1983; Walker et al, 1988), studies of evapotranspiration from leaves (Allison et al, 1985), and studies of water movement in the soil-plant-atmosphere interfaces (Bariac et al, 1983; Brunel et al, 1991; Walker and Brunel, 1990). These naturally occurring isotopes of water have more recently been used to investigate the functioning of roots in natural environments, and the influence of these root functions on the local distribution of species and the coexistence of species within the community (Dawson, 1993).

In the case of oxygen, the ratio of the heavy isotope ^{18}O relative to the more abundant ^{16}O is measured ($\delta^{18}\text{O}$), and in the case of hydrogen the ratio of the heavy isotope deuterium ^2H to protium ^1H is measured ($\delta^2\text{H}$). The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in plant water is compared to the concentration in water of various components of the environment from which the plant might possibly be receiving its supply. The ratio of the heavy to the light isotopes found in the tissues of plants is assumed to reflect the isotopic composition of the water that they have extracted from the soil.

Differences in the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of water commonly occur within the root zone. Rainfall which is generally enriched in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ may be reflected in the soil profile if evaporative

processes are not predominant. All other waters are precipitation derived but the isotopic composition of these waters is significantly influenced by other processes. Natural isotopic variation depends on fractionation of isotopes. This depends on thermodynamic equilibrium and kinetic processes which affect the individual isotope. The different isotopes relate differently to fractionating processes as a result of differences in their masses (Broecker and Oversby, 1971). Fractionation of hydrogen and oxygen isotopes is caused principally by transport processes (Gat, 1981), and phase transitions through both the atmosphere and the lithosphere (Barnes and Allison, 1983). Rainfall when entering the soil profile will become further fractionated as a result of evaporative processes causing it to be enriched in heavy isotopes (^2H and ^{18}O) as light isotopes are removed (Allison et al, 1983). This will be most prevalent in the upper layers of the soil profile and may also occur in the unsaturated zone through vapour movement from the groundwater up the profile. The groundwater will have a different isotopic signature, depending on the source of recharge, which will depend on the atmospheric influences on this source at the time of recharge. Surface waters may also be isotopically distinct, and will reflect the atmospheric influences of the upstream environment, along with precipitation.

There are a number of assumptions that allow the isotopic composition of the trees to be compared to that of possible sources. These assumptions concern both the processes that occur as water moves into the plant, and the sampling and analysis of plant and soil material. It is assumed firstly, that there has been no significant fractionation (1) when water is taken up by roots, or (2) when it moves from roots to leaves; secondly, that no significant translocation of evaporated water from leaves has occurred down to other parts of the plant; thirdly that water can be extracted in the laboratory from plant material without fractionation of isotopes (Thorburn et al, 1993b). There is fractionation of leaf water due to transpiration (Allison et al, 1985). These assumptions have been validated for many plants (Zimmerman et al 1967; Allison et al, 1983; White et al, 1985; Sternberg and Swart, 1987; Brunel et al, 1990; Thorburn et al 1993b). These assumptions have also been proved invalid for the salt excluding halophyte *Rhizophora mangle* (Lin and Sternberg, 1993). Deuterium depletion in the stem water was observed, and hypothesised to be associated with the salt exclusion mechanisms of this species.

Studies of plant water sources, using $\delta^2\text{H}$ and $\delta^{18}\text{O}$, have been conducted in forest (White et al, 1985), coastal (Sternberg and Swart, 1987), arid (Ehleringer et al, 1991), semi arid (Brunel et al, 1990; Flanagan et al, 1992), and riparian communities (Dawson and Ehleringer 1991;

Smith et al 1991; Thorburn et al, 1994b). White et al (1985) in one of the earliest plant water source studies using ^2H , investigated a white pine forest to distinguish between recent precipitation and groundwater sources. The results showed that the pine trees alternated between deeper and surface soil layers, depending on the recent history of precipitation events. $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of twig water have been used by Sternberg and Swart (1987) to distinguish between fresh and salt water sources for coastal mangroves growing on the salt water fringe. The results indicated that hardwood hammock species growing towards the inland of the Florida keys were using freshwater and succulent species growing in the inland margin of mangrove forests were using a mixture of ocean water and freshwater. However the mangrove species had a range of water usage ranging from freshwater to ocean water, resulting in the hypothesis that the mangrove species were able to use freshwater, but were limited to the ocean margin because of competitive exclusion through their ability to use salt water (Sternberg and Swart, 1987).

^{18}O and ^2H isotopes have been used to identify the sources of water used by desert shrubs (Ehleringer et al, 1991). The scrub community growing near the Arizona border were all found to use winter recharge precipitation for early spring growth (Ehleringer et al, 1991). Studies of plant water sources using $\delta^2\text{H}$ and $\delta^{18}\text{O}$ have also been conducted in an Australian semi arid mallee community (Brunel et al, 1995). In this study measurements of soil water potential were made in conjunction with stable isotope measurements, to further define the areas of plant water uptake with the assumption that trees take water from an area of highest potential. This study indicated the usefulness of the combination of stable isotope measurements with measurements of soil water availability (Brunel et al, 1995). Another study in the semi arid region of the South Western United States used $\delta^2\text{H}$ to determine the relative uptake of summer precipitation by four co-occurring trees and shrubs (Flanagan et al, 1992). $\delta^2\text{H}$ measurements were combined with measurements of pre-dawn plant water potential indicating a negative correlation between pre-dawn plant water potential and stem water $\delta^2\text{H}$ and differences in uptake of precipitation among these species through differences in rooting patterns (Flanagan et al, 1992). This study also showed the usefulness of using plant water potentials in conjunction with stable isotope measurements to determine plant water sources.

Trees growing in a riparian ecosystem in the Intermountain West of the United States were investigated by Dawson and Ehleringer (1991). $\delta^2\text{H}$ analysis indicated that mature trees growing next to perennial streams were taking groundwater in preference to the stream water. In a similar area, $\delta^2\text{H}$, along with investigations of plant water relations, was used to identify

and explain the water stress imposed on riparian vegetation that was growing on streams containing low flow caused by stream diversion. The trees were compared to others growing on non-diverted streams which contained high flow. It was found that in dry periods when the trees showed water stress, that the groundwater was identified as being their chief source of water (Smith et al, 1991). Riparian *Eucalyptus camaldulensis* on a saline floodplain of the River Murray in South Australia were investigated using $\delta^2\text{H}$ and $\delta^{18}\text{O}$ and it was suggested that their sources of water may be both groundwater and surface soil water, but that creek water was not the dominant source of water for the trees on the creek (Mensforth et al, 1994; Thorburn et al, 1994b). The usefulness of using both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ to identify water sources of trees was particularly highlighted in this study. Where *Eucalyptus camaldulensis* was using sources of water with similar $\delta^2\text{H}$ but different $\delta^{18}\text{O}$, these different sources could be identified, whereas using measurements of $\delta^2\text{H}$ alone would not have detected the differences (Thorburn et al, 1994b).

5.2 Methodology

Rationale for methodology

To identify the sources of water for *M. halmaturorum* it is necessary to identify root activity in water uptake as opposed to the root presence. The stable isotopes of water were therefore used to identify the sources of water. However there should be correlations between the presence and the activity of roots so traditional techniques of root observation were made to back up the stable isotope results and as a test of the isotope technique. Root distribution observations were assessed on field trees to observe both the development of new root and changes in root biomass. The former was carried out with the use of root observation chambers while the latter was studied using soil cores.

5.2.1 Stable Isotopes

(a) Fractionation glasshouse experiment: Validation of technique under saline waterlogged conditions

This experiment was conducted to test the assumption that *M. halmaturorum* does not fractionate isotopes when taking up water under conditions of salinity and waterlogging (previous section). Twenty-one day old seedlings (~30 cm tall) were grown in a potting mix in a glasshouse under constant temperature and humidity. They were supplied with distilled water of known isotopic composition (doped water) under control (C), waterlogged (W) and saline conditions (S) (6 replicates per treatment). A saline waterlogged treatment was also

conducted (SW) but plants were near death at the end of the experiment so results are not presented because of possible errors associated with low stem water fluxes (c.f. Yakir and Yechieli, 1995). Waterlogging was achieved by placing the potted plant in another container, which was filled with the doped water (distilled water) to 1 cm above the surface of the pot (c.f. Denton and Ganf, 1994). The non waterlogged treatments, which included the saline treatment and the control, were also set inside another container and the water level (either saline or distilled water) was restricted to approximately 2 cm above the bottom of the outside container. The saline (S) treatment was irrigated from the top using saline water (30 dS m^{-1}) every 3 days to leach out any accumulated salt. All free water surfaces were covered by a layer of vegetable oil, and bare soil surfaces were covered in wax beads, to prevent isotopic fractionation of water through evaporation. The plants were weighed daily to determine the volume of water being transpired. When the volume of water transpired equalled at least double the weight of the plant (after 21 days) it was concluded that the 'dope' water had passed through the plants twice.

The plants were then harvested, leaves were removed and discarded, and water was extracted from woody material as outlined in Thorburn et al (1993b). A sub-sample of soil was taken from the pots and then azeotropically distilled in kerosene to extract the water (Revesz and Woods, 1990). This method has been validated for soil by Revesz and Woods (1990), and for *E. camaldulensis* by Thorburn et al (1993b). The method involves the distillation of the sample with kerosene to form an azeotrope between the kerosene and the water in the sample. An azeotrope has the property that its boiling point is different from those of either of its constituents (Revesz and Woods, 1990). The water then condenses out of the azeotrope, as it has a higher boiling point, and can be retrieved since water and kerosene are completely immiscible at ambient temperature. Twig pieces, soil, and water samples were distilled in a Dean-Stark apparatus. The water retrieved was stored in glass Macartney bottles and the surface was covered in wax. The wax was melted to remove any residual kerosene which would be harmful to the mass spectrometer.

The water extracted was analysed through stable isotope mass spectrometry for $\delta^2\text{H}$ by performing a reduction of 25 ml of water to H_2 over uranium at 800°C . $\delta^{18}\text{O}$ was measured (for next section) using a modification of the Epstein and Mayeda (1953) technique, reported by Socki et al (1990): One ml of water was equilibrated with CO_2 in small, pre-evacuated, rubber-topped vials. Measurements were made for ^2H and ^{18}O with a V G Micromass mass spectrometer. Isotopic concentrations were expressed as delta (δ) values in per mille (‰) relative to the standard SMOW (Standard Mean Ocean Water) and the standard SLAP

(Standard Light Arctic Precipitation). The isotopic composition of SMOW is known, and the absolute isotopic composition of the sample was compared to this. Delta values were calculated using the formula:

$$\delta(\text{‰}) = (R_i / R_s - 1)1000$$

where R is the ratio of heavy:light isotope, i is the isotope sample, s is the standard, $\delta^2\text{H}$ refers to ^2H and $\delta^{18}\text{O}$ refers to ^{18}O . There is a precision in sampling and analysis of $\delta^2\text{H}$ values of approximately $\pm 1.3\text{‰}$ and for $\delta^{18}\text{O}$ values of $\pm 0.3\text{‰}$ for *E. camaldulensis* (Thorburn et al, 1993b) and soils (Revesz and Woods, 1990).

(b) Field study

When using the stable isotope technique for field analysis it must be assumed that there are no significant errors in sampling, extraction and analysis of plant and soil isotopes. Thorburn et al (1993b) in laboratory and glasshouse experiments quantified the accuracy of sampling, extraction, and analysis of water from *E. camaldulensis* by azeotropic distillation (as above), and concluded there was no additional error found in field sampling, indicating there was no significant variability in sampling between twig and trunk analysis.

These errors were minimised by taking multiple samples of twigs within the canopy to reduce the variability and produce twig isotopic values that were more representative of the entire canopy. Spatial variability in the canopy was investigated through multiple sampling of twigs from a tree at time 7. In addition, on 26.10.93 samples were taken from a number of parts of the tree and analysed separately to investigate sampling strategies within the tree and the effect of bark on the isotopic composition of water. Sapwood and bark were sampled from the main trunk and secondary branch. Primary and secondary twigs were sampled and analysed with the bark removed and without the bark removed. Roots were also sampled. The main sampling procedure was designed taking into account results of these preliminary investigations.

To investigate the water sources, samples of soil, twigs and groundwater were taken at 9 times from October 1993 to January 1995. Twigs were sampled from three trees each time. Three twigs were cut from each of the trees and combined to obtain one composite sample. Outer bark was removed quickly because it may have been isotopically enriched by absorbing small amounts of water vapour from the atmosphere (Walker and Richardson, 1991). The twigs

were cut into 5 cm pieces and were placed into 500 ml screw cap glass jars full of kerosene, and sealed air tight with plastic electrical tape. Soil was sampled from beneath these same trees at 0.1 m intervals to the groundwater (or to an underlying calcrete layer if it was impenetrable) and groundwater at the depth of the watertable was also sampled. Samples were stored in 500 ml screw cap glass jars which were sealed air tight with plastic electrical tape. The water from the twig, soil, and groundwater samples was extracted using azeotropic distillation and analysed for stable isotopes as outlined in the previous section.

Isotope data were analysed in two ways. The source of water present in the twig was identified by comparing the $\delta^2\text{H}$ values and $\delta^{18}\text{O}$ values of the twig water to the $\delta^2\text{H}$ values and $\delta^{18}\text{O}$ values of the possible source waters for each time. This was done for one isotope alone to identify patterns of uptake over time and the ratio of $\delta^2\text{H}$ to $\delta^{18}\text{O}$ was used to identify the proportion of each water source in the twig water. A simple mixing model was used as outlined in Thorburn et al (1993b). For each time period all values of soil, groundwater and twig water $\delta^2\text{H}$ were plotted against $\delta^{18}\text{O}$ from the same samples and a line was drawn that dissected the twig water and the possible water sources. Through this process, the closeness of the twig water to the groundwater values and the surface soil values was used as an indication of the quantity of groundwater that was being used by the trees (Fig 5.1). This could be interpreted as an identification of the quantity of groundwater in the region of soil containing the majority of roots, or the quantity of groundwater obtained from more than one region of soil and mixed within the tree water. Where there was more than one possible solution, information of soil water availability (Chapter 4) was used to identify the end members of the mixing model (Fig 5.1).

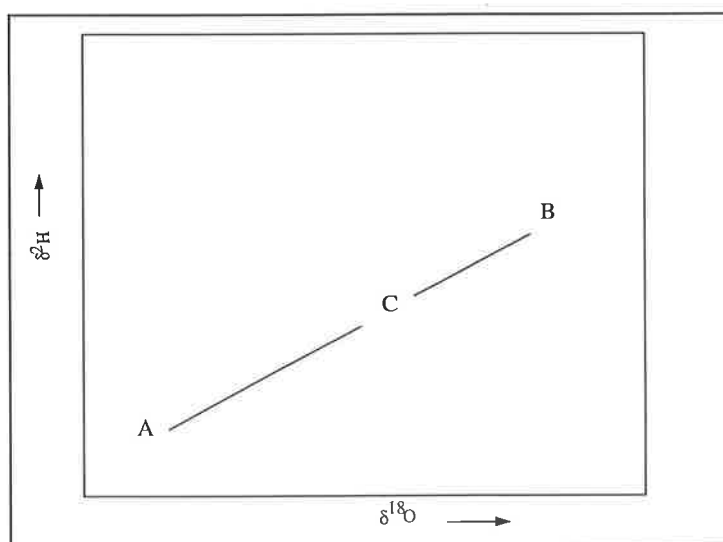


Figure 5.1: Mixing model theory for analysis of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data from all twigs, soil and groundwater samples. A and B represent two possible sources of a known isotopic composition, which may be mixed to give C. The line represents the “mixing line” between waters A and B which are the “end members” of the mixing model. (Figure from Thorburn, 1993)

5.2.2 Root mass measurements: Soil coring

At each of the sites soil cores were taken during the September 1994 sampling. Soil was sampled to 40 cm depth, at which a hard calcrete layer prevented any further samples being taken at 3 of the sites (Duck Island, Hanson and Lesron). Samples were taken in 0.1 m depth increments from 6 holes around the 3 test trees and combined for root extraction. At Jaffray, soil was collected at an extra depth interval of 70 cm. Roots were extracted from soil using high pressure water filtration. Roots were not separated into old and young roots as it was not obviously apparent which roots were young. However organic material that was obviously not functional root material was removed after filtration. Root mass density was calculated per volume of soil for each 0.1 m depth increment (Böhm, 1979b) by dividing the mass of roots (g) by the volume of soil in the sub-samples (cm³).

5.2.3 Root Observation: Chamber

At Duck Island an observation chamber was constructed from a plastic box 60 cm by 25 cm with a perspex gridded wall inserted in the side (squares 5 cm by 5 cm). A pit was dug within 0.5 m of the tree to expose part of the root system at a vertical face. The observation chambers were set in the pits with the perspex wall against this face and soil was replaced around the chamber, carefully backfilling against the perspex wall (Böhm, 1979a). The wall was covered inside the chamber with a sheet of polystyrene and black plastic to prevent exchange of heat and light to the root system. The chamber was closed with a lid to further insulate it. New root appearance and disappearance at the perspex wall (root tip/ grid cell) was manually recorded at 7 sampling times from February 1993 to November 1994 by mapping the root system at each time. From this data the new root tips / cm² of observation wall space was calculated.

5.3 Results

5.3.1 Stable Isotopes

(a) Validation of isotope technique

Results from the glasshouse experiment indicated that when the mean plant and soil water $\delta^2\text{H}$ were compared for the salinity and the waterlogging treatment there was no significant difference ($p < 0.05$) indicating no fractionation of $\delta^2\text{H}$ through uptake of water (Fig. 5.2).

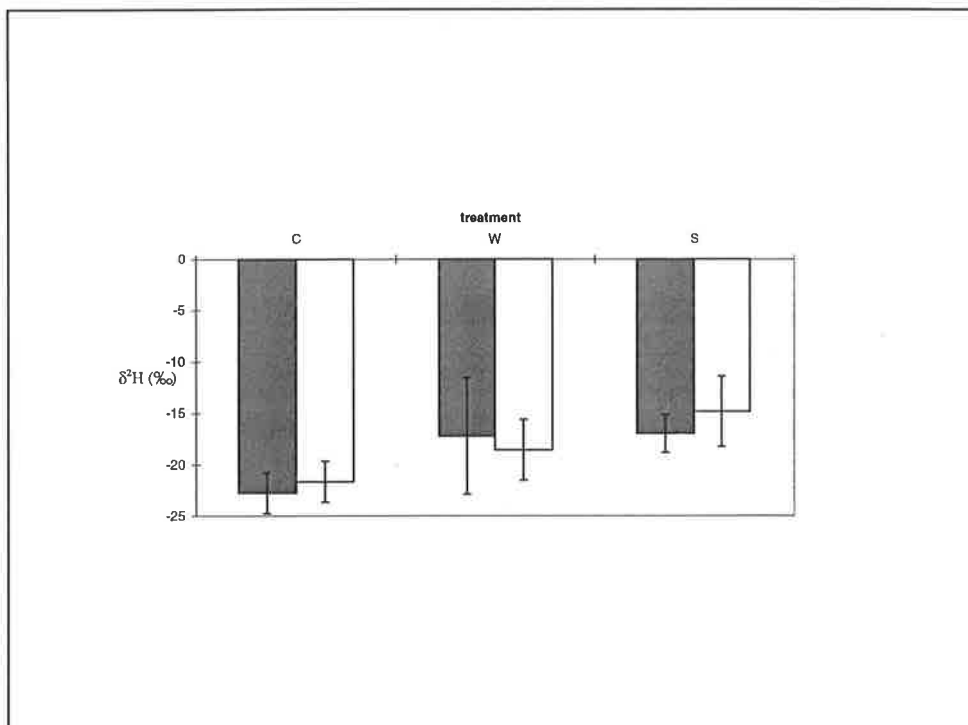


Figure 5.2: Mean $\delta^2\text{H}$ of twig water (white) and soil water (grey) for *Melaleuca halmaturorum* seedlings irrigated with distilled water (C), saline water (S), and flooded with distilled water (W). The 95 % confidence interval is also shown indicating a lack of significant difference ($p < 0.05$) between plant and soil $\delta^2\text{H}$ for all treatments and the control.

Results from the intensive field sampling of twig and sapwood samples from various parts of the tree on 26.10.93 are shown in Fig 5.3. The first twigs (on the ends of branches) usually had high $\delta^2\text{H}$, indicating evaporative enrichment, and the presence of bark did not increase the value of $\delta^2\text{H}$ of these twigs (Fig 5.3). Water from the 2nd twigs (closer towards the trunk) had values of $\delta^2\text{H}$ closer to the source water (considered to be reflected by the main trunk sapwood and the soil information; Fig 5.4a) but when bark was left on these twigs the $\delta^2\text{H}$ were high (Fig 5.3). Bark analysed separately from the secondary branch (closer to the main trunk) indicated high values of $\delta^2\text{H}$ and sapwood from the same secondary branch was also higher than expected. This could be a result of errors in evaporation when sampling sapwood directly as compared to sampling full twigs and rapidly removing the bark. Root $\delta^2\text{H}$ values were high and similar to the surrounding soil. On 24/5/94 composite twig samples from 3 adjacent trees at Duck Island were -17.1, -14.6 and -17 ‰ $\delta^2\text{H}$ respectively indicating differences between trees at this time were within experimental error. Based on all of this information, it was considered that the second twig could be sampled and the bark removed to accurately represent the source water.

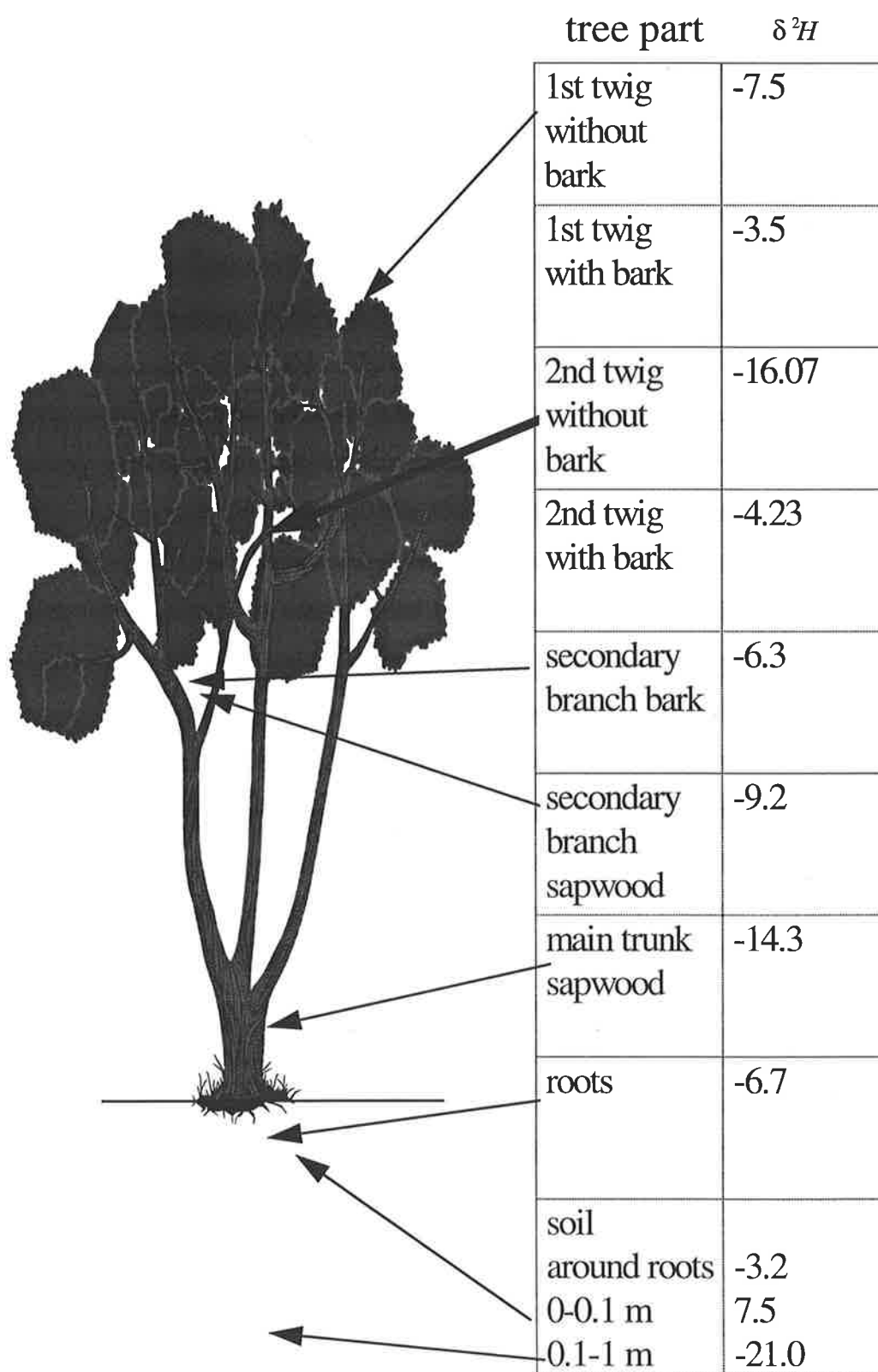


Figure 5.3: Field sampling results of δ^2H taken from separate parts of the tree on 26.10.93 to test for fractionation of δ^2H associated with bark and sampling strategy.

(b) Isotope Field Studies

At Duck Island the isotopic composition of the groundwater (depth of 0.3 to 1.2 m) remained reasonably constant over the study period (mean of $-22\% \pm 1.5 \delta^2\text{H}$; Fig. 5.4a). The $\delta^2\text{H}$ of soil samples decreased with depth to approximately 0.4 m in summer (Fig. 5.5 a) and to 0.15 m in winter (Fig. 5.5b) and then remained at constant values similar to the groundwater at subsequent sampling depths to the groundwater. The $\delta^2\text{H}$ of the soil samples from 0-0.1 m depth fluctuated 20 ‰ throughout the season ranging between 7.5‰ and -13.7‰ (Fig. 5.4). The $\delta^2\text{H}$ of soil samples from 0.1 - 0.2 m depth fluctuated only 8.7 ‰ (-9.7 ‰ to -18.4 ‰) and were more negative than the shallower surface soils. At Duck Island the twig $\delta^2\text{H}$ values followed a broadly similar seasonal pattern to the seasonal pattern of the surface soil (Fig. 5.4a). The values reached a maximum of -7‰ and a minimum of -20.5‰, a value which was similar to the groundwater. Therefore actual values were depleted in $\delta^2\text{H}$ compared to the surface soil resulting in them falling between the 0-0.10 m soil samples and either the groundwater $\delta^2\text{H}$ values or other soil samples. The difference between the twig value and the soil water value at 0- 0.1 m became greater over the summer (Fig. 5.4a). These patterns were also observed when the ratio between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of the twigs was matched with this ratio of the soil waters (Fig. 5.6). It was observed from these plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ that the soil values from 0.25 m and deeper were usually similar to the groundwater and surface soil values (0.05 and 0.15 m intervals) were usually more enriched from evaporation and probably were influenced by rainfall also. In late winter, spring and early summer, twigs matched with surface soil values and groundwater or the surface soil values only (Fig 5.6). During late summer, autumn and early winter twigs matched with either of the surface soil values (0.05 or 0.15 m) and the groundwater or deeper soil values alone (which would have contained close to 100% groundwater). The interpretations of possible water sources from the stable isotope data are outlined in the discussion.

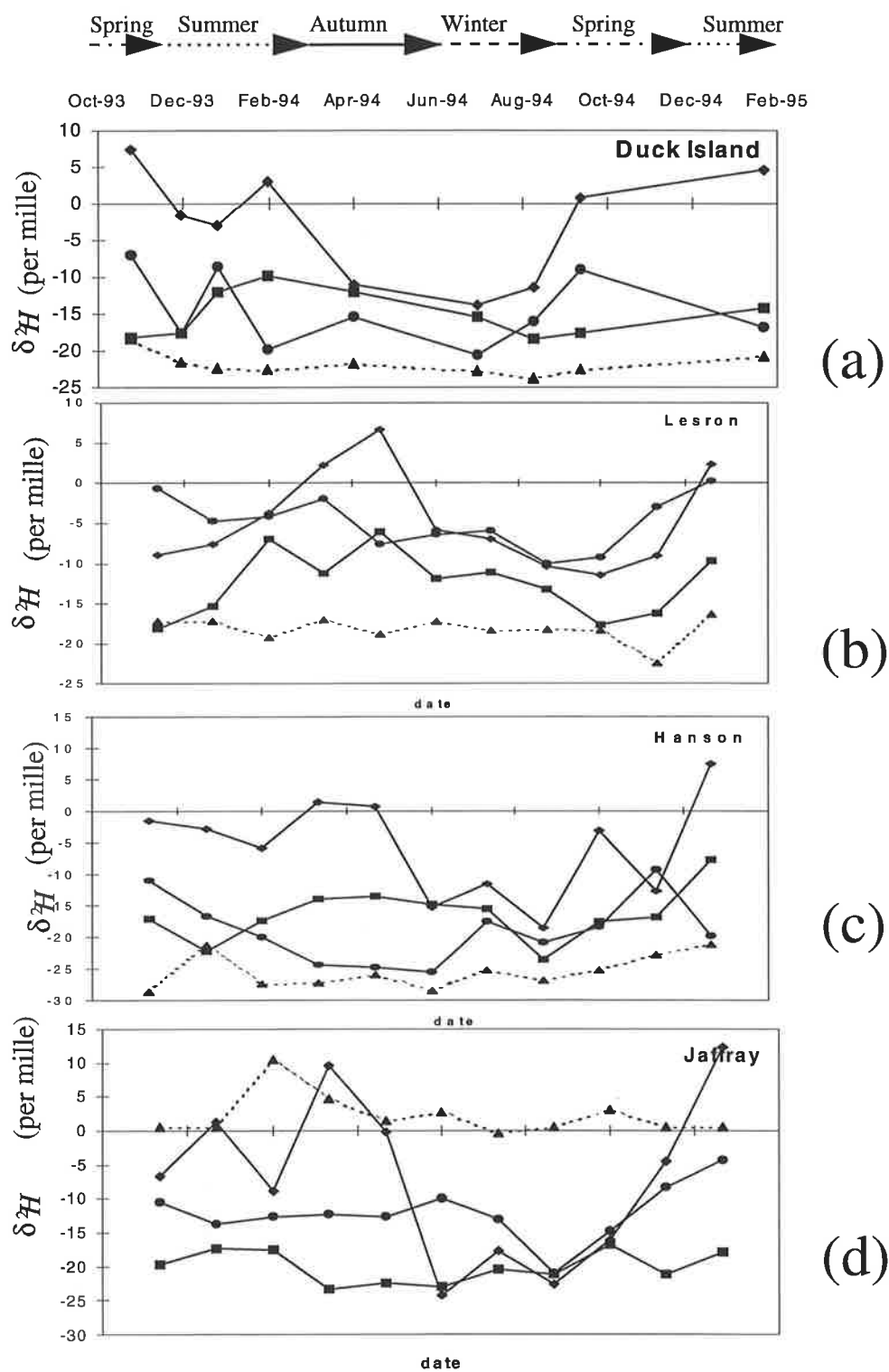


Figure 5.4: Deuterium composition ($\delta^2\text{H}$; ‰) for tree stem water (●), soil water at 0-0.1 m (◆), soil water at 0.1-0.2 m (■), 0.4-0.5 m (Jaffray), and groundwater (▲) for Duck Island (a), Lesron (b), Hansons (c) and Jaffray (d). from October 1993 to February 1995.

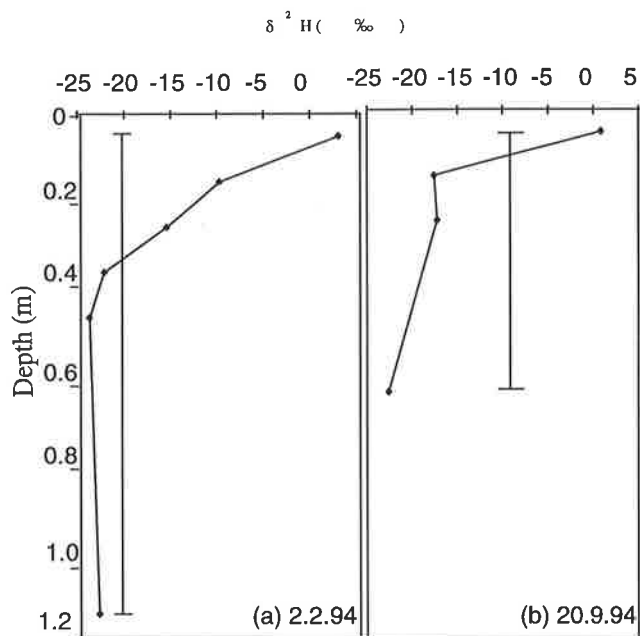


Figure 5.5: $\delta^2\text{H}$ (‰) for tree stem water (straight lines; error bars indicate analysis error) and soil water (◆) at Duck Island at the end of summer (a) and Autumn (b).

At Lesron the groundwater isotopic composition also remained fairly constant over the study period (mean of $-18\text{‰} \pm 1.5$ $\delta^2\text{H}$; Fig. 5.4b). Soil $\delta^2\text{H}$ values showed a similar pattern to Duck Island with the highest isotopic values in the surface soils (7‰). Twig values ranged from 0.2 at the end of winter to minimum of -10‰ at the end of summer. Twig values usually matched with, or were higher than, the 0-10 interval soil sample apart from at the end of summer when the twig value matched with the 10-20 cm soil interval. The twig values never matched with the groundwater values (Fig 5.4b). When the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values were plotted against one another the soil values also lie along an evaporation line from the groundwater (Fig 5.7). The twig values usually matched with the surface soil values however at some times the values moved away from the surface soil values and towards the groundwater values. This only occurred in summer and autumn (Fig 5.7) while in winter and spring the twig values always matched with surface soil values.

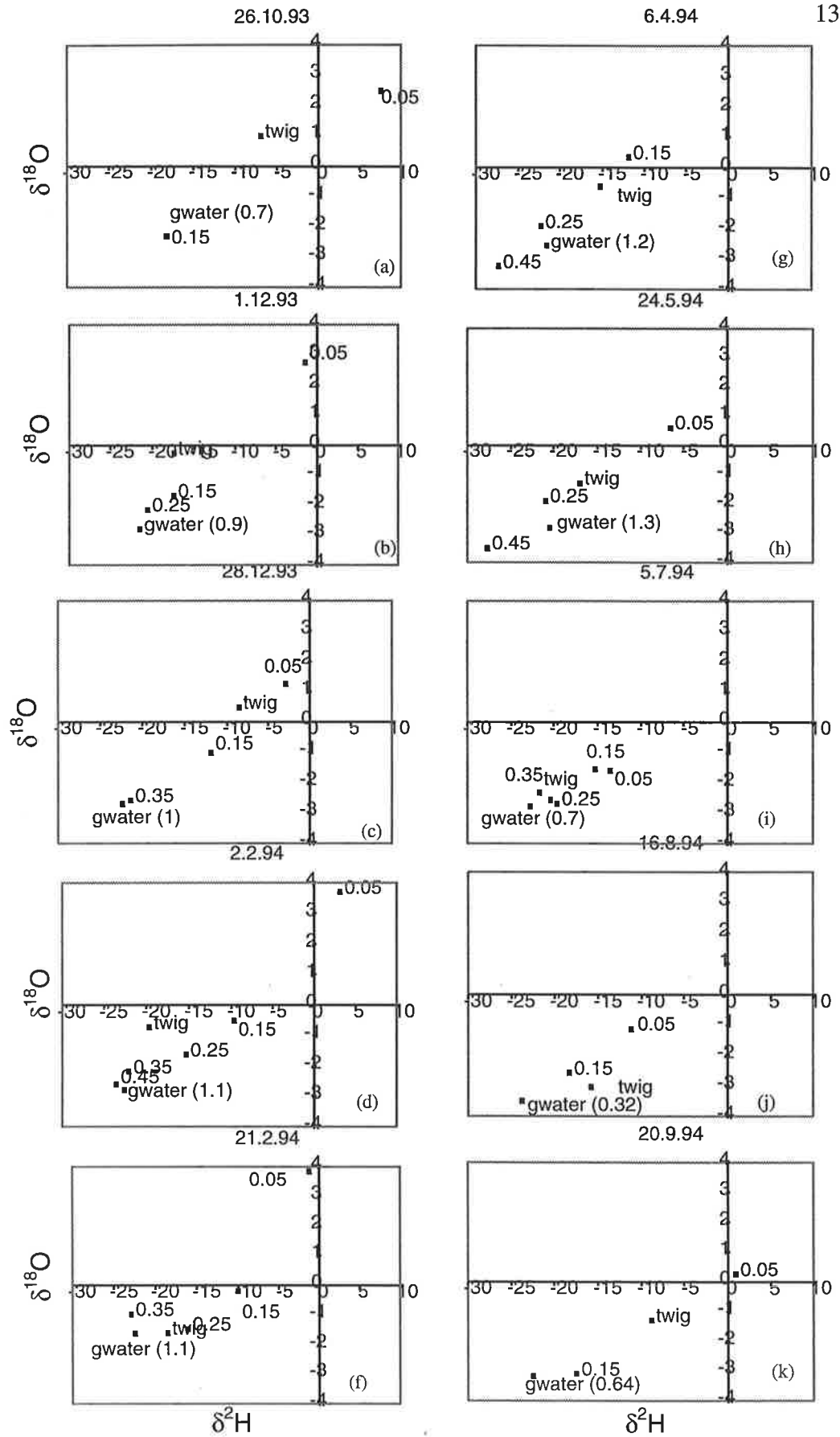


Figure 5.6: Plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for all twig, soil and groundwater samples taken at Duck Island.

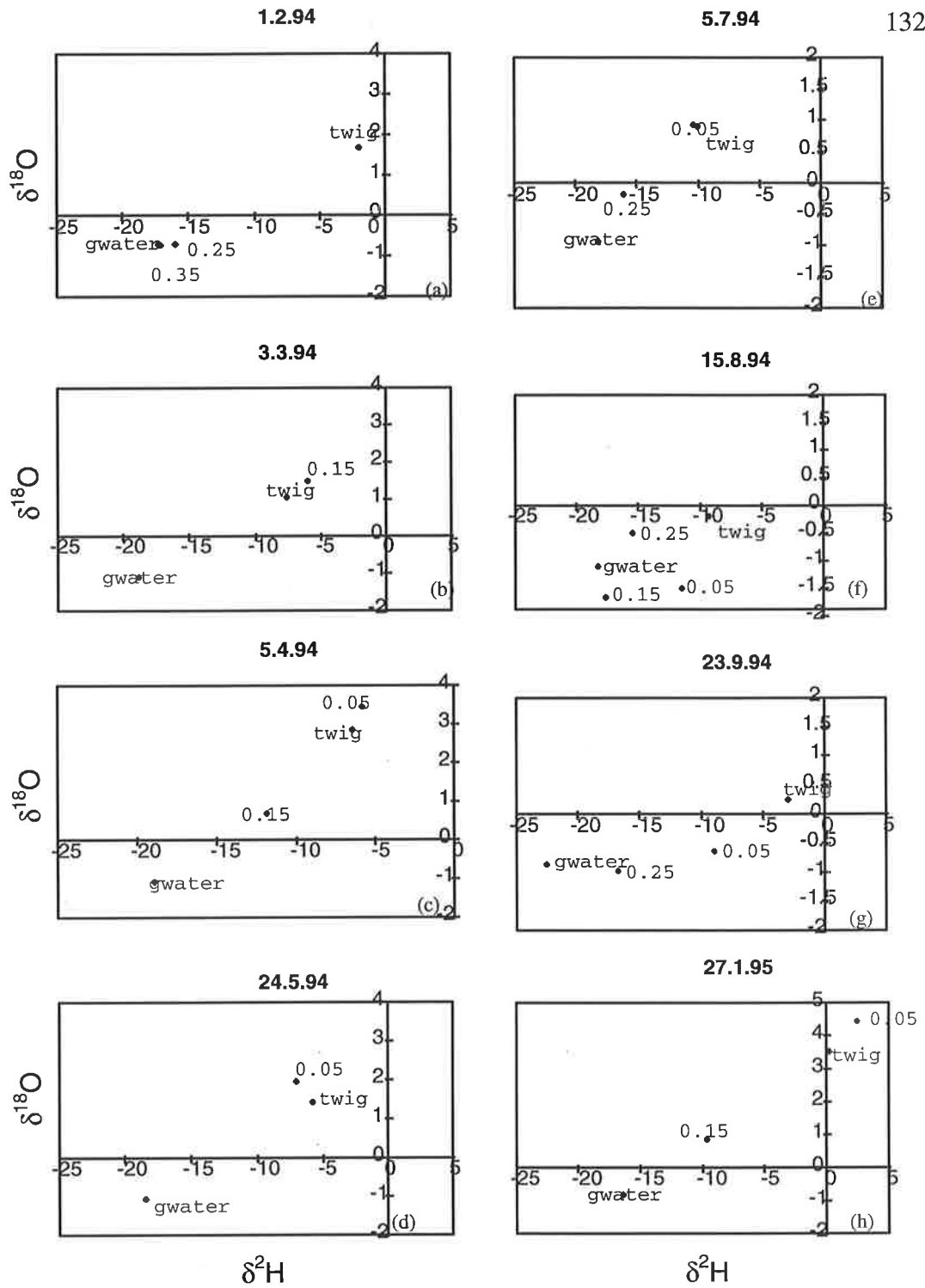


Figure 5.7: Plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for all twig, soil and groundwater samples taken at Lesron. Note the different scales for $\delta^2\text{H}$ (c) and for $\delta^{18}\text{O}$ (e-h).

At Hansons the groundwater also retained a constant isotopic composition (mean of $-28\text{‰} \pm 1.5 \text{‰} \delta^2\text{H}$; Fig. 5.4 c). The soil profile had a similar pattern with depth as was observed at Duck Island with values of up to 2‰ being found in the surface soil. Twig values matched with soil values in a similar way to that at Duck Island. Twig values had a minimum summer value of -25 and a winter maximum of -7 . Twig values matched with surface soil values at the end of summer, and throughout winter and were between the groundwater and soil values throughout mid to late summer and autumn (Fig 5.4 c). Through examining the plot of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ it can also be seen that there is two patterns (Fig 5.8). In winter and spring the twig values frequently appear to match with the surface soils and during summer and autumn the twig values frequently match with soil values that are deeper and closer to the groundwater (Fig 5.8).

At Jaffray Swamp the soil profile followed a different pattern than at the other sites. The groundwater had higher isotopic values (mean of $2\text{‰} \pm 1.5 \text{‰} \delta^2\text{H}$; Fig. 5.4 d) maybe as a result of an adjacent body of surface water that may have been connected to the groundwater. The surface soil values were often as enriched as the groundwater and often (during winter) had more negative values (-22‰), therefore reversing the pattern in the isotope profile seen at other sites. The rest of the soil samples from the unsaturated zone were more negative than the groundwater and averaged (-22‰). The twig values averaged (-13‰) and sometimes were between the unsaturated zone values and the groundwater or the surface soil (summer) and sometimes were between the groundwater and the surface soil/ deeper soil (winter) (Fig 5.4 d). At many sampling times in winter and spring the twig values of $\delta^2\text{H}$ matched with surface soil values and at many sampling times in summer the twig values matched with soil from 0.15 to 0.25 depth. There was very rarely a unique solution at this site. This was reflected in the plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ where the 0.05 soil sample was often similar to the groundwater (Fig 5.9). The conclusions from this data were therefore not complete apart from the end of winter and early spring when twigs matched with surface soil water only.

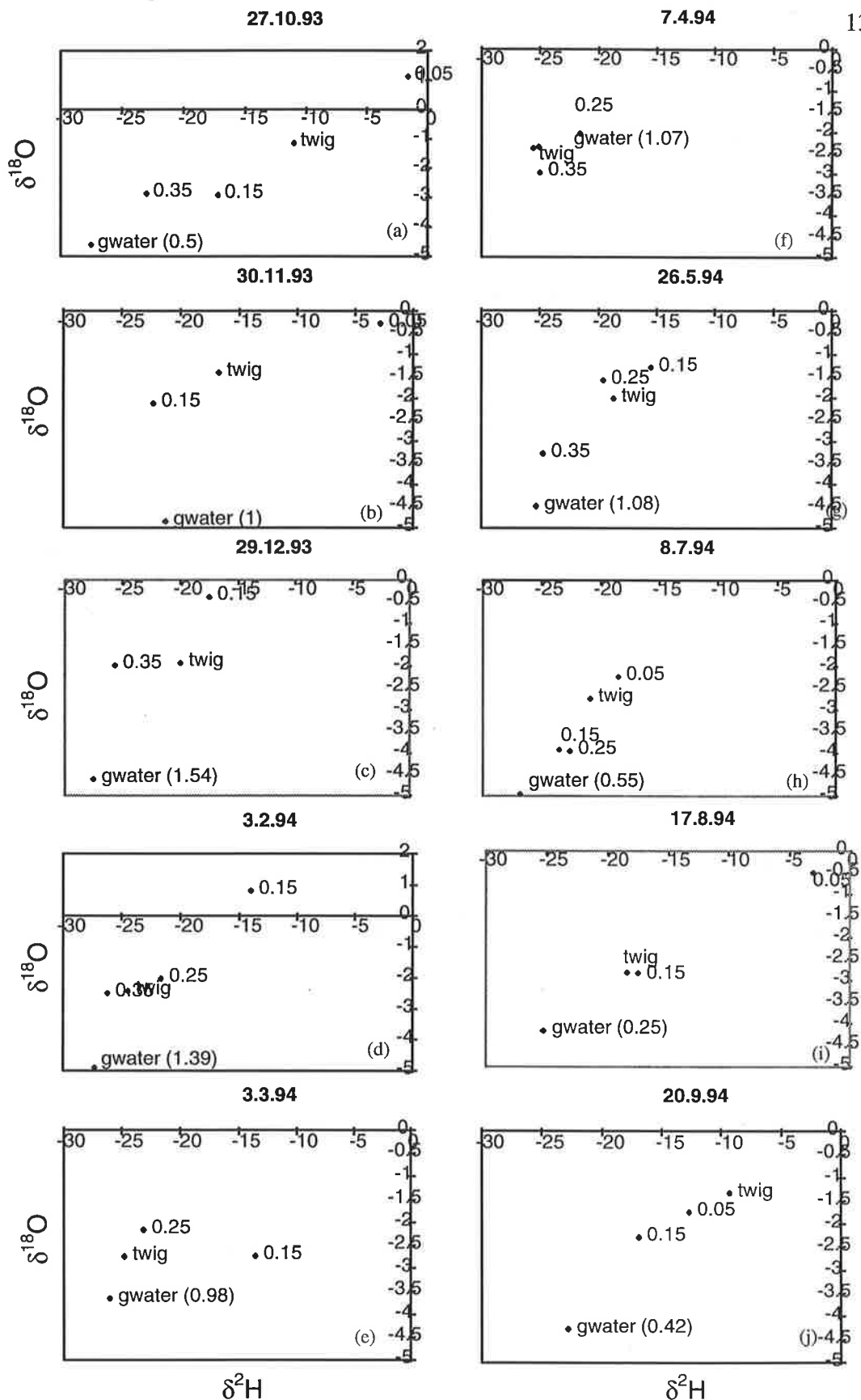


Figure 5.8: Plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for all twig, soil and groundwater samples taken at Hansons. Note the different scales for $\delta^{18}\text{O}$ (a and d).

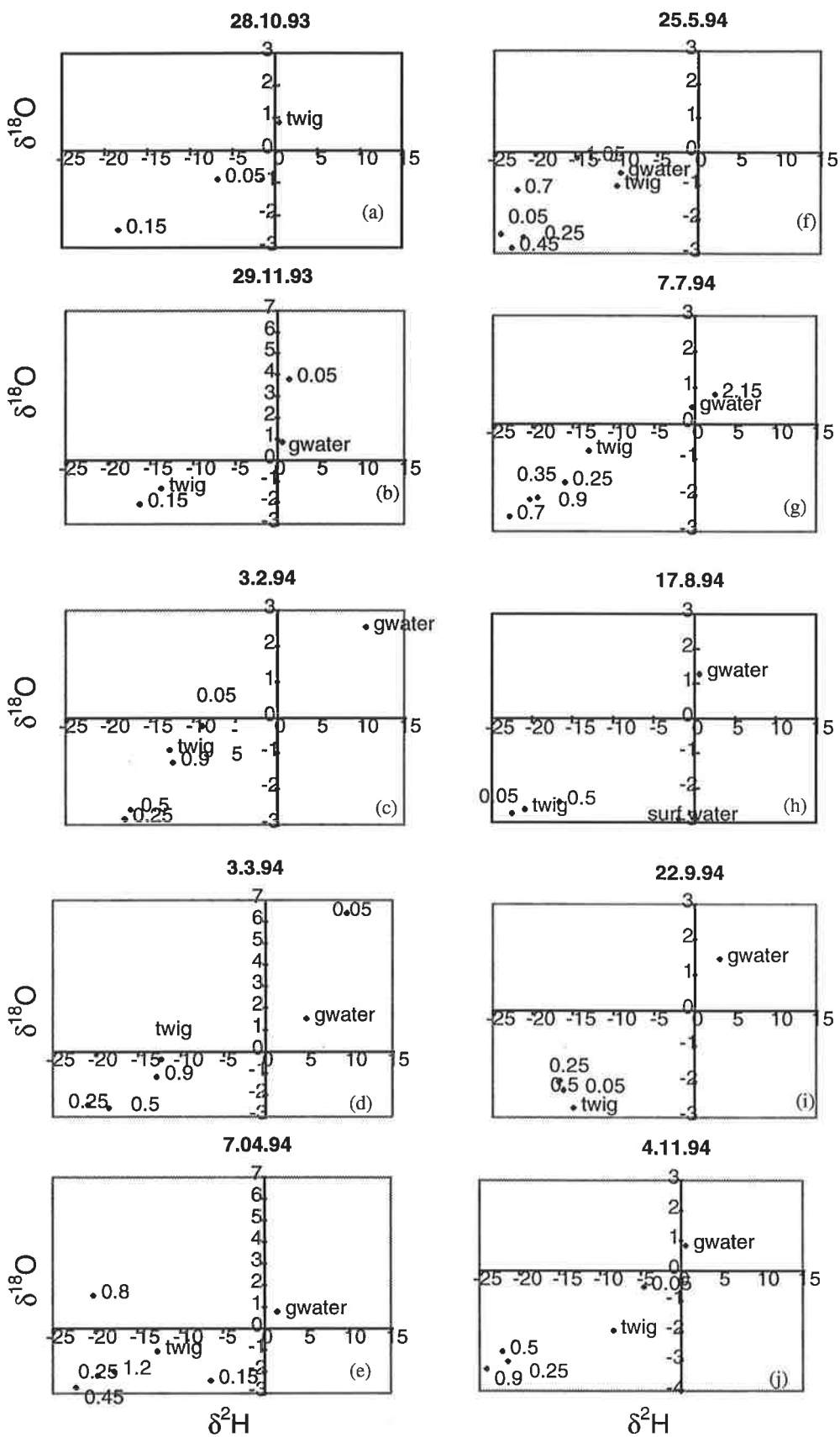


Figure 5.9: Plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for all twig, soil and groundwater samples taken at Jaffray. Note different scales for $\delta^{18}\text{O}$ (b and d).

5.3.2 Root mass measurements

At all sites, root densities were concentrated in the top 20 cm and then decreased with depth. The highest recorded root mass was 0.021 g cm^{-3} of soil at Lesron. Root mass was highest in the top 20 cm for trees at Lesron, next highest for Jaffray and then Duck Island and Hansons. However for the 20- 30 cm and 30-40 cm interval the root mass at Jaffray was higher than at the other sites with (Lesron, Duck Island and Hanson) which were all similar. Jaffray was also measured at a deeper interval again (50-70 cm) and significant roots were found (Fig 5.10).

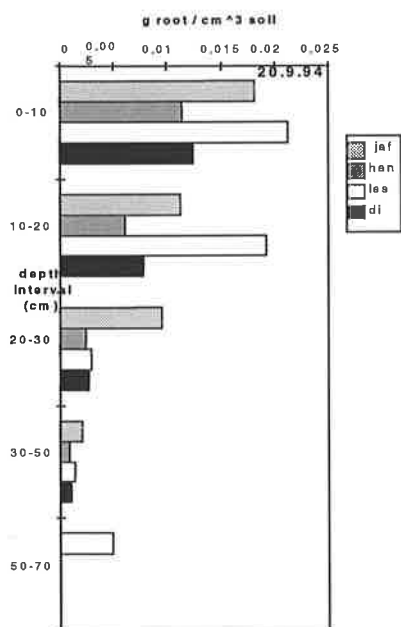


Figure 5.10: Root mass (g/cm^3) estimated from sampling of 6 soil cores at all sites on 20.9.94. Root mass was greatest in the top 0.2 m and then decreased with depth at all sites.

5.3.3 Root Observation

New root appearances were observed at Duck Island. The position of maximum new root growth was observed to proceed down the profile through the summer and autumn period (Fig. 5.11). There were few new roots during mid-winter sampling and most new root growth in early spring (September) was near the surface. By the end of spring sampling (Fig. 5.11) new roots began growing deeper in the profile as the water table dropped. New root growth during this period was partly from old roots.

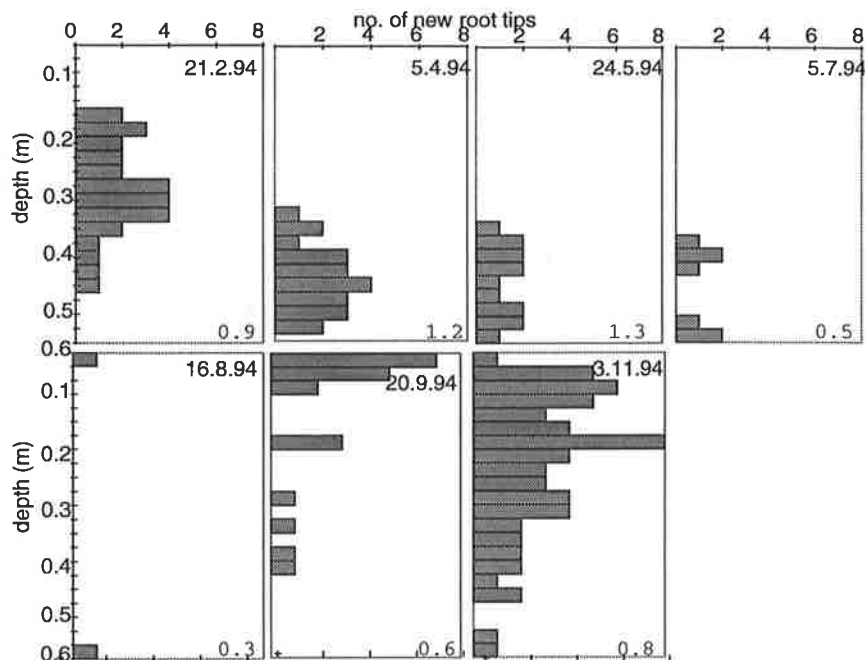


Figure 5.11: New root tip appearance at 7 times from February 1994 to November 1994 at an observation window placed next to a *Melaleuca halmaturorum* tree root system. Groundwater depth at each sampling time (m) is shown at the bottom of each Figure. New root tip appearance per depth interval increased at greater depths over the summer and then at shallower soil depths over the winter months.

5.4 Discussion

5.4.1 Interpretation of Sources of Water

The information from the stable isotopes was used to identify possible water sources (Table 5.1). If there was not a unique solution (ie the twig composition was between a number of possible sources) information on soil water availability was used to identify water sources that were unavailable for plant water uptake. This was combined with an interpretation of the soil profiles (from chapter 4) to conclude the pattern of water sources from each site.

At Duck Island during winter, results indicated that surface soil water was being used. At the end of winter groundwater was closer to the soil surface (0.3 m) and this combined with rainfall had caused the soil salinity in the unsaturated zone to be diluted resulting in high osmotic potential (closer to 0) in the surface soils. There were three kinds of evidence that water uptake was mostly from the top 0.1 m during winter. The first was the stable isotopic data where twig water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values were similar to a mixture of water sources from the 0-0.1 m depth and the 0.1-0.2 m depth (or the groundwater). No root growth was observed to occur in deeper regions during these times so it was assumed that water was

being drawn from 0-0.1 m and 0.1-0.2 m depths and mixed within the plant. Root observations were supported by root mass measurements during winter which showed a larger proportion of roots in the surface soil during this time. Supporting evidence came from the root chamber observations, where roots were shown to be actively growing in the top 0-0.1 m from the middle of winter to the end of winter 1994. The third set of evidence came from the water potential data where a return to high water potential at the end of winter reflected the return to high surface soil water potential mentioned above. Waterlogging was also prevalent with depth making it unavailable for water uptake. This water source in the surface soil was a combination of rainfall and groundwater, as in winter the groundwater rose to within 30 cm of the soil surface, and was thought to be at least 50% groundwater (Table 5.1 a).

At the end of summer, groundwater was deeper (1.2 m). Total soil water potential during this period was very negative in the surface soils due to the high soil salinities caused by evaporative concentration of the saline groundwater. The water sources were considered to be a mixture taken up from the surface soil and the groundwater (Table 5.1a). As with the winter data there were 3 kinds of evidence that water uptake was from deeper in the soil profile in summer. First, the stable isotopic data showed that twig water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were between surface soil values and groundwater but did not respond to fluctuations in surface soil values as in winter. A similar pattern was observed by McEwan et al (1994) for Duck Island in the previous year. As water was unavailable to plant use in the 0-0.1 m depth, the water sources were considered to be a mixture taken up from 0.2 m and the groundwater. Secondly, these results were supported by root observations which showed that the root growth was concentrated in the deeper parts of the soil profile during the summer sampling. The third line of evidence came from comparison of plant and soil water potential. Leaf water potential was usually between the surface soil and the groundwater as surface soil became more saline in the summer. However the leaf water potential often indicated shallower water sources than the stable isotopes, which may be a result of the large root biomass in the top 20 cm skewing the leaf water potential towards more negative soil water sources when it equilibrated overnight. Despite these discrepancies it was calculated that based on the closeness of the twig values to the groundwater as compared to the soil values during summer and autumn 60 to 100% of water used was groundwater. (Table 5.1a)

A similar result was concluded for Hansons Swamp as for Duck Island. During winter water sources were considered to be from the surface soils (Table 5.1b). The twig isotopic composition matched with this region and the water was available for water uptake in the

surface soils during winter. In addition, the mass of roots was highest in the surface soils when measured at the end of winter indicating that water uptake was probably dominated by surface soils activity. This site was visibly flooded for longer periods at the end of winter probably because of its lower elevation. Soil waterlogging was often indicated at 20-40 cm in the subsoils making these water sources unavailable for water uptake. However it was often not possible to take samples from soil below 40 cm, making it impossible to estimate the conditions below this depth. Waterlogging was not apparent during the middle of winter maybe as a result of (1) rainfall flushing the soils of reduced compounds, or (2) the groundwater was unusually oxygenated at this site and recharged the soil with oxygen when it rose. During winter the groundwater component of water in these surface soils was estimated to be 50 % (Table 5.1 b).

During summer, very low soil water potentials were often recorded at Hansons as a result of high salt masses in the soil surface combined with low moisture contents. As at Duck Island the isotopic composition of twig water was between a number of surface soil values and the groundwater. The unavailability of water in the surface soil interval of 0-0.2 m however meant that the surface soils of 0.2 to 0.4 m were often identified as water sources. The pre-dawn water potential also indicated uptake from the groundwater during summer but reached very negative values in the middle of summer when surface soils were most saline, indicating that there was still some connection with the surface soils. There was potential for more groundwater to be used at this site than at Duck Island as (1) groundwater was used for longer, (2) periods when soils water was used in conjunction with groundwater were less, and (3) twig isotopic values were closer to the groundwater values (ie deeper root activity). The root mass in the surface soil measured in winter was lower than at Duck Island. There may have been a greater mass of roots at depth at Hansons than at Duck Island that were not measured in this sampling (only to 40 cm). During summer the groundwater was mixed with soil water and the proportion that was groundwater ranged from 25% at the beginning of summer to 100% at the end of summer (Table 5.1 b).

Lesron indicated a different pattern of water sources than the other ephemeral swamps (Duck Island and Hansons). The isotopic composition of twig water rarely matched to soil water below 15 cm and trees at this site were therefore concluded to be taking most of their water from the surface at all times (Table 5.1 c). In conjunction with this the root mass measurements also showed a large mass of roots in the top 20 cm of the profile. The root mass was the highest measured for all sites and probably constitutes the majority of the root system which is concentrated in the top 20 cm of the soil.

Table 5.1: Water sources for each sampling time (depth interval; m) based on the isotope technique combined with information of soil water availability.

(a) Duck Island

Season	Date	Unavailable (salinity)	Unavailable (waterlog)
Spring	26.10.93		-
Early Summer	1.12.93	0-0.2	-
Early Summer	28.12.93		-
Late Summer	2.2.94	0-0.1	-
Late Summer	21.2.94	0-0.1	-
Autumn	6.4.94	0-0.1	-
Late Autumn	24.5.94		0.4-0.7
Winter	6.7.94		0.1-0.3
Late Winter	16.8.94		0.2-gwater
Early Spring	20.9.94		

(b) Hansons

Season	Date	Unavailable (salinity)	Unavailable (waterlog)
Spring	27.10.93		-
Late Spring	30.11.93	0-0.1	-
Early Summer	29.12.93	0-0.1	-
Late Summer	3.2.94	0-0.2	-
Early Autumn	3.3.94	0-0.1	-
Autumn	7.4.94	0-0.2	0.6-gwater
Late Autumn	26.5.94	0.1-0.2	0.2-gwater
Winter	8.7.94		0.2-gwater
Late Winter	17.8.94		
Early Spring	20.9.94		0.2-gwater

(c) Lesron

Season	Date	Unavailable (salinity)	Unavailable (waterlog)
Late Summer	1.2.94	0-0.2	-
Early Autumn	3.3.94	0-0.2	-
Autumn	5.4.94	0-0.1	0.2-gwater
Late Autumn	24.5.94	0-0.2, gwater	0.2-gwater
Winter	5.7.94	0.1-0.2	0.1-gwater
Late Winter	15.8.94	0.1-0.2, gwater	0.1-gwater
Early Spring	23.9.94	gwater	0.2-gwater
Summer	27.1.95	gwater	0.2-gwater

(d) Jaffray

Season	date	Unavailable (salinity)	Unavailable (waterlog)
Spring	28.10.93	0-0.1	-
Late Spring	29.11.93		-
Late Summer	3.2.94	0-0.3	-
Early Autumn	3.3.94	0-0.3	-
Autumn	7.4.94		0.5-1
Late Autumn	25.5.94		1.3-1.5
Winter	7.7.94		0.8-0.9
Late Winter	17.8.94		0-0.1
Early Spring	22.9.94		-
Late Spring	4.11.93		-

During winter, water was taken from the surface soils where soil water was most available and where waterlogging did not occur. Water taken from the surface soils during winter may have been comprised of up to 50 % groundwater because of the shallow groundwater during this time (Table 5.1 c). During summer, there were extremely high salinities in the surface soils and soil was also often waterlogged below 20 cm resulting in conditions of salinity combined with waterlogging in much of the profile. During summer, soil surface water was also being taken despite the high salinities in the surface soils (Table 5.1 c). Water was only taken from below 20 cm during the peak of summer when surface soils were most saline. During summer uptake from this surface soil source also included uptake of some groundwater (5-13%; Table 5.1 c). The lack of use of soil water and groundwater from deeper in the profile during summer seems to be associated with the apparent soil waterlogging and high salinities at depth. Consequently plant water potentials (Chapter 4) were observed to reach very negative values here probably because of the lack of ability to explore less saline soil away from the soil surface.

Jaffray showed a different pattern of root water uptake than the other sites. Interpretation of results from the end of summer when soils were the most dry and saline and the end of winter when rainfall had re-hydrated and freshened the surface soils provide information on plant responses to these soil conditions. During the end summer and the beginning of autumn when the water potential of surface soils were too low for water uptake, groundwater was used from deep in the profile (0.9 m) or mixed from a number of depths and the groundwater. Unique solutions of water sources were obtained with the isotope technique at the end of summer and autumn when the twig isotope values matched with the groundwater values and so primarily groundwater was used. At this site the isotopic composition of the groundwater was often high and similar to the surface soil values. This meant that the isotopic composition of twigs were often between a number of possible sources. However at times the surface soils were unavailable for water uptake and so the groundwater was considered the water source. During this time twig values always averaged -10 to -13 per ‰ $\delta^2\text{H}$. In conjunction with this, the pre-dawn plant water potential always matched with the deeper soil values, even when it was indicated that surface soil water was being used. They did not follow the water potential fluctuations in the surface soil as occurred at the other sites, despite fluctuations in the surface soil being large at this site through large changes in matric water potential. This was all evidence for deep rooting trees at this site. This was supported by root mass measurements which indicated high root masses at depth (Table 5.1d).

During the end of winter and early spring a unique solution was also found when twig isotope values matched with surface soil values (Table 5.1 d). Twig isotopic values matched with surface soils values and reached $-22\text{‰ } \delta^2\text{H}$ at one stage and $-15\text{‰ } \delta^2\text{H}$ at another with groundwater always remaining reasonably constant at $+1\text{‰ } \delta^2\text{H}$. At this time the values were closer to the soil values and furthest from the groundwater. The root density measurements supported water use from the surface soils and deeper soils during winter, as root mass was spread fairly evenly throughout the profile.

The groundwater depth at Jaffray did not fluctuate to the extent that it did at the other sites and so the salt that was discharged into the unsaturated zone appeared to remain constant unlike the other sites where it was flushed out of the soil during winter. Soil salinities therefore remained constant over the year and were higher than at Hansons during the winter, despite the lower groundwater salinity at Jaffray. Salt was accumulated fairly evenly throughout the profile supporting the theory of even uptake of water throughout the soil profile, however there was an obvious drying front above the groundwater indicating significant root activity in water uptake at depth. There was also an obvious concentration of salts above the water table at depth indicating groundwater discharge by roots. However the soil zones at the surface of the soil profile and above the groundwater often appeared lower in salinity as a result of rainfall (at the top) and groundwater fluctuations (at the bottom). These patterns of soil salinity and matric potential provide evidence for root activity at the two zones in the soil profile that are separated by a saline zone of soil (mid profile) and are preferred by roots as a result of annual flushing of salt by various processes (Table 5.1 d). Soil waterlogging was low at Jaffray although mid-profile samples were often found to be waterlogged. This did not seem to be associated with season, remaining constant over the year and may be associated with the very heavy clays that were found in the mid-profile of these soils.

5.4.2 Ecophysiological implications for *M. halmaturorum*

M. halmaturorum is able to adjust its root water uptake to the availability of soil water. At Duck Island and Hansons during summer *M. halmaturorum* switched to using saline groundwater in response to increased salinisation (and hence unavailability) of the surface soil water. This pattern of root water uptake is similar to that modelled by Thorburn et al (1995) where *Eucalyptus largiflorens* did not use water from the surface soils because it was too dry for water uptake. Groundwater of much higher salinity was used by *M. halmaturorum* than was recorded for *E. largiflorens* in the study of Thorburn et al (1993a).

fresher source of water (groundwater) is different than that observed for the red dwarf mangrove (Lin and Sternberg, 1994) where it was found that in a coastal fringe environment, when the groundwater was recharged by fresh imported water, mangroves continued to use saline water in the surface soil and did not respond by using fresh groundwater as surface soils became salinised over the dry season. This species may have had a shallow root system in response to permanently anaerobic sub-soils as opposed to *M. halmaturorum*, with its deeper and more extensive root system, which was able to adjust root water uptake to available water sources in a soil profile with a varying water table. At Lesron however during summer, water was not used from the subsoils as the soil profile became salinised and this was thought to be a result of soil waterlogging at depth. This inability to escape from accumulation of salt in the surface soil over summer resulted in very low leaf water potential (-12 Mpa) and a decline in health of *M. halmaturorum* at this site (Webb, 1993). Flexibility in root water uptake has been suggested to contribute to the survival of some plants that occur in tidal marshes, where use of deeper, fresher water sources has been hypothesised to produce a higher than expected water status in some plants (De Jong and Drake, 1981).

Some water uptake occurred from the surface soil in winter at all sites. This may be in response to freshening of the soil profile which occurred through a combination of winter rainfall and the subsequent groundwater rise which diluted stored salt in the unsaturated zone. This process is of obvious importance in maintaining the survival of trees at these sites. Salt accumulates in the unsaturated zone over the summer period as a result of groundwater discharge. However salt is prevented from long term accumulation to concentrations that would kill the trees by rainfall and the annual fluctuation of groundwater which redistributes salts in the soil and groundwater.

Responses of root water uptake to rainfall leaching of the surface soils in saline environments have been observed in other species. For example, *Eucalyptus* species which use saline groundwater during dry times have been observed to supplement this source with rainfall present in the surface soils during winter (Thorburn et al, 1993a; Mensforth et al, 1994). Lin and Sternberg (1994) did not observe this in the red mangrove as surface water was always used, but did observe an increase in fine root density in the soil surface when rainfall was high. Responses in water uptake of fresh flood waters have been observed in halophytes on the Dead Sea shores (Yakir and Yechiell, 1995). An isotopic model and data show that this is very likely because the freshest water occurs in soil macropores, which plants take up first (Emerman and Dawson, 1995). A response in water sources to rainfall freshening of the surface soils was also observed at Jaffray. Groundwater was used solely over summer but

when water becomes available in the surface soil it is used from the top of the salt front. It was suggested that a split (dimorphic) root system separated by an accumulation of salt in the middle of the soil profile, allowed a rapid response in water sources to changing water availability in the surface soil. Mensforth et al (1994) found evidence for a dimorphic root system in *Eucalyptus camaldulensis* where fresh water was used in response to rainfall and saline groundwater was used over summer.

Another explanation for the change in water source from groundwater to surface soil water at the end of winter may have been to avoid soil waterlogging in deeper regions of the soil resulting from rising groundwater. This process is likely to produce anaerobic conditions in the soil, a process often thought to explain the concentration of mangrove roots in the surface layers of the soil profile (Gill and Tomlinson, 1977). *M. halmaturorum* seedlings have been shown to be relatively insensitive to a variety of levels of soil waterlogging (van der Moezel et al, 1991) and flooding (Denton and Ganf, 1995). However new root growth was observed to occur above the water table in response to groundwater rise rather than rainfall freshening the soil profile (which occurred before the groundwater rose significantly) and roots did not survive for long below the groundwater. In addition water sources of trees at Lesron appeared to be controlled by waterlogging with no water uptake occurring from waterlogged soils.

There is also evidence that *M. halmaturorum* may be able to make these rapid adjustments in depths of root water uptake by the re-activation of dormant roots when conditions become suitable for water uptake. New root growth in the spring of 1994 recommenced from where it left off the previous summer with new root tips developing from old dormant roots indicating an adaptive response to this dynamic environment. This behaviour would require the maintenance of a mass of dormant roots in the soil matrix from which new roots can become active at the depth where water is available. This was evident in the higher root biomass measured in the surface soils in this study. A high root biomass has been observed for *Atriplex* species in response to high soil salinities, with the majority of the roots concentrated in the surface soils (Galloway and Davidson, 1993).

5.5 Summary and Conclusions

M. halmaturorum at each of the sites was reactive to changing soil water availability conditions. Surface soil water was used in winter in response to greater soil water availability in the surface soils and waterlogging in the subsoils in response to rising as groundwater rose. At Duck Island and Hansons, when soil water became unavailable during summer due to salt accumulation in the surface soils, trees used water from progressively deeper soil layers as the groundwater dropped and more salt accumulated in the soils. Where groundwater salinity was lower trees appeared to use more groundwater for longer. Where the subsoil was waterlogged for significant periods of time, water was used from the surface at all times and so there was an apparent decrease in the quantity of groundwater used. Where trees occurred in a permanent wetland as opposed to an ephemeral swamp and so groundwater was deeper and did not fluctuate to the surface, groundwater was used from deeper in the soil at most times but responded to rainfall apparently through the presence of a spatially separated dimorphic root system.

Chapter 6: Modelling and quantifying groundwater discharge.

6.1 Introduction

Results from the field studies outlined in the previous chapters indicate that *Melaleuca halmaturorum* has varying water use strategies depending on the conditions in the root zone. Water use strategies will influence the use of groundwater and the timing of the use of groundwater. These processes can be modelled to support conclusions from these studies and to assist in clarifying results, and to investigate hypotheses arising from these field studies. This chapter attempts to model the water use strategy and groundwater discharge by *M. halmaturorum* in these ephemeral swamps by using a simple model of root water uptake. This section brings together information from chapters 3-5 to identify the water use strategy for each of the ephemeral swamps (Duck Island, Hansons and Lesron), summarises this information into a general water use strategy for *M. halmaturorum* and then attempts to represent these processes with a simple analytical model.

6.1.1 Key results from each site.

(a) Duck Island

Groundwater at Duck Island had an average EC of 63 dS/m and rose to 30 cm below the surface at the end of winter, and dropping to 130 cm below the surface at the end of summer (Fig 4.3). Trees at Duck Island used groundwater from the soil surface at the end of winter after groundwater had risen and inundated the profile (Fig 4.3). As the groundwater dropped over the summer and salt accumulated in the surface soil, trees used water from deeper in the soil profile and so the proportion of groundwater increased (Fig 5.4). This progressive use of deeper water was made possible by the growth of new root tips from old dormant roots (Fig 5.1). Plant water potential reached values of -6 MPa allowing uptake from saline soils (Fig 4.6). The amount of groundwater used by trees at Duck Island was dependent on the transpiration rate and the rooting depth. Trees used up to 2 mm/day of water in summer when groundwater use was at its highest and used ~0.8 mm/ day of water in winter when the groundwater was closest to the surface and when rainfall was also highest in the surface soils (Table 3.3). The transpiration rate was multiplied by the proportion of groundwater that was thought to be in the water source to quantify the groundwater use (ie Thorburn et al , 1993a). The proportion of water that was groundwater was estimated as 30 to 80% depending

on the depth of water uptake and the total amount of groundwater used for the year was 276 mm (Table 6.1 a).

(b) Hansons

Groundwater salinity was lower at Hansons (average of 14 dS/m) than at Duck Island but groundwater fluctuations were similar with groundwater rising to 15 cm below the soil surface at the end of winter and dropping to 120 cm at then end of summer (Fig 4.3). As at Duck Island root water uptake was from the surface soil at the end of winter in response to groundwater rise and was from deeper in the profile over the summer as the groundwater dropped (Fig 5.4). However the majority of root water uptake at the end of summer appeared to be from deeper in the soil profile than at Duck Island (Fig 5.4). Although these fluctuations in groundwater depth and tree water sources were similar to the other sites, soil salinity reached higher concentrations in the surface soil over summer at Hansons probably as a result of the higher transpiration rates found at this site (Fig 4.5). The minimum plant water potential observed was -3 MPa and this was higher than that observed at Duck Island (Fig 4.6). However the groundwater salinity at Hansons was significantly less that at Duck Island (Fig 4.3). The transpiration rate per m² of leaf area was the same as for trees Hansons as at Duck Island but there was a higher leaf area index at Hansons (Table 3.2). Trees used up to 3.5 mm/day of water in summer when groundwater use was at it's highest and used ~1.5 mm/day of water in winter when the groundwater was closest to the surface and when rainfall was also highest in the surface soils (Table 3.3). The proportion of water that was groundwater was estimated as 50 to 100% depending on the depth of water uptake and the total amount of groundwater used for the year was ~600 mm (Table 6.1 b).

(c) Lesron

At Lesron groundwater salinity was higher than at Duck Island (average of 70 dS/m) and in addition to this soils at Lesron were much more waterlogged (Fig 4.3). Groundwater depth however fluctuated to the same extent as at Duck Island, coming to 15 cm within the surface at the end of winter and then falling to 150 cm over the summer (Fig 4.3). Water sources were at the surface at the end of winter in response to rainfall and groundwater rise as at the other sites but differed from the other sites over summer being concentrated in the soil surface 20 cm at all times despite salt accumulation over summer (Fig 5.4). This was reflected by the root distribution in addition to observations of large roots in the surface soil at all times. This was thought to be a result of waterlogged soils at depth. The use of water

Table 6.1: Quantity of groundwater used (G; mm) for each month as determined by the % of groundwater use at each sampling time and the monthly transpiration.

Duck Island

Season	date	% gwater	T (mm)	G (mm)
Spring	Oct.93	50	52.3	26.2
	Nov.93	30	51.3	15.4
	Dec.93	70	47.3	33.1
summer	Jan.94	80	40.4	32.3
	Feb.94	80	38.9	31.2
	Mar.94	60	31.7	19.0
Autumn	Apr.94	60	32.4	19.5
	May.94	80	31.2	25.0
	Jun.94	60	32.7	19.6
Winter	Jul.94	50	32.1	16.1
	Aug.94	50	35.7	17.8
	Sep.94	50	42.2	21.1
Total				276.4

Hanson

Season	date	% gwater	T (mm)	G (mm)
summer	Nov.93	60	77.7	46.6
	Dec.93	50	117.4	58.7
	Jan.94	75	67.5	50.6
	Feb.94	80	93.6	74.9
	Mar.94	100	89.2	89.2
Autumn	Apr.94	90	75.9	68.4
	May.94	80	66.3	53.0
	Jun.94	50	57.7	28.8
Winter	Jul.94	50	55.0	27.5
	Aug.94	50	61.7	30.8
	Sep.94	50	59.9	29.9
Spring	Oct.94	50	64.9	32.5
Total				591.0

Lesron

Season	date	% gwater	T (mm)	G (mm)
summer	Nov.93	0	18.6	0
	Dec.93	0	24.1	0
	Jan.94	15	23.2	3.5
	Feb.94	10	21.4	2.1
	Mar.94	12	22.6	2.7
Autumn	Apr.94	10	21.5	2.1
	May.94	5	18.5	0.9
	Jun.94	0	19.2	0
Winter	Jul.94	0	19.5	0
	Aug.94	0	17.7	0
	Sep.94	0	18.5	0
Spring	Oct.94	0	22.1	0
Total				11.4

from the surface soils meant that roots were unable to escape the accumulation of salt, and low plant water potentials (to -12 MPa) were observed in trees at this site (Fig 4.6). It was considered from the stable isotopes that up to 50 % of water used could be groundwater at the end of winter, but over the summer 0 to 5 % of water used was groundwater as groundwater became deeper. Transpiration rates at Lesron were lower than at Duck Island and leaf areas were only slightly lower (Table 3.2). The transpiration rates were estimated to be 0.7-0.9 mm/day (Table 3.3) and groundwater use as a proportion of this was estimated at 26 mm/year (Table 6.1 c).

6.1.2 General water use strategy

There are a number of conclusions that can be drawn from examining the water use strategies of trees at the Duck Island, Hansons, and Lesron sites which all vary in their environmental conditions but are similar in their hydrology (ephemeral swamps). These are summarised in Figure 6.1. At the end of winter groundwater rose, inundating the soil profile and the roots responded to this by coming to the surface. Water was sourced from the surface first and then deeper in the soil profile over the year as groundwater fell and salt accumulated towards the soil surface. Roots responded to changing soil water availability by the growth of new root tips. Where waterlogging occurred water sources did not respond to salt accumulation the surface soils because of unavailability of water at depth. The amount of groundwater used was dependent on the transpiration rate which in turn was dependent on the leaf area which appeared to equilibrate with the soil (groundwater) salinity at each of the sites. The leaf area index was a function of groundwater salinity. Stomatal control was limited and the trees always appeared to have low stomatal conductance. Leaf water potential decreased with groundwater salinity and appeared to define the threshold to water uptake. The amount of groundwater used increased as the groundwater salinity decreased. This was a result of higher transpiration rates and the ability to root deeper and so use more groundwater for more of the year.

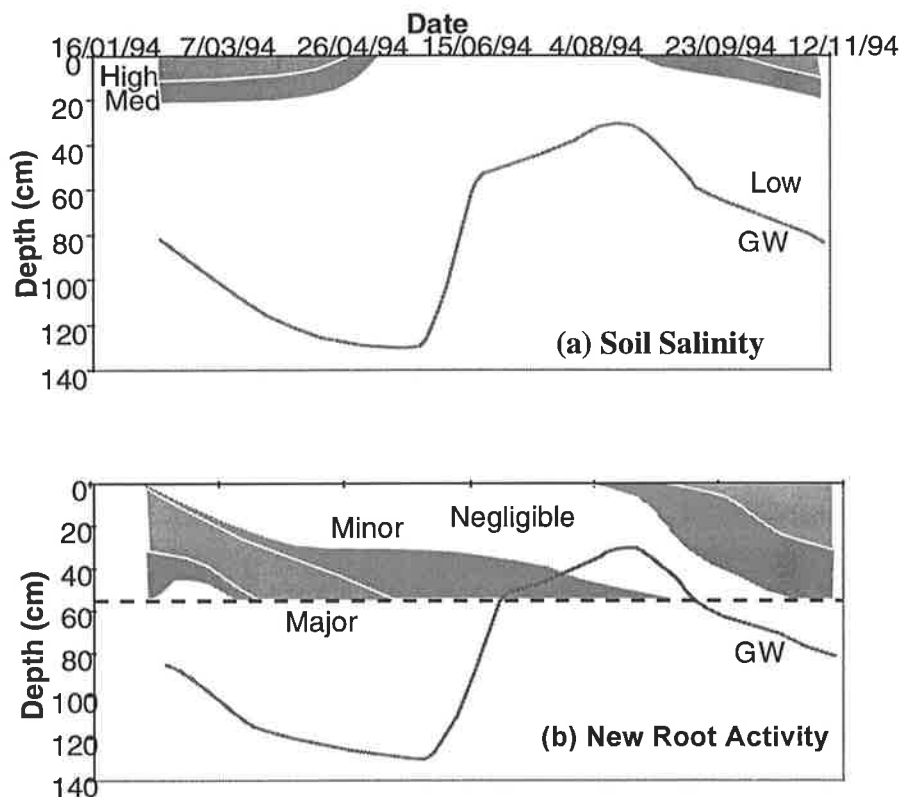


Figure 6.1: Water use strategy; Soil salinity (a) and new root appearance (b) over the year for *Melaleuca halimifolia* at Duck Island. GW indicated the groundwater depth and the dotted line in (b) indicates the limit at which data was taken.

These conclusions form the basis for a general quantitative model of tree water use in these saline swamps, with the information and concepts developed from the field studies. Components of this model are then used in water balance calculations to predict the role of *M. halimifolia* in groundwater discharge.

6.2 Modelling

6.2.1 Modelling groundwater discharge

Groundwater use by trees will influence the water balance as represented by T in;

$$G_{net} = (E + T + D) - (R + L) + \Delta S \quad (1)$$

Where G_{net} is net groundwater discharge (mm), E, T and D are evaporation, transpiration and drainage respectively (mm), R is recharge (rainfall+ flooding, mm), L is aquifer upward leakage mm, and ΔS is the change in soil water storage (Table 6.2). Groundwater use by trees will result in a long term drop in groundwater levels if the groundwater use results in net groundwater discharge. Net groundwater discharge may also result in an increase in salinity if the groundwater is saline. Therefore to understand the role of groundwater discharge by trees on the water balance it is necessary to quantify the other components of the water balance.

Table 6.2: Description of all parameters discussed in chapter and used in the model their definition and dimensions.

Parameter	Definition	Dimensions
E	Evaporation	mm/day
T	Transpiration	mm/day
ET	Evapotranspiration	mm/day
D	Drainage	mm/day
R	Recharge (infiltrated rainfall and flood waters)	mm/day
L	Upward leakage	mm/day
S	Soil water storage	mm/day
G	groundwater discharge	mm/day
G net	net groundwater discharge	mm/day
calc G _T	estimated transpirational groundwater discharge	mm/day
calc G _E	estimated evaporational groundwater discharge	mm/day
Z _{th}	depth of salt front	cm
Z _{gw}	depth of groundwater	cm
Z _{root}	depth of root water uptake	cm
C _{th}	Salinity threshold to water uptake	mg/L Cl or MPa
C _{gw}	Salinity of groundwater	mg/L Cl or MPa
θ _w	wet soil water content	dimensionless
θ _d	dry soil water content	dimensionless
S _y	specific yield	dimensionless
l	leakage factor	mm/day/cm of head difference
P	head pressure difference	cm
A	soil conductivity	
n	soil constant	dimensionless
f	fraction of soil water used	dimensionless

Groundwater discharge by trees is influenced by groundwater salinity (Passioura et al, 1992; Thorburn et al, 1993a; Smith et al, 1995), groundwater depth, with more water being supplied from shallow water tables than deep water tables by capillary upflow, (Talsma, 1963; Meyer et al, 1990) and soil type, through an influence on rooting depth and the rate of flow of water from the groundwater to the roots (Gardner, 1960). Groundwater discharge by trees has been found from 0.1 mm/day to 2 mm/day depending on groundwater salinity, groundwater depth and soil permeability (Thorburn et al, 1993a). Capillary upflow from shallow saline groundwater in lysimeters was thought to be dependent on rooting depth, soil conductivity, and groundwater salinity (Smith et al, 1995).

Groundwater discharge will also be influenced by the water use strategy of the plant. The quantity of water that is able to be used by the plant may be determined by the ability to maintain leaves under adverse conditions. Groundwater use by tall wheat grass was found to be lower than expected as a result of the senescence of the plant over the summer when

groundwater discharge would have been the highest (Bleby et al, 1996). The amount of groundwater discharge in tree species has been suggested to be limited by the physiological limits to water uptake (plant water potential) (Passioura et al, 1992; Thorburn et al, 1993a). Root response to adverse conditions may also influence the ability of plants to use groundwater with the ability to maintain deeper roots resulting in higher rates of groundwater uptake from saline watertables (Smith et al, 1995).

Groundwater discharge is often estimated through direct or indirect techniques. Examination of the change in groundwater depth (piezometric) during times of little rainfall has been used to estimate groundwater discharge by agroforestry plantations (George, 1991). The examination of the change in chloride mass in the unsaturated zone over time has also been used to estimate groundwater discharge as the only source of salts in the soil profile is from the groundwater (ie Talsma, 1963). Lysimeters have also been used to examine the amounts of groundwater used by plants (ie Smith et al, 1995). However in environments where the amounts of water used are small but may make big differences in the groundwater balance (ie in shallow groundwater systems) groundwater discharge may not be able to be measured by these traditional techniques and direct estimates of groundwater use by trees may be more useful (Thorburn et al, 1993a). This was the approach taken in the present study where the combination of measurements of transpiration and water sources were used to estimate the quantity of groundwater used by *M. halmaturorum*.

Groundwater discharge has also been estimated through modelling. Models can also provide insights into the processes affecting groundwater discharge. Simple water balance models have been used to estimate net groundwater discharge where actual evapotranspiration is known using equation 1. The resulting groundwater depth as a result of evapotranspiration is;

$$\frac{dZ_{gw}}{dt} = \frac{(G_{net} - L)}{S_y} \quad (2)$$

where Z_{gw} depth to groundwater (cm), G_{net} is the net groundwater discharge (cm), S_y is the specific yield, and L is the upward leakage.

Where groundwater discharge from water tables is to be predicted there are models which simulate groundwater discharge based on theory of evaporative discharge from shallow saline groundwater tables under steady state conditions. One form of this that has been

used to estimate evapotranspiration from bare soil (e.g. Talsma, 1963; Thorburn et al, 1992; Jolly et al, 1993) is

$$G_E = \frac{A}{Z_{gw}^n} \quad (3)$$

where G_E is evaporative groundwater discharge, Z_{gw} is the depth of the groundwater, and A and n are related to the permeability of the soil (Gardner, 1958; Talsma, 1963; Warwick, 1988). Evaporation is limited in the early stages by external conditions and as the watertable drops the evaporation rate is dependent on the depth to groundwater and the capillary conductivity (Gardner, 1958).

Where plants occur the zone of water uptake is not so easily defined. Modelling plant water uptake is generally based on numerical solutions to the Richards equation from a distributed sink of roots (e.g. Gardner, 1991; Landsberg and McMurtrie, 1984; Barataud et al, 1995). Alternatively, in some systems where water availability is limited by salinity, some workers have simplified the assumptions of rooting depth to uniformly distributed roots (Passioua et al, 1992) or roots distributed in a narrow plane above a region of salt accumulation (Thorburn et al, 1995).

Thorburn et al (1995) used theory described in equation 3 to estimate evapotranspiration from a shallow water table treating the rooting depth (Z_{root}) as the soil surface;

$$G_T = \frac{A}{(Z_{gw} - Z_{root})^n} \quad (4)$$

where G_T is transpirational groundwater discharge, and Z_{root} is the rooting depth (cm). This was incorporated into a model of tree groundwater use using the water balance (as above) with a salt balance to define the rooting depth. Key aspects of this model were (1) groundwater discharge by trees caused salt to accumulate above the water table resulting in the progressive change in water sources to shallower depths and (2) the extent of salt accumulation was determined by the threshold to water uptake as indicated by the minimum plant water potential.

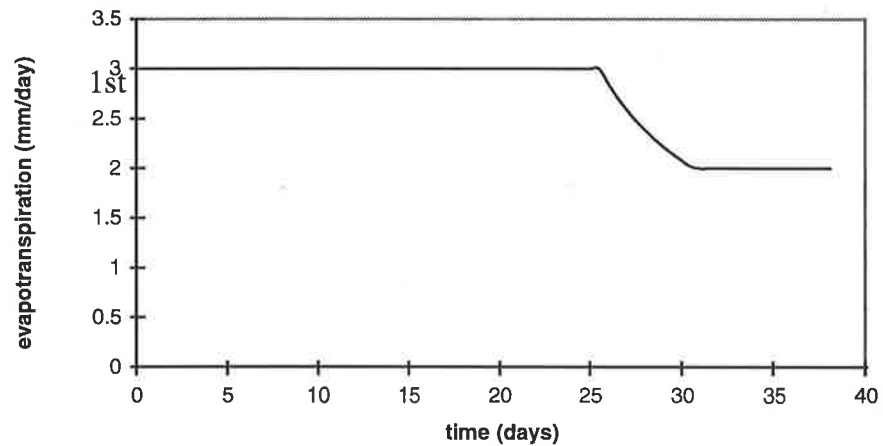
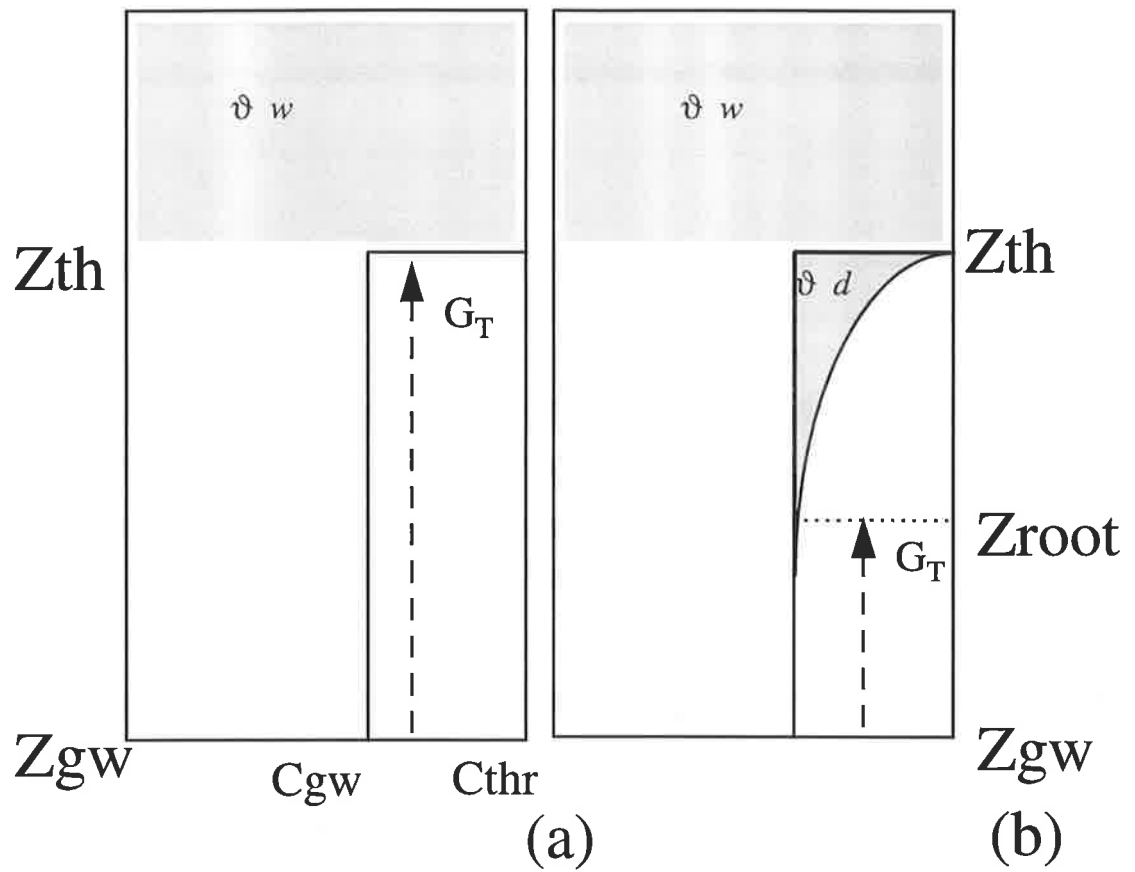
The present study involves a model of groundwater uptake by roots that is based on this theory. It predicts groundwater depth and rooting depth (salt front), and net groundwater

discharge from measured transpiration and rainfall data, and contributes to an understanding of the controlling processes on the water use strategies of these trees.

6.2.2 Model Assumptions

An analytical model was developed to theoretically describe the processes of groundwater uptake by *M. halmaturorum* over the groundwater draw down period from the end of winter to the end of summer (Fig 6.1 a). The model was also used to predict groundwater depth and rooting depth for sites Duck Island, Hansons, and Lesron over a 1 year sampling period where transpiration and rainfall were known. The model is based on the concept that roots will always take up water from the shallowest depth where it is available for plant water uptake. At the end of winter roots are initially at the soil surface. Root water uptake then progresses down the soil profile over the summer period when rainfall is minimal in response to progression of the *salt front* (Z_{th}) and the *groundwater table* (Z_{gw}) (Fig 6.1 a). These two entities are modelled. The assumptions behind the model are:

- The transpiration rate is constant and is dependent on the leaf area index. Stomatal control is thought to be insignificant at this scale of investigation.
- Groundwater discharge by trees is dependent on the distance between the roots and the watertable.
- Initial conditions are when the roots are at the soil surface at the end of winter (Z_{root}). The assumption is made that root water uptake is at the surface at this time as a result of groundwater depth (Z_{gw}) being at the soil surface.
- Root water uptake is responsive to soil water availability and will occur from the shallowest depth where water is available (Z_{th}) (Fig 6.1 a). Where waterlogging occurs the depth of root water uptake is limited to shallow soils by the presence of waterlogged soil at depth.
- Soil water availability is limited by salinity. There is an upper limit (C_{th}) to which roots can extract water from the groundwater (C_{gw}) and this is determined by the soil and plant water potential. The groundwater salinity is set at a constant value (C_{gw}) for the modelling exercise. The relationship between C_{th} and C_{gw} determines the transpiration rate. Where the relationship between C_{th} and C_{gw} is unable to satisfy the transpiration rate, at lower groundwater salinity, an alternative hypothesis is suggested where mining of soil water occurs to substitute groundwater uptake and a new rooting depth is determined (Z_{root}).



(c)

Figure 6.2: Schematic diagram of model theory for the basic model (a) and the model incorporating soil drying (θ_d ; (b)) as described in section 6.2.3. The relative positions of the salt front (Z_{th}) and the groundwater (Z_{gw}) are indicated, as are the concentration of the groundwater (C_{gw}) and the threshold to water uptake (C_{thr}). The evapotranspiration used as groundwater discharge (c) in model calculations incorporates 3 stages, stage 1 soil evaporation driven by PET, stage 2 driven by calculated evaporation, and stage 3 driven by transpiration (G_T in (a) and (b)).

6.2.3 Model Theory

A description of the various parameters used in the modelling exercise are shown in Table 6.1. A water balance indicates that the drop in the groundwater table is determined by equation 2;

$$\frac{dZ_{gw}}{dt} = \frac{(G - L)}{S_y}$$

where Z_{gw} is the depth to groundwater (cm), G is the groundwater discharge (cm), L is leakage, and S_y is the specific yield. Leakage was estimated by the difference of the groundwater depth from a known groundwater depth where leakage did not occur multiplied by the leakage factor (Table 6.2).

The salt balance indicates that the movement of the salt front (Z_{th}) is determined by;

$$\frac{dZ_{th}}{dt} = \frac{G * C_{gw}}{\theta_w * (C_{th} - C_{gw})} \quad (5)$$

where Z_{th} is the depth of the salt front (salt concentration above the threshold to water uptake) in cm, G is the groundwater discharge (mm), t is time, C_{gw} is the salinity of the groundwater and C_{th} is the salinity of soil at the threshold to water uptake. The rate at which salt is accumulated is determined by the threshold at which the soil water becomes unavailable (C_{th}). The ratio of C_{th} to C_{gw} (the concentration of salt in the groundwater) will determine how fast the salt accumulates in the unsaturated zone.

Where after preliminary modelling it was considered that not all water was being used from the groundwater (see “calc G_T ” next section), and some was being mined from the soil water a new rooting depth (Z_{root}) was calculated where;

$$\frac{dZ_{root}}{dt} = \frac{C_{gw} * fG}{(C_{thr} * \theta_d) * (\theta_w * C_{gw})} \quad (6)$$

Where Z_{root} is the new rooting depth (as opposed to Z_{th}), C_{gw} and C_{th} are as previously defined, G is the previously estimated transpirational groundwater discharge for the period, f is the fraction of G that is groundwater and is set at 1 initially;

$$f = \frac{A}{(Z_{th} - Z_{gw})^n \cdot G} \quad (7)$$

and θ_d is the water content of dry soil.

$$\theta_d = \frac{C_{gw} * \theta_w}{(1 - f) * C_{thr} + (C_{gw} * f)} \quad (8)$$

Through this process the rate at which the salt front moves down is increased through an effect of the previously modelled groundwater discharge combined with the concentrating effect of plant roots below this depth (ie the use of soil water) as shown in Fig 6.1 (b).

For the preliminary simulations the groundwater discharge (G) was set (see assumptions) at 3 stages (Fig 6.1 c). When the groundwater table is at the surface the groundwater discharge is set at the rate of PET (stage 1). As the groundwater drops the potential rate of groundwater discharge from the soil surface decreases (stage 2) as determined by equation 3. When this value falls below the set transpirational groundwater discharge (G_T) it is considered that the transpirational groundwater discharge (G_T) becomes dominant (stage 3 groundwater discharge) and this is set as G . For the monthly groundwater discharge calculations G was determined by a summarised version of equation 1;

$$G = T - R \quad (9)$$

where T is measured transpiration (mm) and R is measured rainfall (mm).

6.2.4 Model Validation and Quantifying G_{net}

The model was run on a "Microsoft Excel" Spreadsheet. The groundwater discharge is dependent on the distance between Z_{th} and Z_{gw} at any point in time (equation 4) we can estimate the amount of groundwater that can possibly be discharged from the groundwater to tree roots based on the estimates of Z_{gw} and Z_{th} ;

$$calcTg = \frac{A}{(Z_{gw} - Z_{th})^n} \quad (10)$$

where A and n are constants associated with soil permeability (Warrick, 1988). Therefore the model was considered to be calibrated correctly if this estimated potential transpirational groundwater discharge (calc G_T) was equal to or greater than the measured transpirational groundwater discharge.

For the water balance calculations the calculated drop in groundwater depth was compared to the actual measured groundwater depth to test the accuracy of the predictions. Also for each of these times the depth of the salt front was compared to rooting depth and estimated water sources at each site. Groundwater discharge and % groundwater used was estimated for each month from (1) the water balance (2) the isotope partitioning of the transpiration and (3) the model calculations. For each month the net groundwater discharge, as estimated from field measurements in conjunction with the model validation, was calculated from the water balance estimations combined with estimates of rainfall as per equation 1 but only taking into account transpiration in the evapotranspiration component;

$$G_{net} = (T + D) - (R + L) + \Delta S \quad (11)$$

where G is groundwater discharge (net and actual), T is transpiration, R is rainfall, S is soil water storage, L is upward leakage and D is drainage (not considered).

6.2.5 Model Parameters

From the field investigations of tree water use, transpiration (T mm/month) was identified for each site (chapter 3). Total rainfall was also calculated for each month from weather station data (Appendix 2). Where it was considered that T overestimated groundwater discharge a partitioned flux was used (chapter 3 and 5) as T . For the drawdown simulations of Z_{gw} and Z_{th} , the groundwater depth (Z_{gw}) and threshold depth (Z_{th}) was initially set at the soil surface (Table 6.3). Simulation of Z_{gw} and Z_{th} from the field data occurred during two groundwater drawdown periods end of winter 1993 and 1994 and one period of groundwater rise. During the period of groundwater rise, Z_{gw} was initially set at the maximum groundwater depth recorded (Table 6.3). For the periods of drawdown they were considered to be extension of one another and the initial Z_{gw} was the minimum groundwater depth calculated during the groundwater rise simulations. Z_{th} was set initially at the surface during the groundwater draw down simulations and was not simulated during the groundwater rise but was considered to be at the top of the groundwater (or at the maximum depth calculated if $<$ groundwater depth) and then at the surface during the

periods of groundwater rise (recharge) (Table 6.3). Where it was observed that roots did not take water from below a given depth (as at Lesron) Z_{th} was set at this depth once it was reached.

Specific yield, leakage and various soil parameters (A and n; Warrick, 1988) are indicated in table 6.3. Specific yield and water content (θ_g) were estimated from soil water content data (Appendix 6). For the calculation of Z_{th} , C_{th} and C_{gw} for each site was estimated from the average groundwater salinity at the site and the minimum plant water potential that was observed.

Table 6.3: Values of model parameters used for each of the sites

Parameter	Duck Island	Hansons	Lesron
S_y	0.1	0.13	0.13
G_T	1	1.8	0.1
θ_d	0.3	0.3	0.4
P	30	10	30
l	0.0097	0.012	0.0097
C_{gw} (mg/L) Cl	28500	9000	42000
C_{gw} (MPa)	-3.7	-1.2	-5.4
C_{thr} (mg/L) Cl	77800	77800	77800
C_{thr} (MPa)	-10	-10	-10
G_{ET}	3	3	3
n	3	3	3
A	512000	612000	612000
initial Z_{gw}	0	0	0
initial Z_{thr}	0	0	0
initial Z_{gw} - field sim	110	110	110
initial Z_{thr} - field sim	0	0	0

6.3 Results

6.3.1 Duck Island

Theoretical modelling simulations for Duck Island indicated that during the drawdown period with an average transpiration rate of 1 mm/day resulted in groundwater depth (Z_{gw}) decreasing rapidly from day 0 to day 30 and then decreased more slowly from day 30 to day 250 reaching a maximum of 125 cm depth at day 250 (Fig 6.3 a). The depth of the salt front (Z_{th}) decreased linearly after day 30 reaching a maximum depth of 58 cm at day 250. The potential transpirational groundwater (calc G_T) decreased exponentially as groundwater dropped reaching a minimum of 1 mm/day at day 150 and then increasing gradually as the distance between the groundwater and the salt front decreased (Fig 6.3 a).

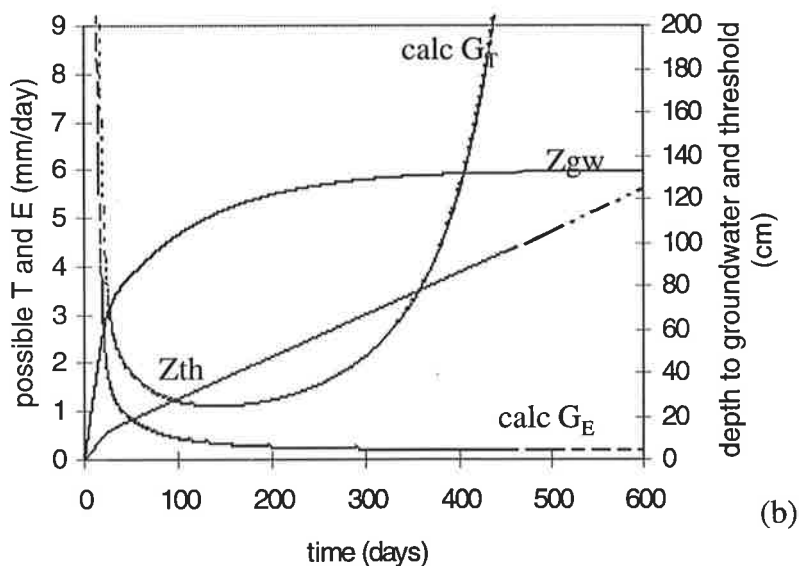
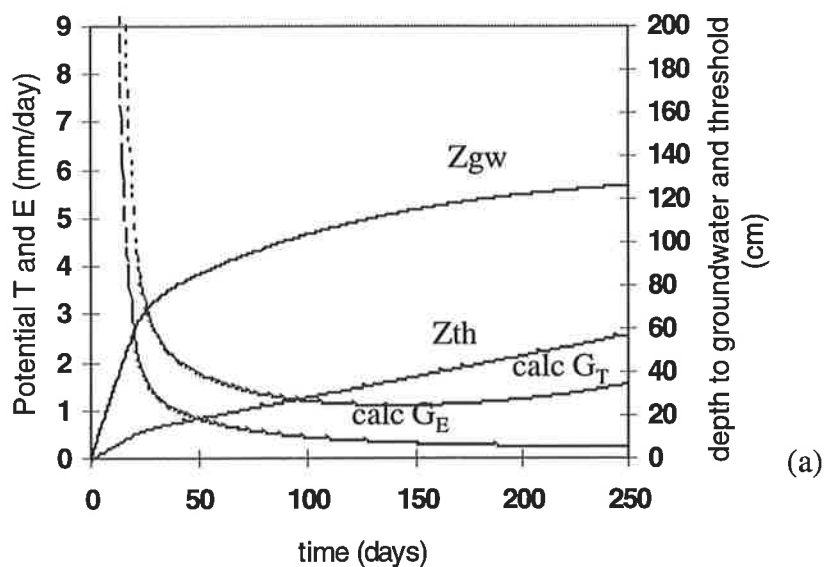


Figure 6.3: Groundwater depth (Z_{gw}), threshold depth (Z_{th}) and groundwater discharge simulations (calc G_T and G_E) for Duck Island for 250 days (a) and long term simulation until Z_{th} reaches the groundwater Z_{gw} (b).

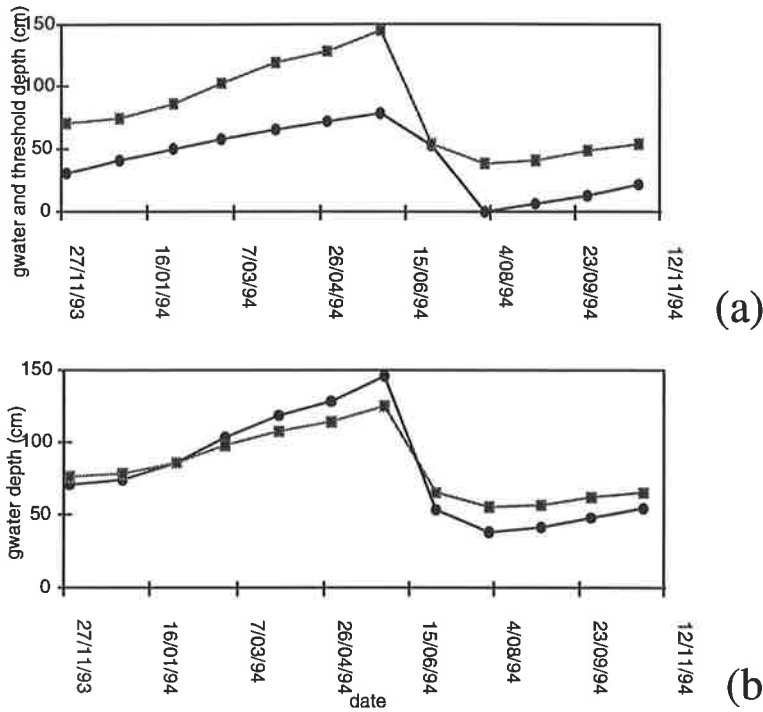


Figure 6.4: (a) Estimated groundwater depth (Z_{gw} ; ■) and threshold depth (Z_{th} ; ●) for Duck Island. (b) Estimated groundwater depth for Duck Island with a specific yield of 0.5 (■) and 1.3 (●).

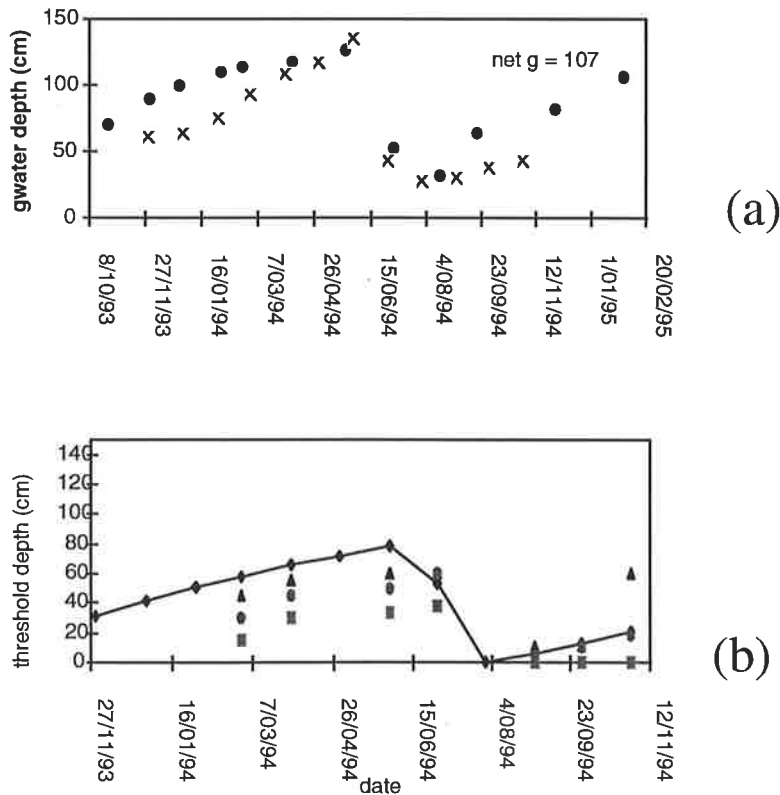


Figure 6.5: (a) Estimated groundwater depth (Z_{gw} ; X) and observed groundwater depth (●) for Duck Island. (b) Estimated threshold depth (Z_{th} ; ◆) and new root appearance at the observation window (From Fig 5.11). The maximum depth of root appearance (▲), minimum depth (■) and depth of maximum new root appearance (●) is indicated.

The time for the entire soil profile to reach the salinity threshold (Cth) was calculated as the time without groundwater fluctuations for which the trees would survive. For Duck Island this occurred at day 600 (Fig 6.3 b).

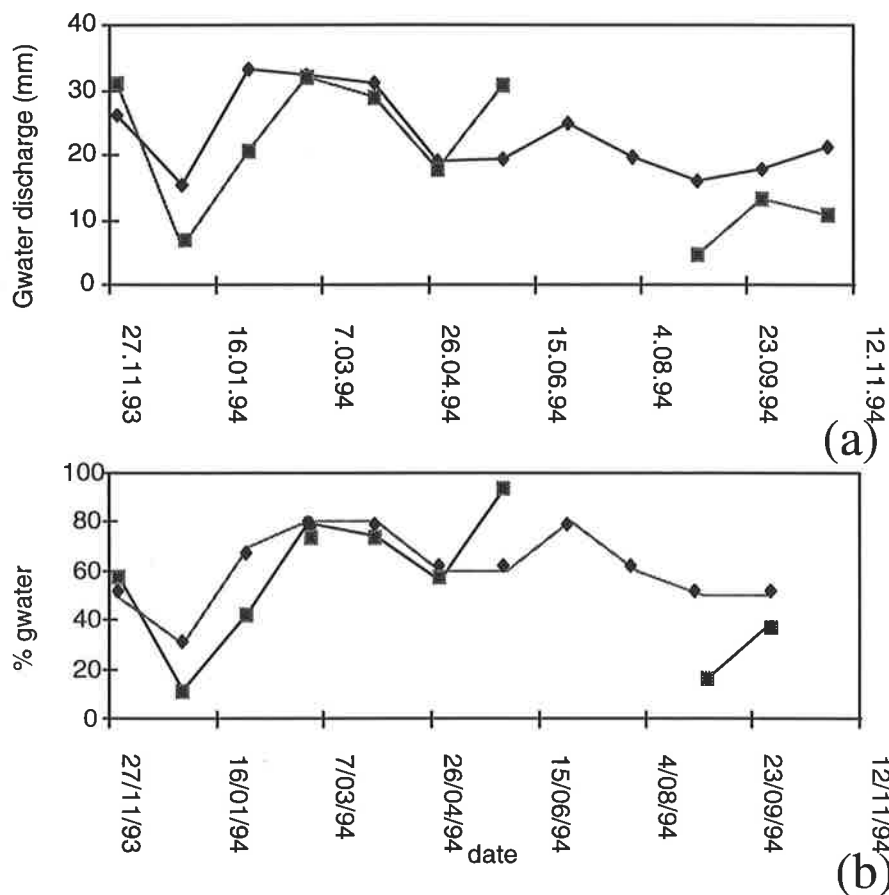


Figure 6.6: Estimated groundwater discharge (a) and % of groundwater used (b) for Duck Island as indicated by the stable isotope partitioned transpiration (◆) and the water balance calculations (■).

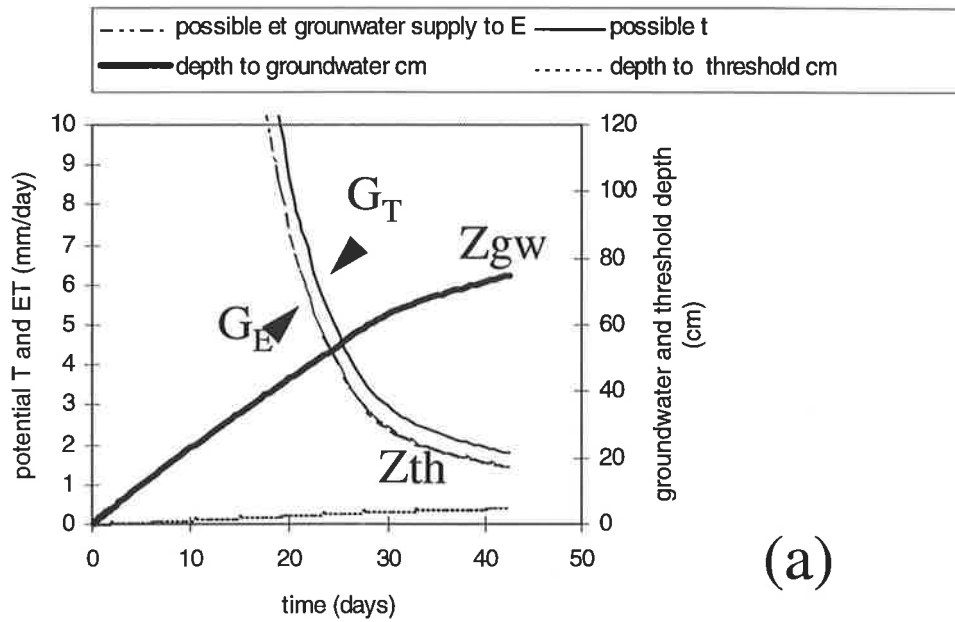
For the water balance calculations the groundwater (Zgw) rose to 32 cm below the soil surface (from an initial depth of 110 cm) and then decreased to a depth of 150 cm over the summer period (Fig 6.4 a). The fluctuations in calculated groundwater depth matched the actual groundwater depths at most of the sampling times, with the calculated minimum depth to groundwater reflecting the actual minimum depth to groundwater (Fig 6.5 a). The exception being that the actual groundwater appeared to drop initially faster than the modelled groundwater (Fig 6.4 b) and this may be associated with errors in T, leakage, Sy, or stored soil (remnant groundwater) water may have been used during this time (see Discussion). Specific yields affected groundwater depth as indicated in Fig 6.4 b.

The Zth simulations indicated the salt front (and so minimum depth of root uptake) was initially at the surface and then progressed to a depth of 50 cm at the end of summer (Fig 6.4 a). This depth was allowed to rise with the rise in groundwater and was forced to the surface at the beginning of the simulation at the end of winter (Fig 6.4 a and 6.5 b). The

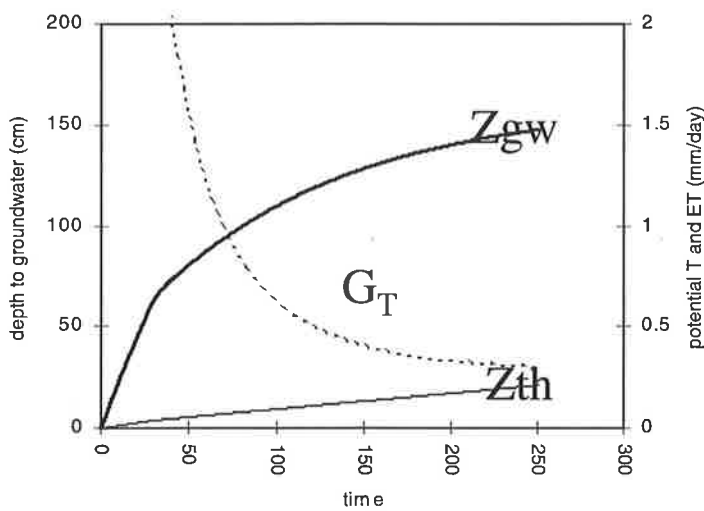
Z_{th} matched with the observed maximum rooting depth from root observations (Fig 6.5 b). The proportion of groundwater used by the trees and the actual groundwater discharge as estimated by the stable isotopes was similar to that estimated by the water balance during summer (Fig 6.6 a and b). During times of rainfall in winter the stable isotope partitioning of transpiration often indicated groundwater use but the water balance indicated groundwater recharge indicating difficulty in estimating groundwater use when the groundwater is close to the soil surface at the end of winter (Fig 6.6 a and b). When the potential transpiration from the groundwater (based on the distance between Z_{gw} - Z_{th}) was estimated for each time interval for Duck Island it was never lower than 50 mm and was always above the calculated transpiration rate indicating the validity of the groundwater discharge estimates. Based on these estimates of groundwater discharge from the water balance, the calculated net groundwater discharge was ~100 mm/year from this site. This would result in an increase in salinity of the groundwater over a year of 3000 g/L (Table 6.4).

6.3.2 Hansons

Theoretical modelling simulations during the draw down period for Hansons using an average transpiration rate of 1.8 mm/day resulted in groundwater depth (Z_{gw}) and the salt front (Z_{th}) proceeding similarly to Duck Island for stage 1 and stage 2 groundwater discharge (Fig 6.7 a). At the end of this stage the groundwater was at ~80 cm depth and G_T was at 2.2. mm/day (Fig 6.7 a). However when the model was run further, Z_{th} did not sufficiently approach the watertable to satisfy the known G_T (Fig 6.7 b) and so the Z_{root} was calculated (equation 6) (Fig 6.8). During the third stage the groundwater depth proceeded to a maximum depth of 160 cm at day 250. Z_{root} decreased with time reaching 100 cm depth at time 250 days (Fig 6.8).



(a)



(b)

Figure 6.7: (a) Stage 1 and 2 groundwater discharge simulated for Hansons and (b) stage 3 groundwater discharge all simulated with model 1 indicating groundwater depth (Z_{gw}), salinity threshold (Z_{th}) and potential transpirational (G_T) and evaporation groundwater discharge (G_E).

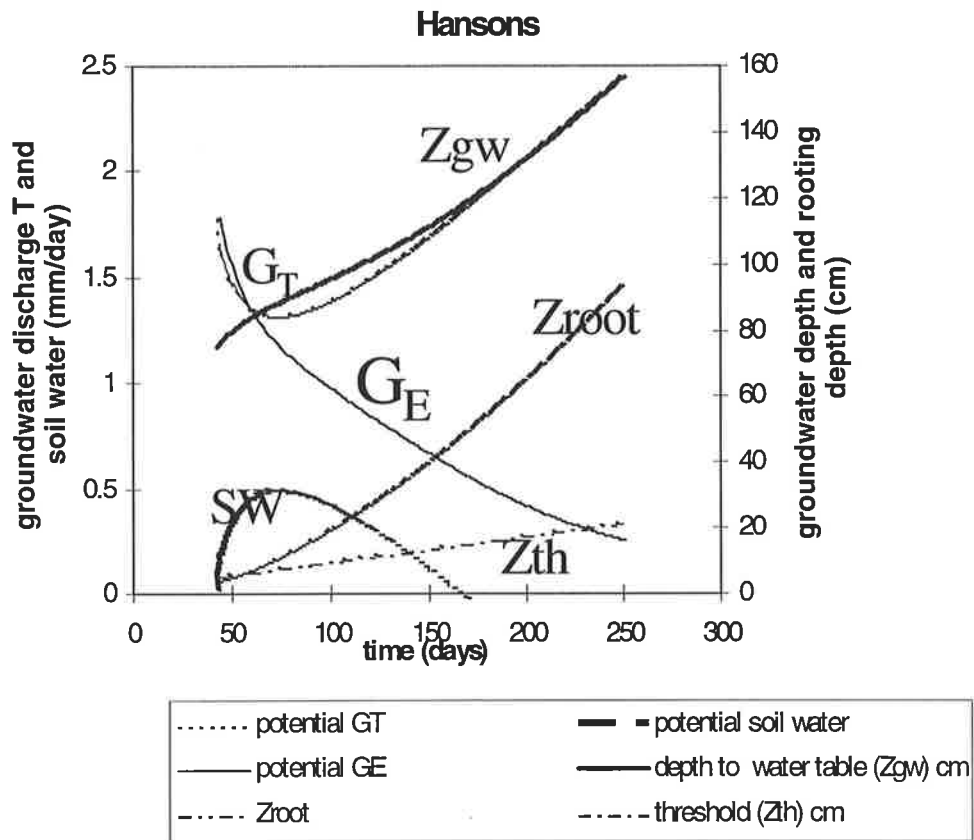


Figure 6.8: Simulations of groundwater depth (Z_{gw}), depth to threshold (Z_{th}), rooting depth (Z_{root}), potential transpirational groundwater discharge (G_T), evaporational groundwater discharge (G_E), and potential soil water use (SW).

For the water balance calculations groundwater depth (Z_{gw} ; Fig 6.9 a) followed the same pattern as at Duck Island (6.4 a) and was deeper than observed groundwater depth at all times (Fig 6.9 b). The predicted Z_{th} (rooting depth) was also shallower than measured water sources (Fig 6.9 a). These discrepancies could be a result of a number of factors (see discussion) including an overestimate of transpiration or an underestimate of rainfall, however an overestimate of transpiration would result in a faster movement of the salt front. Use of groundwater from the soil (ie a further soil drying) would result in less direct groundwater discharge and would not influence recharge at the point in time of the estimate. Equation 7 was used to estimate soil water use and groundwater use for each time interval.

The water balance calculations therefore involved the calculation of Z_{gw} and Z_{root} at Hansons. G was estimated by (1) an isotope partitioned transpirational flux where T was considered to be utilised for groundwater discharge (ie $T-R$) and soil water use (which may have been remnant groundwater stored in the root zone) and (2) a calculated partitioned transpirational flux which will be discussed in the following sections.

During the groundwater draw-down the concentrating effect of the use of stored groundwater in the soil zone enhanced the development of Z_{root} and reduced the depth of Z_{gw} (because less water was used from the groundwater). The resulting Z_{gw} ranged from 30 cm depth to 200 cm depth and were closer to observed values than previously but predicted values were still deeper than observed values at most times (Fig 6.10 b).

Z_{root} ranged from the soil surface to 140 cm depth (Fig 6.10 a). Z_{root} was unpredictable during the time of groundwater rise and so only results during the drawdown are relevant. The water sources as indicated by the stable isotopes were often in the range between Z_{root} and the previously simulated Z_{th} indicating that the rooting depth at this site was more spread through the soil profile and was not at the shallowest depth below the Z_{th} as was assumed in the initial model. The observed water sources to compare to the Z_{root} are better represented as a % groundwater. The groundwater discharge at Z_{root} (Fig 6.11 a) was expressed as a % of transpiration and the difference between rainfall and groundwater discharge was expressed as % soil water use (Fig 6.10 c).

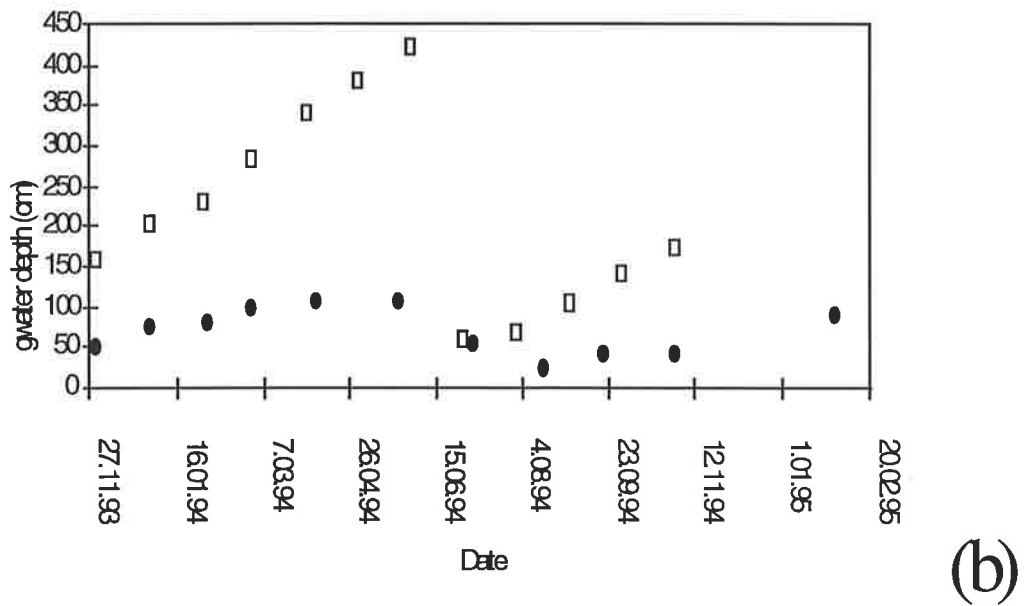
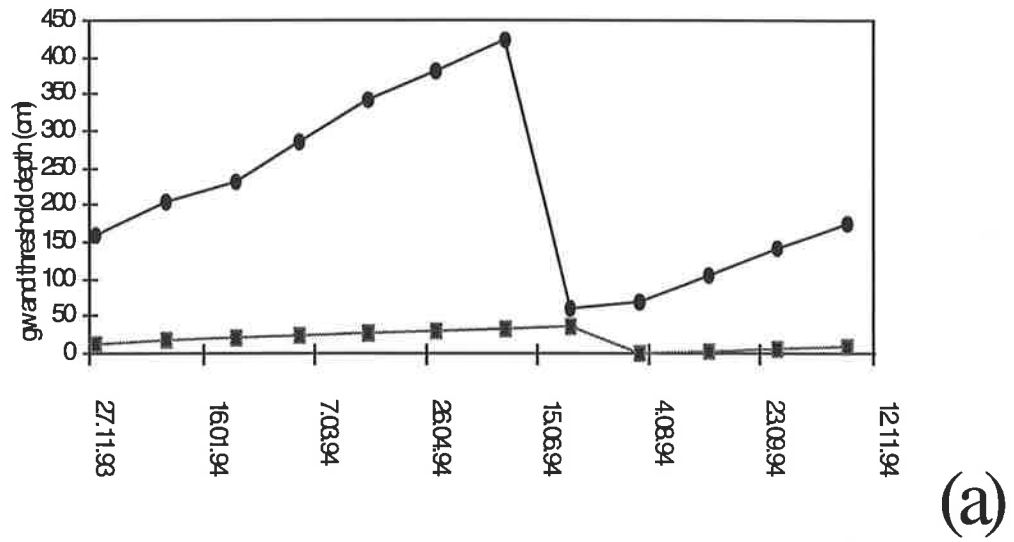


Figure 6.9: (a) Estimated groundwater depth (Zgw; ●) and threshold depth (Zth; ■) for Hansons. (b) Estimated groundwater depth (Zgw; □) and observed groundwater depth (●) for Hansons from field data.

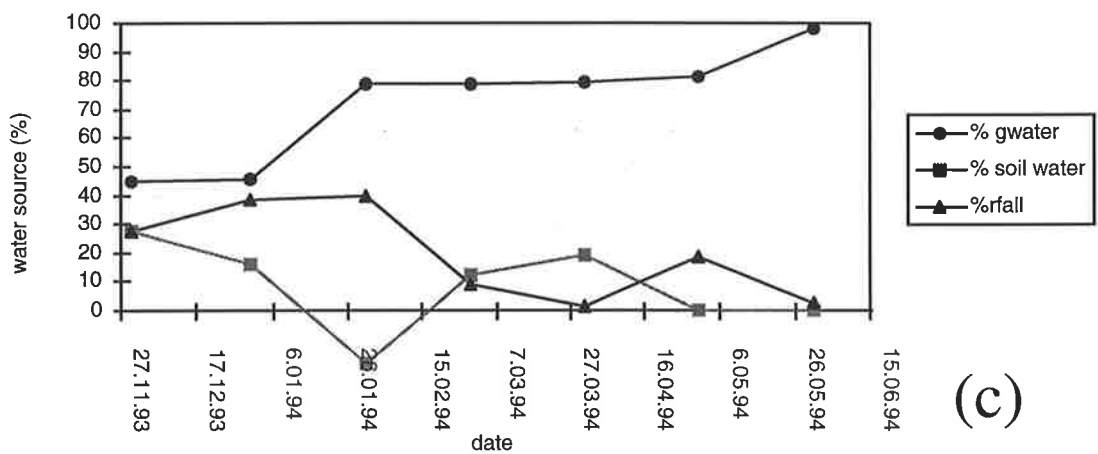
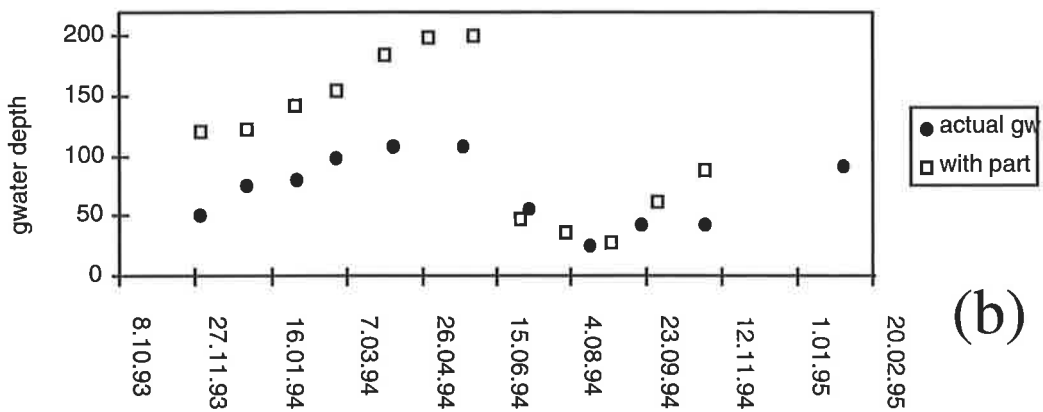
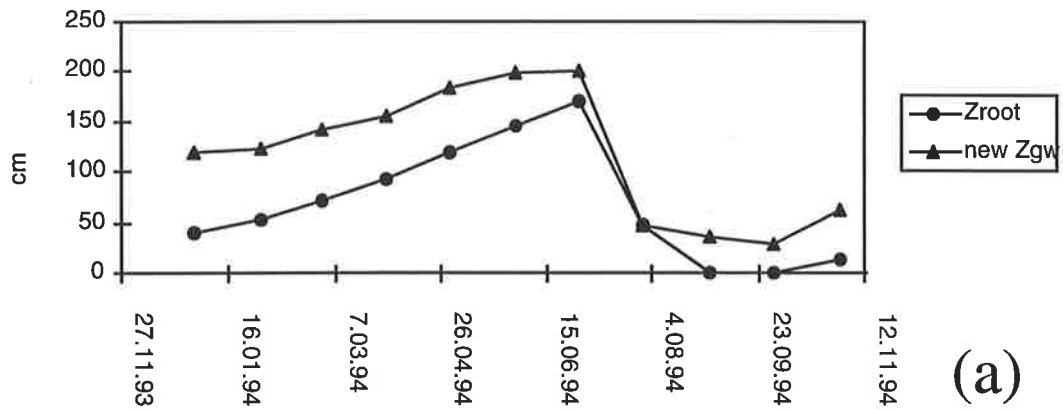


Figure 6.10: (a) Estimated groundwater depth (Zgw; ▲) and rooting depth (Zroot; ●) for Hansons. (b) Estimated groundwater depth (Zgw; □) and observed groundwater depth (●) for Hansons from field data. (c) Estimated % groundwater (●), % soil water (■) and % (▲) rainfall as estimated from the model.

The % groundwater, soil water and rainfall was used at each month over the drawdown (6.10 c) and ranged from 45 to 100 % for groundwater use, 35 to 0 % for rainfall use and 0 to 20 % for soil water use over summer. The groundwater discharge and % groundwater use was compared to the groundwater discharge from the water balance and groundwater use as estimated from the stable isotopes (Fig 6.11 a and b). Patterns of groundwater use and groundwater discharge were higher for the isotope partitioning during winter when recharge occurred. When the pattern of groundwater recharge and discharge was compared to the partitioned estimates of groundwater discharge it could be seen that whenever it was considered that 100% of groundwater was used (based on stable isotopes), groundwater discharge was estimated from the water balance (Fig 6.11 a and b). However at times when it was considered that a majority of groundwater was used, as estimated from the distance of roots to the groundwater, the use of stored soil water at depth may have reduced the actual amount of groundwater that was used. Therefore a deeper use of water did not necessarily mean a use of more groundwater.

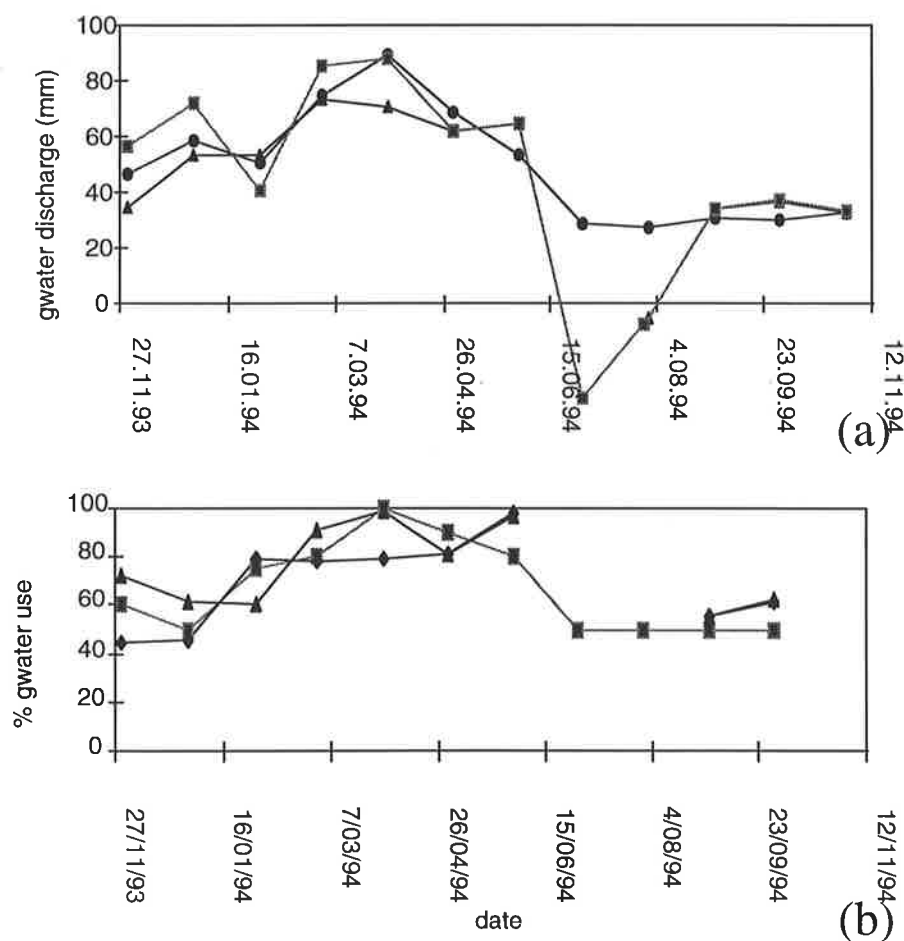


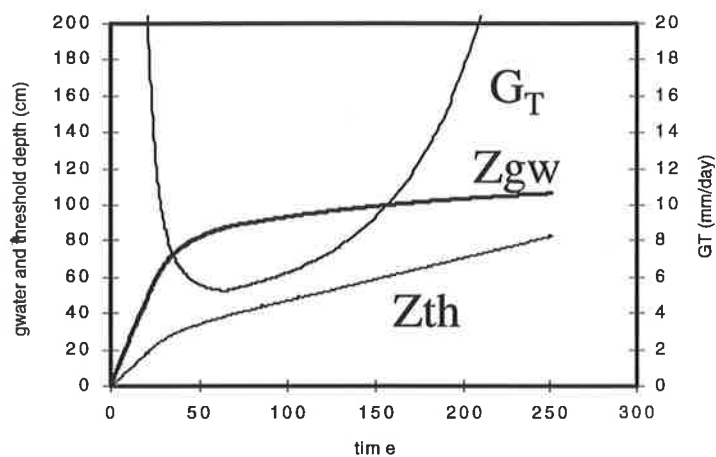
Figure 6.11: Estimated groundwater discharge (a) and % of groundwater used (b) for Hanson's as indicated by the stable isotope partitioned transpiration (●), the water balance (■), and the model (▲).

The estimated net groundwater discharge as estimated for *M. halmaturorum* at Hansons was complicated by the use of stored soil water from groundwater left in the soil profile and so the need to recharge this used water store before groundwater could be recharged and rise to the soil surface when rains occurred in winter. There was therefore a reduction in the groundwater rise when this was taken into account and this did not match the observed groundwater rise to the surface. Annual net groundwater discharge was therefore best estimated by the annual transpiration minus the annual rainfall and was ~ 500 mm/yr. This would result in 4500 g/L of Cl increase in groundwater salinity in a year. An additional source of recharge in the model (ie floodwaters) would have resulted in this groundwater discharge being reduced (see discussion).

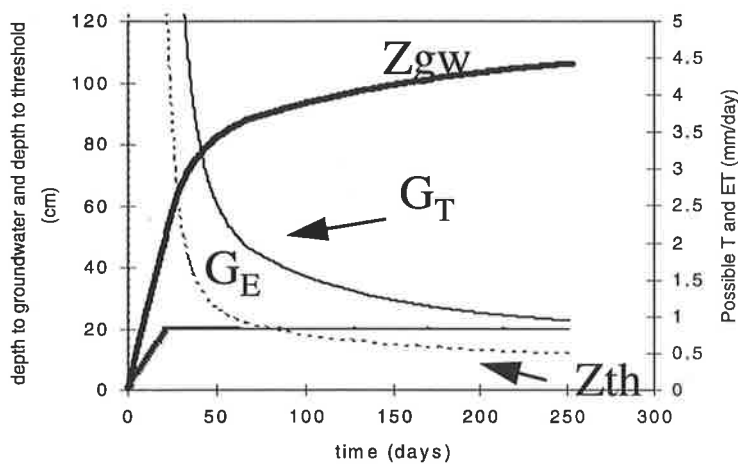
6.3.3 Lesron

For Lesron theoretical modelling simulations used a groundwater discharge rate of 0.8 mm/day. Groundwater depth (Z_{gw}) and threshold depth (Z_{th}) followed a similar pattern as at Duck Island, increasing exponentially with time from day 1 to day 30 and then plateaued at ~100 cm (Fig 6.12 a). Z_{th} linearly increased from day 1 to day 30 and reached 70 cm at day 250. Estimated groundwater discharge was higher than measured transpiration at all times and Z_{th} was obviously below where roots were observed to penetrate (20 cm). Z_{th} was then maintained at 20 cm (Fig 6.12 b) as it was observed because of waterlogging that no water was taken from below this depth (chapter 5). The groundwater discharge plateaued at 1 mm/day, a rate similar to the observed transpiration (Fig 6.12 b). When the model was run until the entire soil profile reached the salinity threshold the time this took to occur was calculated as the time without groundwater fluctuations for which the trees would survive. For Lesron this occurred at day 365 (Fig 6.12 c).

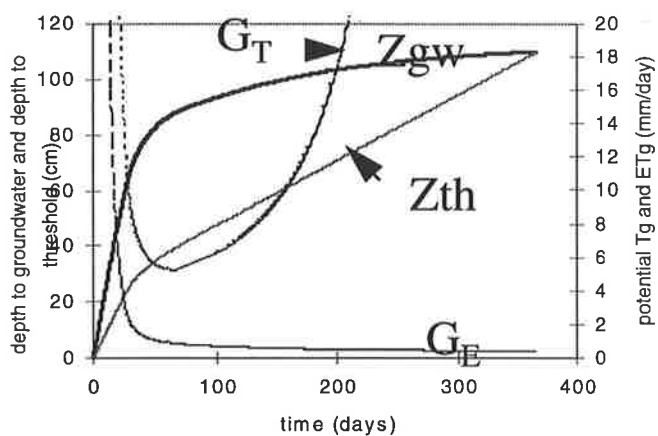
When the groundwater depth was calculated for each time using the groundwater discharge of T-R, the depth to groundwater ranged from 0 cm to 50 cm depth (Fig 6.13 a) with the groundwater appearing to remain at the surface for most of the time. This was less than the measured groundwater depth at all times (Fig 6.13 a). Soil evaporation may have been more important in groundwater discharge at this site than as modelled. In addition it was noted in the preliminary modelling that soil evaporation was instrumental in producing the initial drop in groundwater depth (Fig 6.12 b).



(a)



(b)



(c)



Figure 6.12: Groundwater depth (Z_{gw}), threshold depth (Z_{th}), estimated transpirational groundwater discharge (G_T) and evaporational groundwater discharge (G_E) for Lesron for 250 days with Z_{th} allowed unset (a) set at 20 cm (b) and long term simulation until Z_{th} reaches the groundwater Z_{gw} (c).

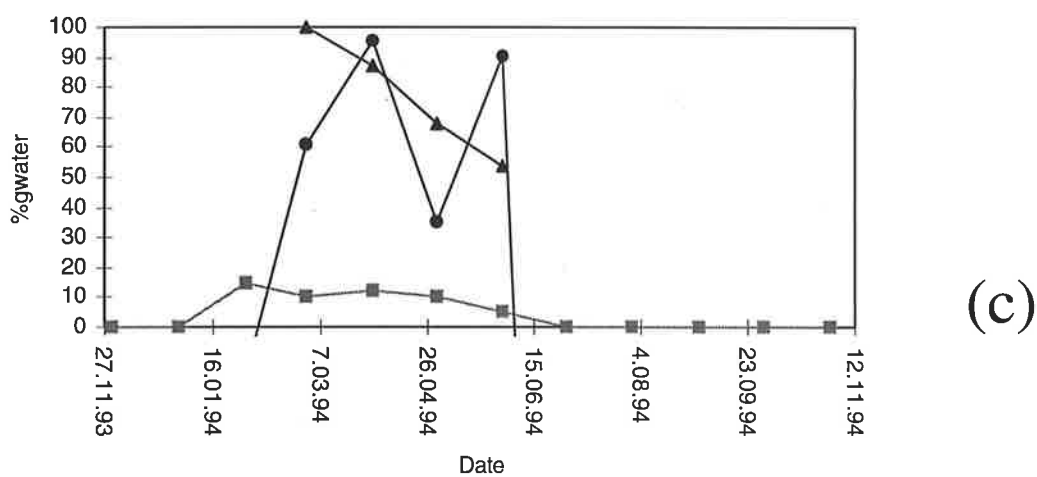
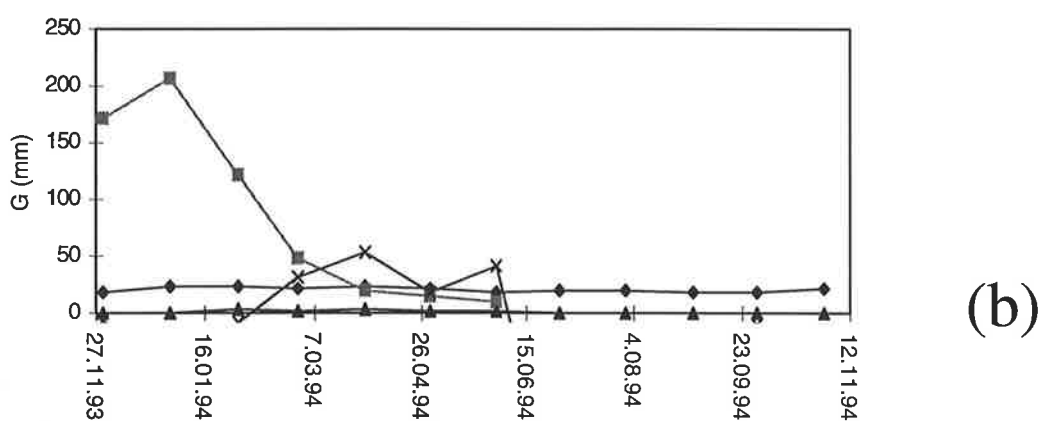
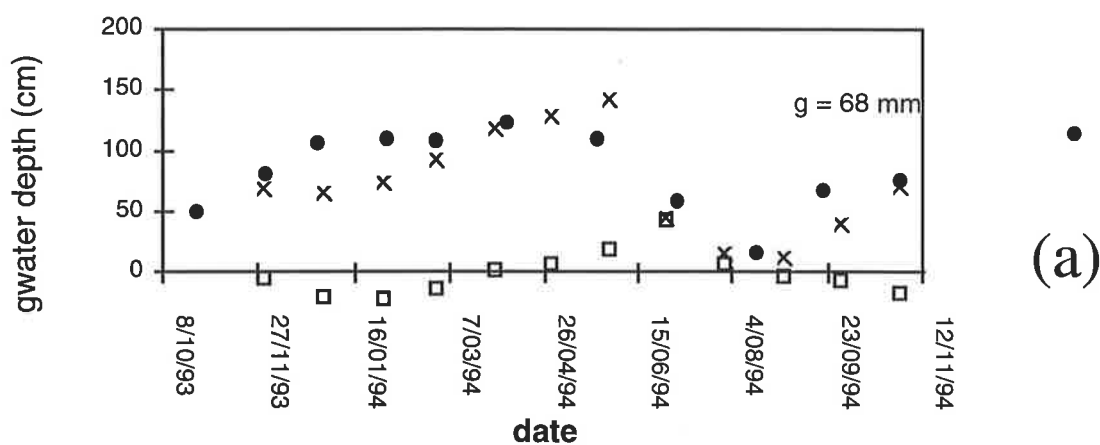


Figure 6.13: (a) Estimated groundwater depth from the field data for Lesron with transpiration groundwater discharge only (Z_{gw} ; \square), estimated soil evaporation combined with transpiration (Z_{gw} ; \times) and observed groundwater depth (\bullet). Estimated groundwater discharge (b) for Lesron as indicated by the stable isotope partitioned transpiration (\blacktriangle), the water balance (\times), and the model (\blacksquare). The total transpiration is also shown (\blacklozenge). (c) The estimated % groundwater use for Lesron by the water balance (\bullet), the stable isotope partitioning of transpiration (\blacksquare) and the model (\blacktriangle).

Soil evaporation is dominant during the times when groundwater is close to the surface but transpiration is the dominant groundwater discharge when groundwater is deeper. When a calculated potential soil evaporation G (Eg; equation 3) was added to the transpirational G (G_T) the resulting groundwater drop from 10 cm to 120 cm over summer was similar to the observed groundwater drop (Fig 6.13 a).

The Z_{th} was not estimated as it was set at 20 cm, as a result of observed waterlogging below 20 cm. For each month the groundwater discharge and % groundwater was estimated from the water balance calculations, isotope partitioning of the transpiration, and the model calculations. The isotope-partitioned groundwater use and the transpiration rate was always smaller than the estimated groundwater discharge from the water balance indicating that what appeared to be soil water use from the stable isotopes may have been groundwater use at some times (Fig 6.13 b).

The amount of water that was brought to the root zone and so could be used by plants was usually larger than the transpiration rate except for the Autumn sampling periods when it was concluded that based on the water balance up to 90 % of water used was groundwater (Fig 6.13 c). This discrepancy may be due to errors in transpiration, rainfall and/or soil parameters.

The transpiration rate measured at this site did not result in a net groundwater discharge alone as net recharge was estimated based on the transpiration rate alone (100 mm). However discharge was indicated by the groundwater depth and when the estimated evaporation was combined with the measured transpiration, was estimated at 69 mm. This would have resulted in net accumulation of salt of 2898 g/L Cl per year.

6.4 Discussion

6.4.1 Implications of model for role of trees in the water balance

Estimated net groundwater discharge by trees ranged from 0 to 500 mm a year depending on site. At Duck Island an estimated annual net groundwater discharge of 107 mm was considered to be a reasonable estimation as groundwater and threshold fluctuations were reasonably accurate. At Hansons the estimated annual net groundwater discharge of 500 mm may have been an overestimate. The maximum depth to groundwater was more for the predicted depth than the actual depth at Hansons. This may be a result of an

overestimation of transpiration, a underestimation of leakage, an overestimation is specific yield, or an underestimation in rainfall. The transpiration rate had been considered to be overestimated in comparison to other measurements of transpiration at Hansons and may in fact be up to 1 mm/day less than indicated (Chapter 3). The specific yield could also be lower than used as a result of the shallow groundwater and calcrete layers (Johnson, 1967 in Domenico and Schwartz, 1990). The leakage is relatively difficult to predict as a result of scarcity of data on this parameter. Rainfall was unusually low in this year but may have varied across the study region as a result of spatial variability. Other errors such as the lack of inclusion of other sources of recharge into the water balance such as flood waters and lateral flows of groundwater may be significant. This may have been important at Hansons, where flood waters were observed to occur as runoff from other parts of the catchment.

There was no net groundwater discharge estimated at Lesron when only transpiration was included in groundwater discharge estimates. Net recharge at the Lesron site will result in groundwater rise, a process that has been suggested to be causing the decline in health of *M. halmaturorum* in the region. The introduction of soil evaporation into the groundwater discharge value did result in a net groundwater discharge for this site however it was small. Soil evaporation may be more important at this site than the other sites because of the waterlogged soils (higher water contents) and so higher transmissivities. This study was conducted in a drought year (below average rainfall) and average conditions may result in net groundwater recharge at this site with greater frequency resulting in soil waterlogging and increased soil salinisation. The implications of this will be discussed in the following chapter (Chapter 7).

Soil evaporation did not appear to be as important in controlling the groundwater balance at Duck Island and Hansons as at Lesron. However the rate of initial groundwater drop was lower for predicted data than observed data at these sites and soil evaporation may be important in groundwater discharge at this stage because of the shallow water tables and relatively transmissive soils as indicated by the initial modelling. Predicted soil evaporation during this modelling for Duck Island peaked at 0.4 mm/day, a value that matched that estimated at the site from Bowen ratio estimates (Appendix 5).

6.4.2 Implications of model for *M. halmaturorum* water use strategy

The water sources of *M. halmaturorum* at these sites have been discussed in more detail in the previous chapter (Chapter 5). The modelling exercise outlined in this chapter provides insights into the interpretation of water sources outlined previously. Discrepancies

between groundwater discharge as estimated by the water balance (transpiration- rainfall) and partitioned transpiration discharge by the stable isotopes indicated that not all groundwater was used when indicated by the stable isotopes. The difference between net groundwater discharge (116 mm) and actual tree groundwater use (280 mm) at Duck Island may indicate that some water that enters the groundwater is rainfall and this is used by the trees. This may occur as a result of the shallow groundwater, which is often at the soil surface, allowing rainfall to enter the system. In addition there were some times when it was indicated by the stable isotopes that not all groundwater was used but the water balance indicated that there was net groundwater discharge occurring. In this case what was determined as a non groundwater source by the stable isotopes may have been groundwater from the capillary fringe. In these shallow groundwater systems, the combination of modelling techniques with these field isotope techniques may be useful in assisting with the interpretation of results.

The suggested use of stored groundwater from the soil at Hansons and the resulting further drying out of the soil profile was indicated by the field data where low relative soil water contents were often observed. It was considered that this process did not occur at Duck Island to the same extent because of the higher groundwater salinity at this site. A higher groundwater salinity of water left behind in the root zone would result in less possibility to withdraw water from this soil for an additional water source until the threshold salinity is reached. However some water may have been obtained in this way at Duck Island.

For Lesron the conclusion from the stable isotope analysis was that because water sources were always in the top 20 cm, only a small percentage of transpiration was groundwater. However there may have been more groundwater obtained from the surface. This was evident during the times of groundwater discharge when the estimated amount of groundwater use ranged from 40 - 95 % for the water balance but was <15 % from the stable isotopes. Therefore the plant roots may have been able to remain at 20 cm and still continue to take up enough groundwater to satisfy their transpiration rate. As salt accumulation would still have occurred within this 20 cm, the maintenance of plant root water uptake without rainfall would have been reliant on the diffusion of salt away from the roots (to deeper soils), the convection of salt to the soil surface in water movement as the surface soil dried, and the increase in the plant threshold to water uptake (plant water potential) so water can continue to be taken up from more saline soils.

Using Ficks law (Marshall and Holmes, 1988), the diffusion of salt $J_d = D \frac{dC}{dz}$ was calculated where D is the diffusivity of the solute, $\frac{dC}{dz}$ is the solute concentration gradient between the root zone and deeper soils, K is the hydraulic conductivity at the average soil matric potential, and $\frac{d\Psi}{dz}$ is the matric potential gradient from the root zone to the soil surface. Estimating D at $10^{-6} \text{ m}^2 \text{ day}^{-1}$ (Thorburn et al, 1994) it was estimated that approximately 4 g m^{-2} of salt could be taken out of the root zone by diffusion (as compared to 34 g m^{-2} of Cl brought in to the root zone by transpiration). Another factor which may result in the maintenance of water uptake at this depth is the pushing of fresh water up from the water table on the capillary fringe which may have sustained plant roots by enhancing water uptake. This may be possible at this site as a result of the wet soils at depth which are not penetrated by plant roots. These factors in combination may serve to sustain water use and survival of *M. halmaturorum* at Lesron.

At Lesron the increase in plant water potential threshold from -8 MPa to -12 MPa would also have resulted in the continuation of water uptake for another 30 days. The threshold concept (ie Passioura et al, 1992; Thorburn et al, 1993a) was used in this modelling exercise however a varying threshold was applied because at each site the minimum plant water potential varied largely (Chapter 4). This is an indication of the large tolerance of this species to drought and salinity (van der Moezel et al, 1991). At Lesron the ability to lower plant water potentials to these very low values indicates that *M. halmaturorum* may use this characteristic to survive decreasing soil water availability rather than other plant water use strategies such as dropping leaves to lower water use. The water use strategy of *M. halmaturorum* will be discussed further in the following chapter (chapter 7).

6.5 Summary and Conclusions

Modelling of the groundwater uptake processes that were observed in the field for *M. halmaturorum* indicated that 1) the processes could be modelled based on soil physics with the most available water source dominating the root dynamics and 2) the model provided further insights into the probable magnitude of groundwater use by *M. halmaturorum*. What was previously considered to be often soil water use at Lesron could be considered groundwater use because of the shallow groundwater system. Conversely where it was previously considered that groundwater was used by *M. halmaturorum* at Hansons and Duck Island, soil water, rainfall in the groundwater, or groundwater stored in the soil may be the water source. Estimated net groundwater discharge occurred at 0 to 500 mm/year depending on site characteristics and water sources. Overestimation of transpiration at Hansons may be responsible for an overestimation of groundwater discharge at this site. Net recharge may occur at Lesron in some years and may be responsible for groundwater rises and soil waterlogging.

Chapter 7: General Discussion and Conclusions

7.1 Groundwater discharge and the water use strategy of *M. halmaturorum*.

M. halmaturorum used 60 to 600 mm a year of groundwater depending on groundwater salinity and waterlogging. Where groundwater was of medium salinity (14 dS/m; Hansons) groundwater use was 1 to 4 mm/day and ~590 mm/year. This groundwater use is similar to ^{that} found in other studies where trees overlie shallow (1- 1.5 m) groundwater of similar salinity (Talsma, 1963; Fraser and Thorburn, 1996) and where trees overlie deeper groundwater (~2-3 m) of lower salinity (~5 dS/m; Fraser and Thorburn, 1996; Huperman, 1995). Talsma (1963) found groundwater discharge under apple trees of 0.1 to 3 mm/day (480 mm/year) and Fraser and Thorburn (1996) showed groundwater use of *Casuarina* trees of 1-3 mm/day with an annual groundwater use of 440 mm where groundwater was 11 dS/m. Where groundwater was deeper (3-5 m) and less saline (5-7 dS/m) *Eucalyptus* trees used ~430 mm of groundwater a year at rates of 1 to 3 mm/day (Thorburn et al 1993a; Huperman, 1995). The similar rates of groundwater use of *M. halmaturorum* to trees, despite differences in groundwater depth and salinity, indicate that for *M. halmaturorum* at low to medium salinity the ability to use groundwater from any depth appears to be the controlling factor on groundwater use. Therefore the ability of *M. halmaturorum* to penetrate roots to the groundwater and so take up significant amounts of saline groundwater appears to be important under moderately saline conditions. Thorburn (1996) suggested that groundwater discharge by trees was not dependent on groundwater depth if there nothing to prevent tree roots from penetrating to depth.

Where *M. halmaturorum* was overlying groundwater of high salinity (63 dS/m) up to 290 mm of groundwater was used in a year (at a rate of 1 to 2 mm/day). This is much higher than reported for trees overlying groundwater of similar salinity where very low rates of groundwater use have been recorded. *Eucalyptus* floodplain trees overlying groundwater of 30-50 dS/m at 3-4 m used 0.1 to 0.3 mm/day of groundwater (40 - 55 mm/year; Thorburn et al, 1993a; Thorburn et al, 1995). Similarly *Atriplex* shrubs used ~10 mm of groundwater a year (30 dS/m at ~ 2 m) at rates of 0.1 mm/day (Slavich et al, 1996). Leaf area indexes in these studies were lower (<0.3) than recorded for *M. halmaturorum* (1.2) at Duck Island (Thorburn et al, 1993a; Slavich et al, 1996).

Surprisingly, groundwater use for *M. halmaturorum* under this high groundwater salinity was similar to that found for pasture plants overlying shallow groundwater but where salinity was much lower (Talsma, 1963). In lysimeters lucerne used up to 360 mm of groundwater and maize used up to 277 mm a year where groundwater was ~ 1 m deep and 15 dS/m salinity (King et al, 1995; Smith et al, 1995). Tall wheat grass also had annual groundwater use of 360 mm where groundwater was 10 dS/m at 1 m. However daily rates of water use and LAI of lucerne and maize was more than double that for *M. halmaturorum* as a result of the use of rainfall and irrigation water by plants (King et al, 1996). This use of surface water sources by both species along with the lower groundwater use of maize than lucerne may be a result of the shallower rooting depth of these pastures. Tall wheat grass is planted in the same area as *M. halmaturorum* is naturally found and so has similar conditions of groundwater depth and salinity. That tall wheat grass had a higher daily water use (4 mm/day) than *M. halmaturorum* but similar annual groundwater use (360 mm) is a result of its senescence at the end of summer (Bleby et al, 1996). Therefore the effect of groundwater use on the annual groundwater budget would have been less than *M. halmaturorum* which occurred nearby and was able to use groundwater over the summer.

Where groundwater was saline the ability to take water from the watertable was apparently associated with a shallow watertable which delivered water to tree roots by capillary rise. This influence of groundwater depth on limiting groundwater discharge by *M. halmaturorum* from highly saline watertables may be a result of the inability of roots to penetrate close to the saline groundwater (e.g. Thorburn, 1996). The ability to use this saline groundwater, and maintain groundwater uptake to rates similar to fresher groundwater systems was associated with the generation of low leaf water potentials. The ability of mangroves to take up water of similar salinity (sea water) to groundwater at Duck Island has been associated with leaf water potentials in the range found for *M. halmaturorum* (<-5 MPa). Transpiration rates (~ 1 mm/day) within a similar range found for *M. halmaturorum* have been suggested for mangroves (Passioura et al, 1993). It appears that the water use strategy of *M. halmaturorum* was similar to that of shallow rooted pasture species (as opposed to trees) overlying groundwater of medium salinity with uptake from more saline groundwater occurring as a result of the ability to lower leaf water potentials and so continue to take up water from saline groundwater and soils. Because of the perennial nature of *M. halmaturorum*, more water was able to be taken up over a season (as opposed to tall wheat grass). In addition, the higher salinity threshold of *M. halmaturorum* allowed groundwater of a greater salinity to be used than the pasture species, and because of the potential deeper rooting of *M. halmaturorum* more groundwater

could be used than the pasture species when groundwater salinity was lower. Similarly groundwater use by pastures may have been lower than groundwater use by *Casuarina* and apple trees under similar conditions as a result in differences of rooting depth and so potential water sources. As the magnitude of *M. halmaturorum* groundwater use is dependent on the rate of groundwater discharge from the shallow groundwater table, the potential of *M. halmaturorum* to use more water than could be evaporated directly from the watertable is limited (Thorburn, 1996).

In summary, placing the water use strategy of M. halmaturorum into a framework of a general tree water use strategy, it can be seen that when groundwater is highly saline, its use by M. halmaturorum is dependent on capillary rise. Rooting depth is not so important but the plant threshold to water uptake is important when the groundwater is highly saline. Where the groundwater is of a lower salinity, its use is not influenced so much by groundwater depth but more so by the ability of roots to penetrate close to the groundwater.

When soil waterlogging was combined with salinity in the root zone (e.g., Lesron), there was a further reduction in groundwater use (to ~67 mm). This was because roots were unable to penetrate close to the groundwater and instead were limited to taking up water from close to the surface. As a result of the shallow groundwater trees were still able to draw from this source, but transpiration rates were reduced resulting in a smaller net groundwater discharge. Reduction in water use by salinity combined with waterlogging was observed in *Eucalyptus* seedlings (Marcar, 1993) but the processes by which transpiration is limited in the field have only been demonstrated in mangrove communities where specialised root adaptations allow survival under these conditions.

Where groundwater is saline the use of water close to the groundwater may result in the rapid accumulation of salt. Therefore where groundwater is shallow and saline the higher rate of potential groundwater uptake may be compensated for by a higher rate of salt accumulation. The accumulation of salt results in salinity limited transpiration which has been the basis for models of water uptake from saline sources (Thorburn et al, 1995; Passioura et al, 1992). The continuous uptake of groundwater despite this accumulation of salt is dependent on a dynamic root system. The pattern of salt accumulation was different for *M. halmaturorum* than observed in other studies of similar groundwater salinity (Thorburn, et al 1993; Slavich et al, 1996) and this controlled the pattern of groundwater use. The position of the salt front not only controls the root dynamics in these different

sites but also controls the amount of water that is moved to the roots from the groundwater (Thorburn, 1996). This is determined by the distance of the roots from the groundwater and the permeability of the pathway. The salt profile that forms in soils of the discharge areas of the Upper South East shows salt accumulating in the surface soil initially and then deeper in the soil profile. When groundwater is close to the soil surface, evapotranspiration results in accumulation of salt in the surface soil with lower values at depth that generally reflect the groundwater salinity concentrations. As groundwater falls over the spring and summer, remnant groundwater is left in the soil pores. Salt accumulates in the region of groundwater uptake and root activity moves deeper into the soil profile escaping this region of salt accumulation and using groundwater from deeper in the soil profile. On the Chowilla floodplain, where groundwater is deeper and more static, a salt front forms at depth initially as a bulge of salt above the groundwater table (Jolly et al, 1993) as a result of the uptake of groundwater. The role of groundwater depth in determining patterns of salt accumulation is also reflected in soil profiles from Jaffray Swamp (Appendix 6), where groundwater is deeper and a bulge of salt is found at depth in a similar way to the Chowilla profiles. For the Chowilla profiles the salt front was thought to move closer to the soil surface over time in response to groundwater uptake. The depth of water uptake changes as this salt front moves towards the surface with root water uptake required to move further away from the watertable towards the surface ahead of the accumulated salt and causing a reduction in groundwater uptake (Thorburn et al, 1995). As a result of the similarities in groundwater depth and patterns of salt accumulation, water uptake by *M. halmaturorum* at Jaffray Swamp may follow a similar pattern.

Salt profiles similar to those in the ephemeral swamps of the Upper South East (Duck Island, Lesron and Hansons) are found in studies of groundwater use of sea barley grass and tall wheat grass overlying shallow groundwater (Talsma, 1963; Bleby et al, 1996) where the groundwater fluctuates to close to the surface and then falls to ~ 1 m depth. In studies of other shallow saline groundwater systems where the groundwater is maintained at a static level salt accumulates above the groundwater in a similar way to the Chowilla floodplain (Smith et al, 1995; King et al, 1996; Huperman, 1995). The pattern of salt accumulation is influenced by the hydrogeology of the site (through influences on groundwater depth and lateral discharge) and this will influence the role of trees in the groundwater balance and sustainability of groundwater discharge.

7.2 Sustainability of trees in groundwater discharge areas and implications for wetland health

As previously discussed, the groundwater use by *M. halimifolium* resulted in accumulation of salt in the unsaturated zone over the year. *M. halimifolium* groundwater use resulted in annual net groundwater discharge of 100 to 500 mm. These trees therefore often had a significant influence on groundwater discharge and so the water balance. Groundwater discharge by *M. halimifolium* corresponded to a net increase in groundwater salinity of up to 4,500 g/L at Hansons and 3,000 g/L at Duck Island. The groundwater salinity at Duck Island was high and may reflect this groundwater discharge-enhanced groundwater salinity. However groundwater salinity at Hansons was lower (14 dS/m) and does not reflect this increased salinity. This may be a result of errors in discharge estimates or may also reflect the influence of landscape hydrogeological features on the groundwater discharge characteristics.

The pattern of salt accumulation (see previous section) has implications for the sustainability of tree water use in groundwater discharge areas. In the Upper South East salt initially accumulated in the soil surface, making them unavailable for water uptake, and then progressed to deeper soils. The rate at which the salt front reached the groundwater (and therefore the entire soil profile was salinised) was determined by the amount of water that was taken up, and this increased as the roots moved towards the watertable. Trees on the Chowilla floodplain initially used water close to the groundwater but as the salt front developed used water from shallower depths, further away from the groundwater. This pattern of salt accumulation influenced the amount of groundwater that could be used by trees and the sustainability of the systems.

Based on this interpretation it might seem that the shallow groundwater discharge areas of the Upper South-East are more suitable for groundwater uptake as the roots are forced to take up water from close to the watertable. However the increased rates of groundwater discharge will result in faster rates of salt accumulation and so the movement of the salt front to the groundwater will develop faster than at Chowilla (Thorburn, 1996). For the Upper South East if the salt profile develops from the soil surface to the groundwater before the groundwater rises (ie within a year) the trees will have no further soil to obtain water from (as all will be above the threshold very rapidly). As opposed to the Chowilla floodplain where the salt profile develops from the groundwater to the soil surface and so active roots ultimately end up at the soil surface where they can at least be sustained with rainfall, roots of trees in the Upper South East will end up at the groundwater and trees will

die. In these natural systems the sustainability is maintained by hydrological processes and leaching events.

Maintenance of *M. halmaturorum* health and sustainability in the short term was established by the annual groundwater rise which diluted salts that were stored in the soil profile, combined with rainfall. Although groundwater was saline it was less saline than the salts that were accumulated in the soil profile over summer. The annual fluctuation of saline groundwater to the soil surface ensures that a regular return to baseline soil salinity concentrations occurs every year. This was important in maintaining the health of trees at these sites and hence the sustainability of their groundwater use. This process combined with rainfall that freshens the surface soils, ensures uptake of fresh water for certain times of the year. Rainfall is higher here than the semi-arid climate of the Chowilla floodplain and so will be a more significant leaching agent. Studies of *E. camaldulensis* on a saline floodplain where groundwater discharge occurs have found that flooding is important in flushing salts from the soil profile and maintaining the health of trees (Jolly et al, 1993; Thorburn et al, 1993; Richter et al, 1996). However the time scales involved in these salt accumulation processes are very different. The rate of salt accumulation on the floodplain is lower (10-15 as compared to 1-2 years until complete salinisation of the soil profile), as a result of deeper static groundwater, and the leaching need not be so frequent (Thorburn, 1996). Faster rates of salt accumulation from shallow watertables have also been observed in lysimeters with lucerne after irrigation is stopped and a saline watertable introduced. However lower groundwater salinity than in the previous study meant that this accumulation of salt occurred over a longer time scale (Smith et al, 1995). *M. halmaturorum* can also be compared to mangrove water use strategies. Mangrove colonies are frequently flooded, and have a small amount of soil volume that can be exploited by their root systems. Salt will build up rapidly if flushing is prevented and this limits transpiration and can lead to death.

On the Chowilla floodplain the regularity of the floodwaters combined with the groundwater salinity (depth is usually relatively constant) determines the extent of the salt front and the health of the trees on the floodplain. Thorburn et al (1995) estimated that the time it would take for the salt front to reach the soil surface matched with the frequency of flooding for healthy trees. The frequency of large floods has been reduced on the floodplain, and salt accumulation has occurred to levels that caused tree death. In this case the infiltration of rainfall is the only factor that maintains the survival of these trees. This long term salt accumulation has also been found to occur under plantations of *Eucalyptus*

species overlying saline groundwater (Huperman, 1995) after the cessation of irrigation. Groundwater discharge resulted in a profile of salt accumulation similar to that found by Thorburn et al. Due to the absence of any other significant leaching or diffusion process, if rainfall is not satisfactory tree health will decline.

Hydrogeology influences both the groundwater depth (and so the salt accumulation processes) and the long term salt removal mechanism. For groundwater discharge areas to be sustainable in the long term there must be mechanisms to remove salt from the site. For the Upper South East lateral groundwater flow rates are low and the fall in groundwater levels after winter is almost solely dependent on discharge by evapotranspiration. Therefore this system may be compared to a bucket which fills in response to rainfall and then empties mainly in response to local discharge. In comparison the lateral flow rates on the Chowilla floodplain are much more significant (Jolly et al, 1993). Groundwater rises in response to high stream levels and hydraulic heads, and when these pressures disappear the groundwater levels drop very fast in response to groundwater discharge to the creeks. At Chowilla the high lateral groundwater flows ensure that salt is removed from the site to the creeks (Jolly et al, 1993). In the Upper South East the lateral flows are relatively insignificant and so the main salt removal mechanism is by surface flows of water. As the majority of salt is accumulated in the surface this will result in removal of a significant amount of salt down catchment. Decline in health of *M. halmaturorum* occurs when excess runoff results in an accumulation of salt and excess groundwater recharge, resulting in these salt removal mechanisms not being satisfactory as at Lesron (Webb et al, 1993). This, along with soil waterlogging, may also explain the decline in health of wetland *Melaleuca* species in other wetlands in Western Australia where secondary salinity has been suggested (Froend et al, 1987).

7.3 Ecophysiological survival strategies in response to environmental stresses and changes.

M. halmaturorum is an example of a species that is naturally adapted to highly saline groundwater discharge areas. The characteristics which enable it to survive where surface soils are seasonally hypersaline and watertables are shallow are (1) a root system that is able to respond dynamically to changes in soil salinity and groundwater depth, (2) the ability to reach low leaf water potentials and so continue to take up water from saline soils and (3) low transpiration rates.

M. halimatum is able to react to changing soil salinity, as a result of discharge enhanced salt accumulation, by taking water from different parts of the soil profile. In this way *M. halimatum* trees are able to take extremely saline soil water, which is groundwater derived, and then switch back to rainfall when it freshens the surface soil layers. This response of the adaptive and dynamic root system accesses parts of the profile where the most available water is located, is achieved through the formation of new root tips from old dormant roots as water becomes available over the season. Although no aerenchymous roots were observed during the study period, large diameter roots (~80 mm diameter) were observed to dominate the root system and may have assisted in water uptake. Mature *M. halimatum* trees are able to adjust their root system dynamics to avoid saline and waterlogged parts of the soil profile. This contrasts with the declines in water use observed in seedlings in pot experiments, where root dynamics are limited, and crop plants where root systems are shallow. Moreover recent models of tree water use in response to salinity have emphasised the importance of the rates of diffusion and convection in substrate and from groundwater in limiting the water use of mature trees in saline environments (ie mangroves; Passioura et al 1992 and *Eucalypts*; Thorburn et al, 1994). In an environment such as the saline swamp that *M. halimatum* occupies, these environmental constraints may work with plant characteristics to maintain water uptake, necessitating the use of field measurement to assess plant-soil relations.

The leaf water potentials found for *M. halimatum* are lower than those generally found for trees, even stress tolerant *Eucalyptus* species (Richter et al, 1996). This is obviously an important characteristic when the uptake of water from saline soil is desired and results in *M. halimatum* using significant amounts of groundwater, even when surface soils are hypersaline. These leaf water potentials are lower than have been observed in many other studies and are important in defining the water use strategies of trees. The ability to survive with low leaf water potential involves cell characteristics to maintain turgor but may also necessitate xylem characteristics to withstand xylem cavitation, as have been observed in mangroves (Sperry et al, 1988).

Where a naturally saline system is also waterlogged, *M. halimatum* was able to survive despite this further stress. This study provides insights into the elasticity of the system which is a function of the physiological characteristics of this species. Under these conditions the combination of groundwater salinity and waterlogging results in the unavailability of soil water at depth and so tree roots are concentrated in the soil surface. *M. halimatum* is therefore greatly influenced by the high rates of salt accumulation in

the surface soil. It appears to be this combination of processes that results in a decline in tree health rather than the salt /waterlogging interaction that has been shown for other plants in the glasshouse (Barrett-Lennard, 1986). The elasticity of the response of *M. halmaturorum* to these conditions appears to occur as changes in leaf water potential and root water uptake rather than changes in leaf area. This elastic response to changing conditions in the root zone allows *M. halmaturorum* to maintain water use at reasonable levels and results in a slow decline in tree health. This conservative response in water use to changes in environment may be associated with the long term low growth rates that have been observed at this site and indicates the need to understand the long term water use strategies of *M. halmaturorum* in order to put these current studies into perspective.

7.4 Conclusions

General conclusion: The water use strategy of *M. halmaturorum* was responsive to processes of salt accumulation and waterlogging in the root zone. Transpiration rates were 0.5 to 4 mm/day (250-800 mm/yr). Groundwater was taken from deep in the soil profile in response to salt accumulation over summer. When groundwater rose at the end of winter and inundated the soil profile, water was taken from the soil surface. This led to groundwater use of 60 to 500 mm/yr and net groundwater discharge of up to 500 mm/yr. The ability to use saline groundwater was enhanced by low leaf water potentials and a dynamically responsive root system along with environmental characteristics such as annual groundwater fluctuations that maintained salinity in the root zone at baseline levels. *In response to the specific hypothesis:*

- Transpiration rates were limited by salinity ranging from 0.5 to 4 mm/day depending on site groundwater salinity and waterlogging characteristics and resulted in groundwater use from 60 to 500 mm a year.
- Where groundwater salinity was low to medium, groundwater use was similar to that observed for trees overlying groundwater of lower salinity or similar salinity and greater depth. This indicated that the potential of *M. halmaturorum* roots to penetrate close to the groundwater played a role in controlling groundwater use when groundwater salinity was low.
- When groundwater was more saline, groundwater use strategies of *M. halmaturorum* were similar to those observed for pasture plants overlying shallow saline groundwater. Rates of groundwater use were also similar to pastures despite the higher groundwater salinity indicating that groundwater depth was the controlling factor in groundwater use when groundwater was saline. The structure and form of the plants appeared to be

unimportant in defining the groundwater discharge by vegetation in this shallow groundwater system, with the rate at which water could be brought to the roots (as influenced by soil type) being the major influence. Plant water potential in this case was instrumental in determining the amount of water that could be taken from this saline groundwater source, and the pattern of groundwater uptake.

- *M. halmaturorum* was able to lower plant water potentials below -5 MPa and so continue to take up water from saline soils and groundwater.
- In the ephemeral swamps Duck Island, Hanson and Lesron *M. halmaturorum* used groundwater from the soil surface at the end of winter in response to groundwater rise and inundation of the soil profile and then used water from deeper in the soil profile in response to salt accumulation in the surface soils. Where groundwater remained deeper (i.e. Jaffray) water was taken from depth at all times resulting in a bulge of salt accumulation above the groundwater.
- Periodic short term waterlogging did not appear to further limit transpiration because root activity shifted toward the soil surface and accessed infiltrated rainfall.
- Long term waterlogging, when combined with salinity, reduced *M. halmaturorum* water use and groundwater use through restrictions in rooting depth. Subsequent salt accumulation in the surface soil over summer resulted in a decline in health. There were no visible morphological changes to waterlogging, but there was a change in root distribution to the soil surface. This salinity/waterlogging interaction is different than those previously suggested.
- Sustainability of *M. halmaturorum* water use and health depended on the annual fluctuating of saline groundwater which diluted accumulated salts in the soil profile.

7.5 Implications for Management

Results from this study illustrate the importance of flooding and groundwater fluctuations in sustaining wetland health in the Upper South East of South Australia. These processes are important in maintaining soil salinity at levels that can be tolerated by *M. halmaturorum*. Results from this study also illustrate the sensitivity of *Melaleuca* health to long term waterlogging with saline water and assist in further defining the tolerance of *M. halmaturorum* to these conditions. These results have implications for the sustainability of trees that are planted in groundwater discharge areas. Where agricultural land is affected by secondary salinisation it has been suggested that trees can be planted in various parts of the landscape to interact with the groundwater and re-establish the hydrological balance. The sustainability of tree plantings in groundwater discharge areas will be influenced by this salt accumulation and any salt removal mechanisms that occur in the environment along with the plant tolerance to salinity. The interactions between plant processes and landscape processes (hydrogeological) will determine their use in groundwater discharge and the sustainability of their performance. In order for these trees to survive, leaching or dilution of salt will need to occur.

7.6 Further Work

Further work should be directed towards developing a general model of tree water use in groundwater discharge areas so as to predict the response of trees planted in such areas. This should include the further studies of systems where there are gaps in the knowledge (e.g. pastures over highly saline groundwater) to see how these different studies fit a general model of tree water use. Further work should be concerned with testing the effects of periods of longer term flooding with fresh and saline water on the water use of *M. halmaturorum*. The current studies were conducted during relatively dry years and so morphological responses to flooded conditions were not observed.

Appendix I . Field study programme

date	DI	LES	HAN	JAF
26/10/93 - 28/10/93	1.1	hp, si, soil, gw	hp, si, soil	hp, si, soil
7/11/93 - 8/11/93	1.2	hp, g, Ψ , gw	hp, Ψ	hp, Ψ
29/11/93 - 2/12/93	2	hp, g, soil, si, Ψ , gw	hp, g, soil, si, Ψ , gw	hp, g, soil, si, Ψ , gw
27/12/93 - 29/12/93	3	hp, g, soil, si, Ψ , gw	hp, g, soil, si, Ψ , gw	hp, g, soil, si, Ψ , gw
1/2/94 - 4/2/94	4	hp, g, soil, si, Ψ , gw	hp, soil, si, Ψ , gw	hp, soil, si, Ψ , gw
21/2/94 - 24/2/94	5	hp trees set up for scaling expt.		
26/2/94 - 2/3/94		scale, hp, si, soil, bratio, g, Ψ , gw, root		
3/3/94 - 4/3/94			hp, soil, si, Ψ , gw	hp, soil, si, Ψ , gw
5/4/94 - 8/4/94	6	hp, g, soil, si, Ψ , gw, root, fe, cut tree	hp, soil, si, Ψ , gw, fe	hp, soil, si, Ψ , gw, fe
24/5/94 - 28/5/94	7	hp, soil, si, Ψ , gw, root, fe	hp, g, soil, si, Ψ , gw, fe	hp, soil, si, Ψ , gw, fe
5/7/94 - 8/7/94	8	hp, g, soil, si, Ψ , gw, root, fe	hp, soil, si, Ψ , gw, fe	hp, soil, g, si, Ψ , gw, fe
15/8/94 - 18/8/94	9	hp, soil, si, Ψ , gw, root, fe	hp, g, soil, si, Ψ , gw, fe	hp, soil, si, Ψ , gw, fe
19/9/94 - 23/9/94	10	hp, g, soil, si, Ψ , gw, root, fe, redox, rm	hp, soil, si, Ψ , gw, fe, redox, rm, scale	hp, g, soil, si, Ψ , gw, fe, redox, rm, scale
3/11/94 - 4/11/94	11	hp, soil, si, Ψ , gw, root, fe	hp, soil, si, Ψ , gw, fe	hp, soil, si, Ψ , gw, fe
30/1/95 - 2/2/95	12	hp, soil, si, Ψ , gw, root, fe, sv, redox	hp, soil, si, Ψ , gw, root, fe, redox	hp, soil, si, Ψ , gw, root, fe, sv, redox
11/2/95	13	Ψ all night		
31/10/95 & 8/3/96		Ψ , pv		

most sampling trips were conducted over a one week period

hp= sap flow installed, data then collected over the rest of the sampling period (chapter 3)

si = samples collected for extraction of water stable water isotope analysis (chapter 5)

soil = soil samples collected for soil water potential (chapter 4)

gw= groundwater sampled from observation bore and depth measured (chapter 4)

g= stomatal conductance measured (chapter 3)

Ψ = leaf water potential measured (pre dawn and mid-day; chapter 4)

scale= site data collected for heat pulse scaling

bratio= bowen ratio measurements taken

root= root growth observations at chamber window (chapter 5)

fe= ferrous iron test for soil waterlogging (chapter 4)

redox= soil cores sampled for redox measurements (chapter 4)

rm= soil cored for root mass measurements (chapter 5)

sv= health and community composition survey (chapter 2)

pv= collection of leaves for pressure volume curve analysis (chapter 4)

Appendix II . Rainfall at Jaffreys Swamp

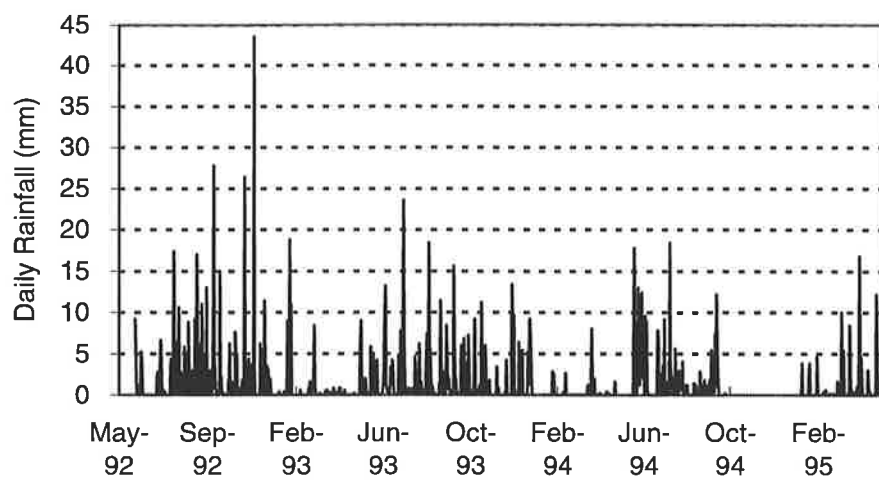


Figure A2: Rainfall (mm) at Jaffreys Swamp weather station from May 1992 to April 1995 (from McEwan and Kennett-Smith, 1995)

Appendix III . Heat Pulse Technique

Sensors should be placed at a variety of depths to identify velocities at high and low velocity parts of the sapwood (see Fig below). In the current study the tree sapwood were generally not very extensive (1-2 cm thick) because of the nature of the environment and so the placement of 4 sensors usually covered the entire sapwood. The following tabulates the characteristics of the wood that were used to identify the placement of the probes and then calculate the flux from velocities.

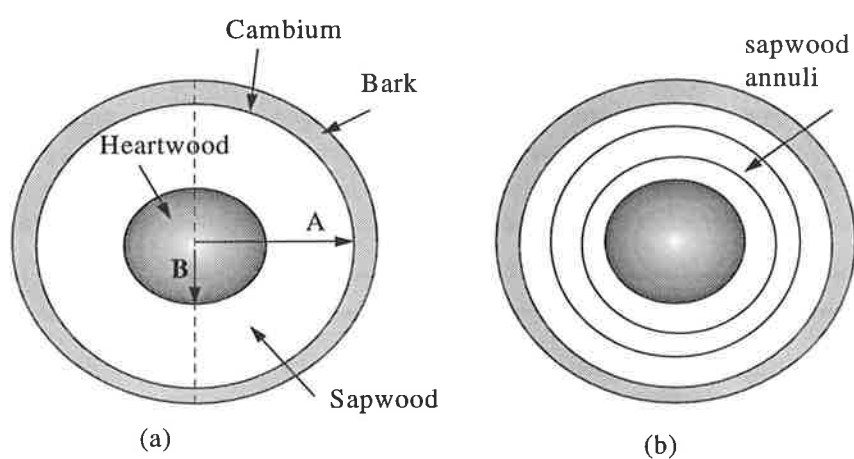


Figure A3: (a) Sapwood, bark and heartwood definitions as used for determination of sensor insertion depths (Greenspan, 1995; A and B are defined in tables below) and (b) sapwood separation into annuli or calculation of flux using the mean weighted average technique (Hatton et al, 1990).

Table A3: Tree parameters for insertion of heat pulse sensors, calculation for sap velocity and flux (as per Greenspan heat pulse manual, 1995).

parameters DI -Single stemmed	probe 1	probe 2
Cambium/Bark thickness (mm)	5	4
Inner Sapwood Radius (mm) B	12	16
Inner Cambium Radius (mm) A	28	33
Volume fraction of wood	0.39	0.39
Volume fraction of water	0.33	0.33
Depth of probe tip (mm)	17	21
Space between sensors (mm)	5	5
Wound diameter (mm)	3	3
Aspect of implant (mm)	W	E

parameters Les - Single stemmed	probe 1	probe 2
Cambium/Bark thickness (mm)	2	2
Inner Sapwood Radius (mm)B	26	25
Inner Cambium Radius (mm)A	35	35
Volume fraction of wood	0.38	0.38
Volume fraction of water	0.29	0.29
Depth of probe tip (mm)	15	15
Space between sensors (mm)	5	5
Wound diameter (mm)	3	2.5
Aspect of implant	S	W

parameters Han - Double stemmed	probe 1 -stem 1	probe 2 - stem 2
Cambium/Bark thickness (mm)	3	3
Inner Sapwood Radius (mm)B	13	13
Inner Cambium Radius (mm)A	21	21
Volume fraction of wood	0.37	0.37
Volume fraction of water	0.41	0.41
Depth of probe tip (mm)	19	18
Space between sensors (mm)	5	5
Wound diameter (mm)	3	4
Aspect of implant	W	E

parameters Jaf - Single stemmed	probe 1	probe 2
Cambium/Bark thickness (mm)	3	3
Inner Sapwood Radius (mm)B	5	5
Inner Cambium Radius (mm)A	32	32
Volume fraction of wood	0.45	0.45
Volume fraction of water	0.33	0.33
Depth of probe tip	18	25
Space between sensors (mm)	5	5
Wound diameter (mm)	1.9	1.9
Aspect of implant (mm)	S	E

Appendix IV . Scaling data for all trees

Table A4: Tree parameters used in scaling experiment; tree diameter (cm), circumference (cm), sapwood area (cm²), leaf area (m²), tessellated ground area (m²) and projected canopy area (m²).

tree no.	mean diam (cm)	mean circ (cm)	sapwood area (cm ²)	leaf area (m ²)	tess ground area (m ²)	canopy proj area (m ²)
DI1	72	226	23	6.4		
DI2	146		37	15.4		
DI2a	66	207	19	6.1		
DI2b	80	251	18	9.2		
LES1	74	232	15.1	2.3		
LES2	86	270	15.2			
HAN1	96	301	16.8	3.46		
HAN1a	48	150.5	7.3			
HAN1b	48	150.5	9.5			
HAN2	62	194.8	17.5	3.46		
JAF1	80	251	35	19.3		
JAF2	118		80.8			
24	123	386	29.82	4.8	14.3	5.726
9	168	527.8	50.67	7.6	6	9.079
10	260.5	818.4	79.86	26	6.1	25.52
11	267.5	840.4	113.5	16.8	15.3	17.72
12	209.5	658.2	65.82	13.2	9.9	15.55
23	65	204.2	18.54	1.6	11.4	1.887
13	334	1049.3	192.5	22	9	44.18
22	65	204.2	19.16	0.6	12.7	0.785
15	225	706.9	86.16	6.4	7	12.25
16	345	1083.8	149.6	14.8	12.1	28.27
20	397	1247.2	184.4	12.8	11.7	12.25
20.1	179.5	563.9	93.65	4		
20.2	98	307.9	35.78	3		
20.3	119.5	375.4	54.98	3		
19	112	351.9	37.17	11.6	9.3	6.951
17	537.5	1688.6	286.9	30.8	14.5	46.57
21	24	75.4	3.53	0.4	10.1	0.866
14	38.5	120.9	7.21	0.8	4	1.327
18	465	1460.8	158.1	39.2	23.1	56.08
1	104	326.7	34.31	4.2	8.9	4.811
2	45.5	142.9	4.712	0.8	7.7	0.332
3	314	986.5	56.34	15.6	9.3	13.2
3.1	75	235.6	14.33	4.4		
3.2	65	204.2	14.14	3.6		
3.3	60	188.5	7.862	2.4		
3.4	114	358.4	20.01	5.2		
4	442.5	1151.4	97.04	21.2	11.9	18.86
4.1	93	292.2	18.35	3.6		
4.2	113	355	31.79	4.8		
4.3	160.5	504.2	28.92	12.8		
5	76	238.7	17.98	12.8	14	1.767
6	553	1737.3	153.2	29.2	18.4	15.9
6.1	120	376.9	36.95	5.2		
6.2	78	245	19.7	5.2		
6.3	129	405.3	35.94	5.6		
6.4	96	301.6	21.36	5.6		
6.5	130	408.4	39.21	7.6		

Appendix V . Actual Evapotranspiration; Bowen ratio

The energy balance, or Bowen ratio method, was used to determine vapour flux above the *M. halimaturorum* swamp forest. The ratio of heat transferred as sensible heat (H) to that transferred as latent heat (λE_t) by transpiration is called the Bowen ratio (β) where;

$$\beta = \frac{H}{\lambda E_t}$$

The Bowen ratio is usually small over moist surfaces (0.1-0.5) and large over dry, arid surfaces (~5) (Stull, 1988).

The technique measures the finite differences of temperature (T) and humidity (e) in the boundary layer and relates their ratio to that of the sensible and latent heat fluxes by the Bowen ratio (β);

$$\beta = \left(\frac{PC_p}{L\varepsilon} \right) \left(\frac{\Delta T}{\Delta e} \right)$$

Where P is atmospheric pressure, C_p is specific heat of dry air, L is latent heat of vaporisation, ε is the ratio of molecular masses of water to dry air, and ΔT and Δe are finite differences of potential temperature and vapour pressure. The latent heat flux was then calculated as follows;

$$LE = \frac{R_n - G}{1 + \beta}$$

Where net radiation (R_n) and ground heat flux (G) densities were positive downwards.

Measurements were made by Frank Dunin and Wybe Reyanga of CSIRO Division of Plant Industry as described in detail by (Dunin et al, 1989). Measurements were made on a section of the forest where it was considered at least 90 m of fetch was available from the Melaleuca forest. This measurement site was ~ 10 m from the long term investigation trees and ~ 50m from the trees involved in the intensive scaling measurements (Chapter 3).

Continuous measurements were made at 3 m above the forest, from sunrise (0700 hrs) to sunset (2000 hrs) over a 7 day period from 25.2.94 to 3.3.94. R_n was measured with a net radiometer (Middleton) and ground heat flux was measured with 3 heat flux plates buried at 2 cm (Middleton). Hourly values were integrated for radiation (both solar and net), temperature and humidity, wind run and rainfall (measured at canopy height). A mast 100 m south west of the heat pulse site supported differential psychrometers interchanging each 15

min to provide half hourly values. An averaged value of temperature and humidity was also determined each 15 min at the mid-point between sensors. Temperature and vapour pressure was measured over 1 m interval with the lowest sensors between 0.25 -0.4 m above the canopy. Mean wind direction was recorded each hour.

On most measurement days net radiation peaked at 600 W/m^2 in the middle of the day and VPD peaked at 15-20 mb in the middle of the afternoon (eg 1/3/94; Fig A5.1a). The Bowen ratio was usually greater than 1 being at a minimum in the morning and reaching values of 3-5 in the afternoon (eg 1/3/94 Fig A5.1b). Latent heat ranged from 0.7 to 4 Wm^2 and reached a peak mid-morning and declined in the afternoon (eg 1/3/94 Fig A5.1b). Sensible heat flux peaked in the middle of the day at $\sim 580 \text{ Wm}^2$. Hourly evapotranspiration calculated from these fluxes followed the pattern of net radiation and peaked at 0.18 to 0.2 mm / hr in the afternoon and will be discussed further in chapter 3. Daily totals of evapotranspiration ranged from 1.4 to 1.6 mm/day (Fig A5.1 c).

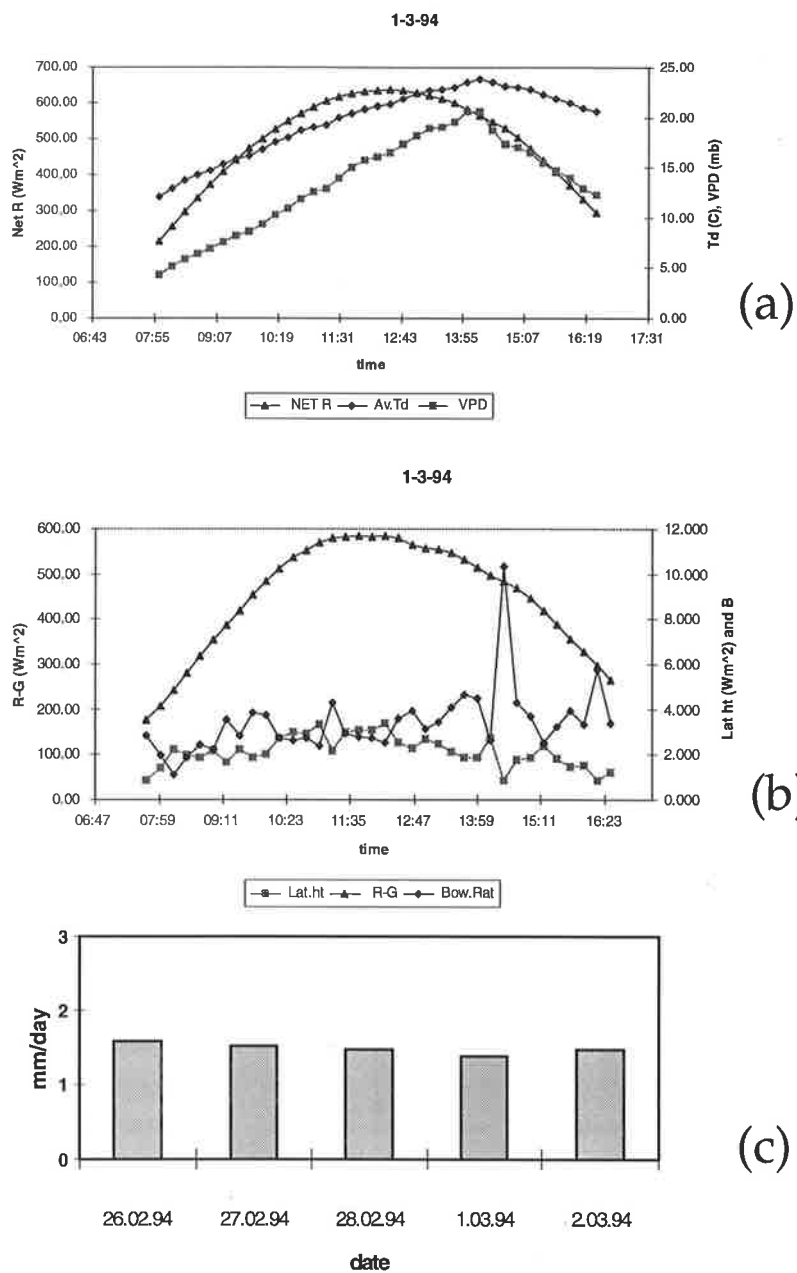
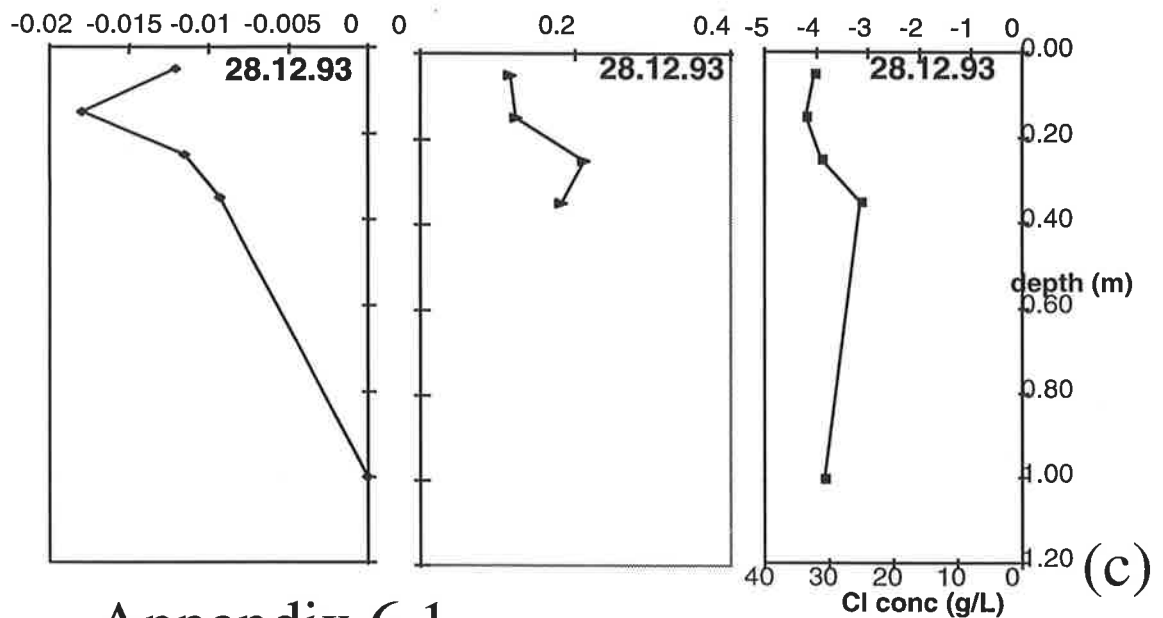
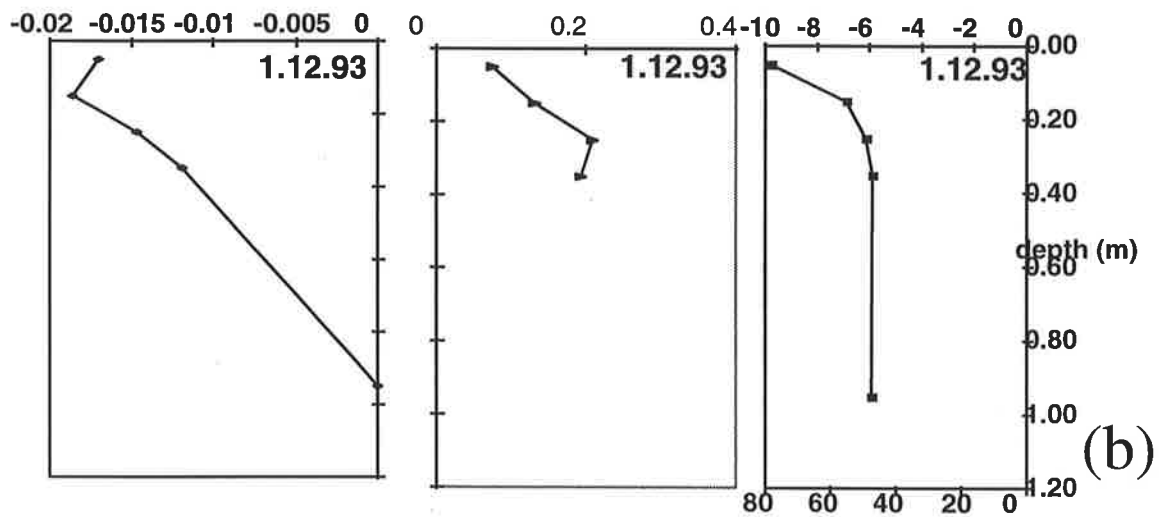
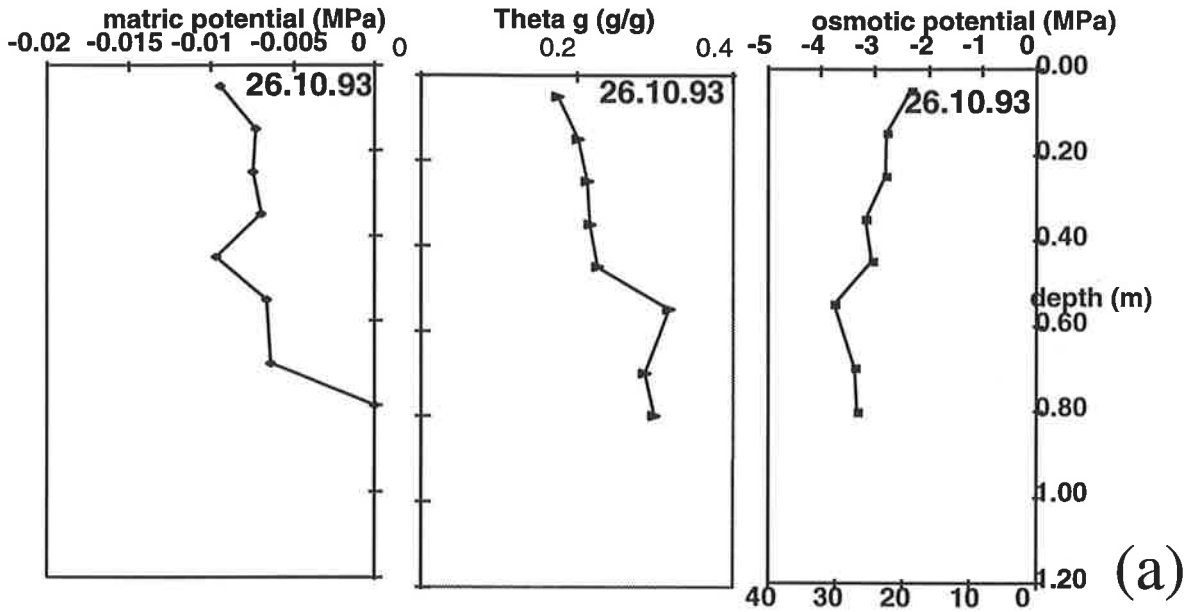


Fig A5: Data obtained during the measurement of actual evapotranspiration with the Bowen Ratio. Incoming net radiation (W/m^2), dry bulb Temperature ($^{\circ}\text{C}$), and VPD (mb) for 1/3/94 (a), R-G (W/m^2), Latent heat production (W/m^2), and the Bowen Ratio (b), and estimated evapotranspiration from this data (mm/day; (c)).

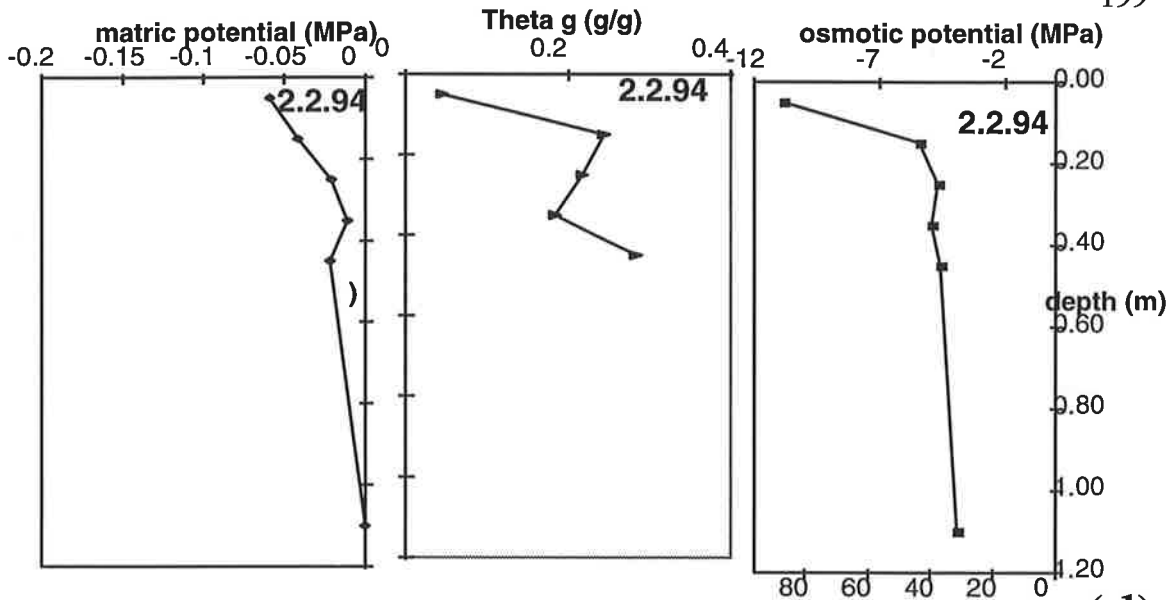
Appendix VI . Soil profiles for all sites at all sampling times.

Soil matric potential, theta g, Soil Chloride and estimated osmotic potential for Duck Island (6.1; a-k), Lesron (6.2; a-k), Hansons (6.3; a-k), and Jaffray (6.4; a-j) for all sampling times.

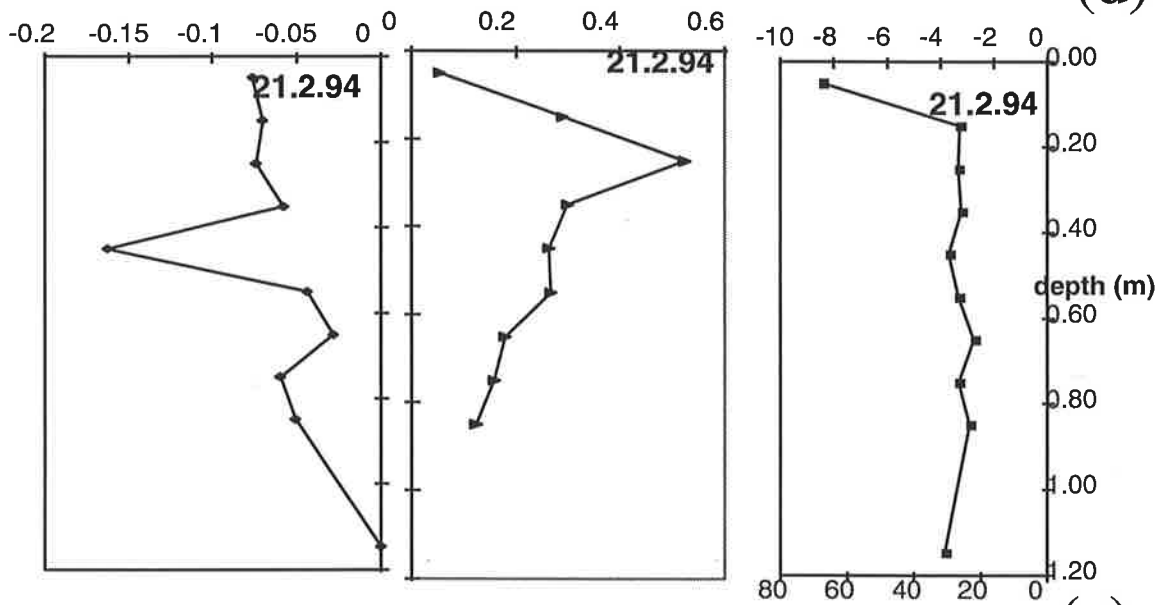
Duck Island



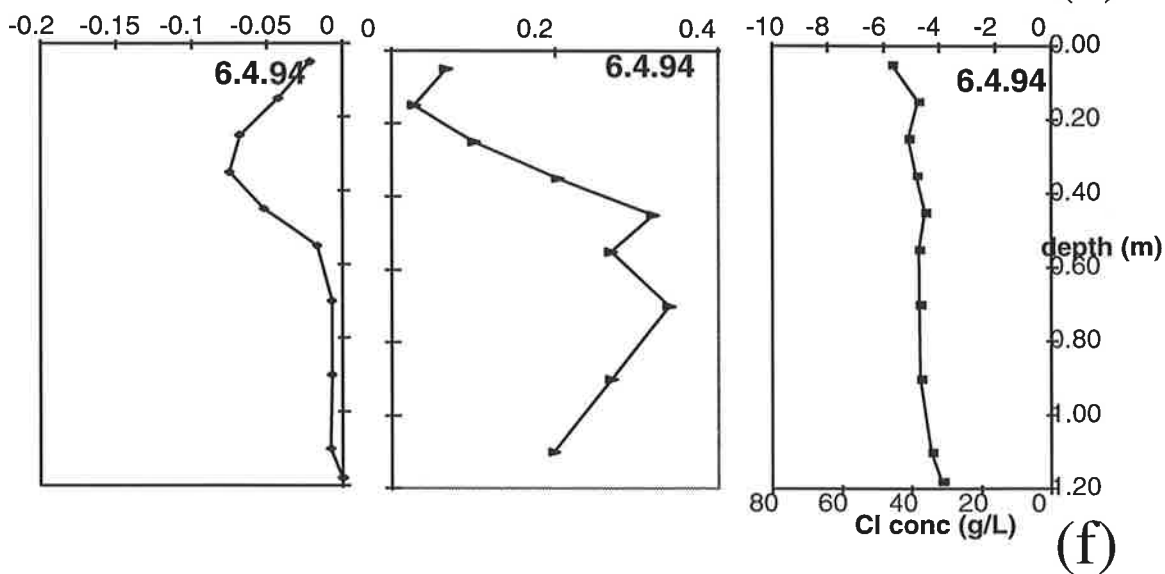
Appendix 6.1



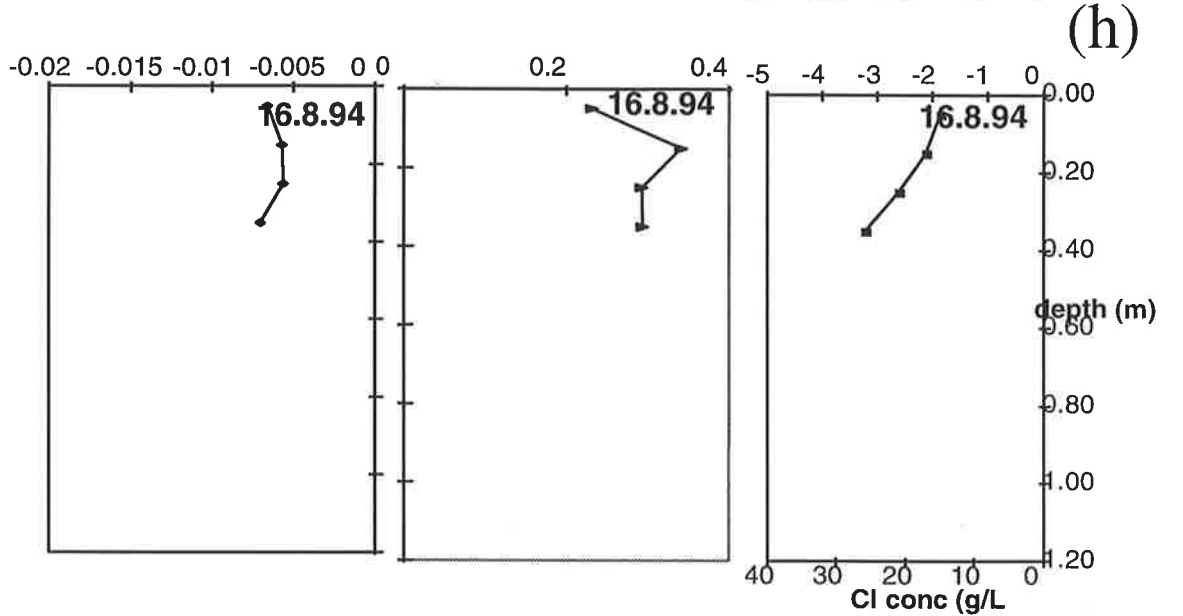
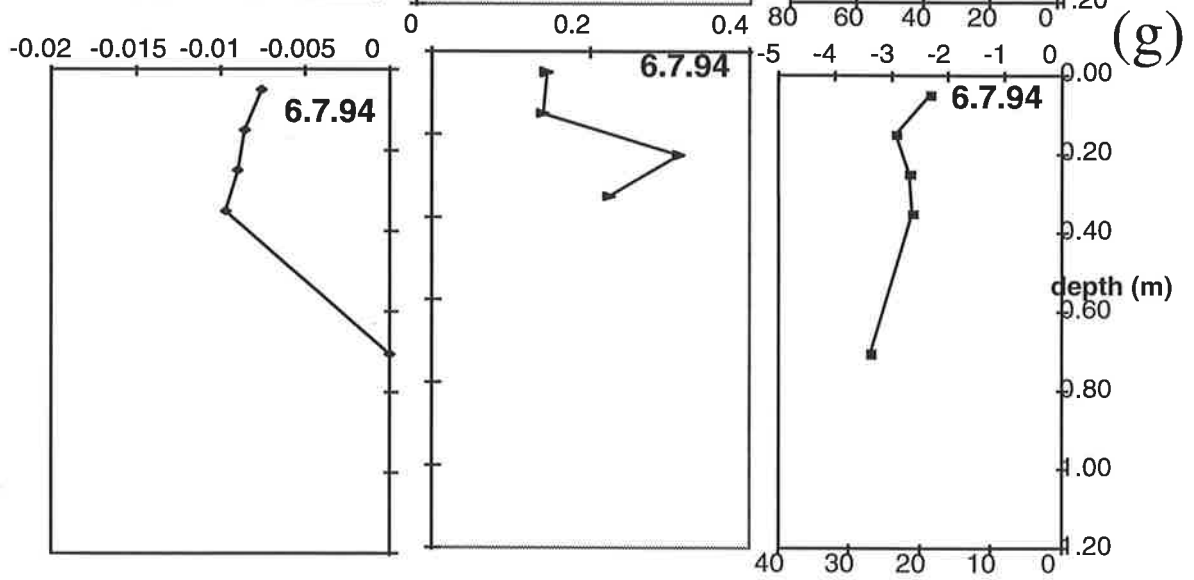
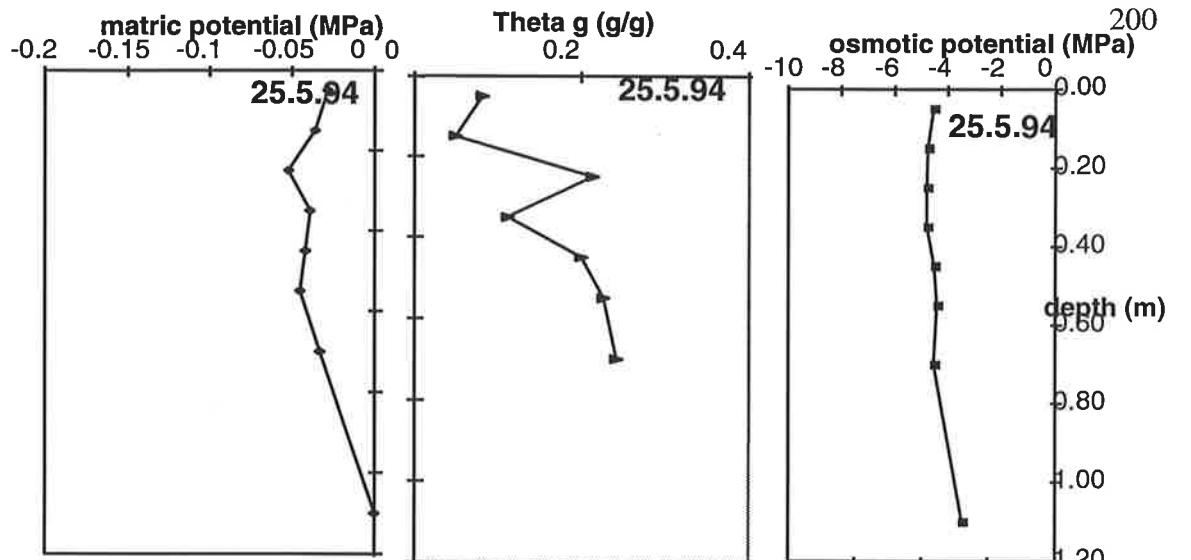
(d)



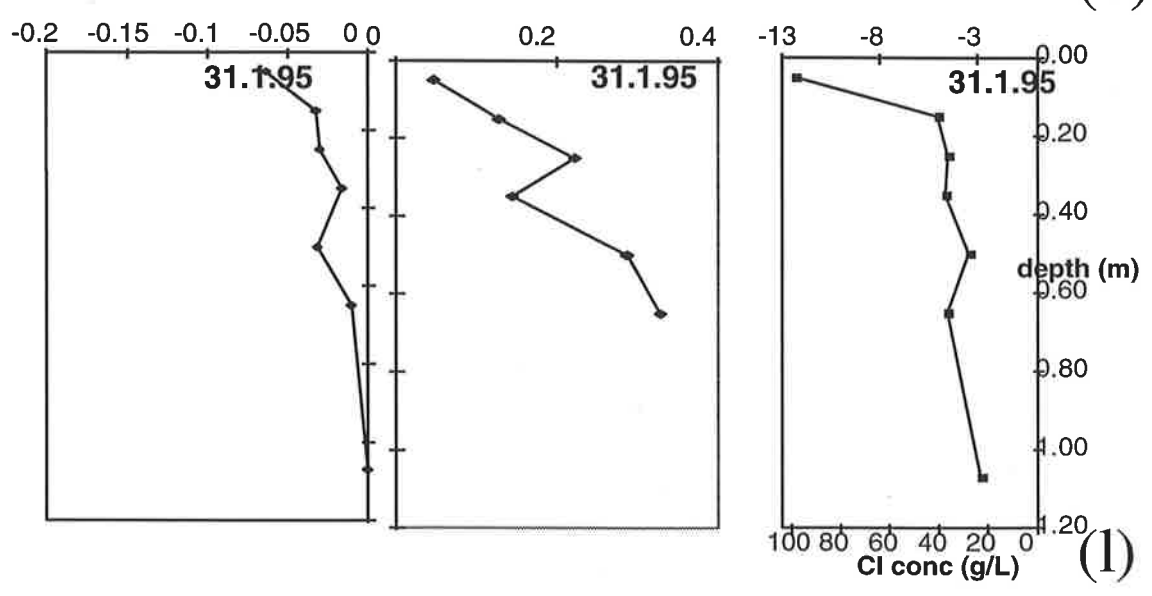
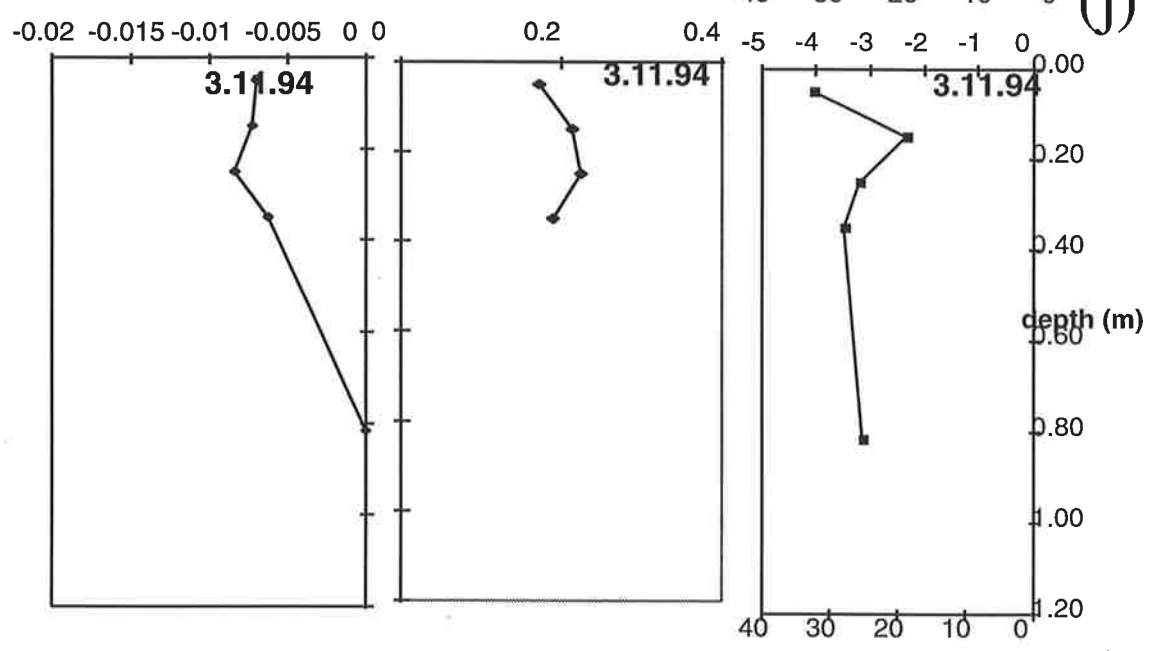
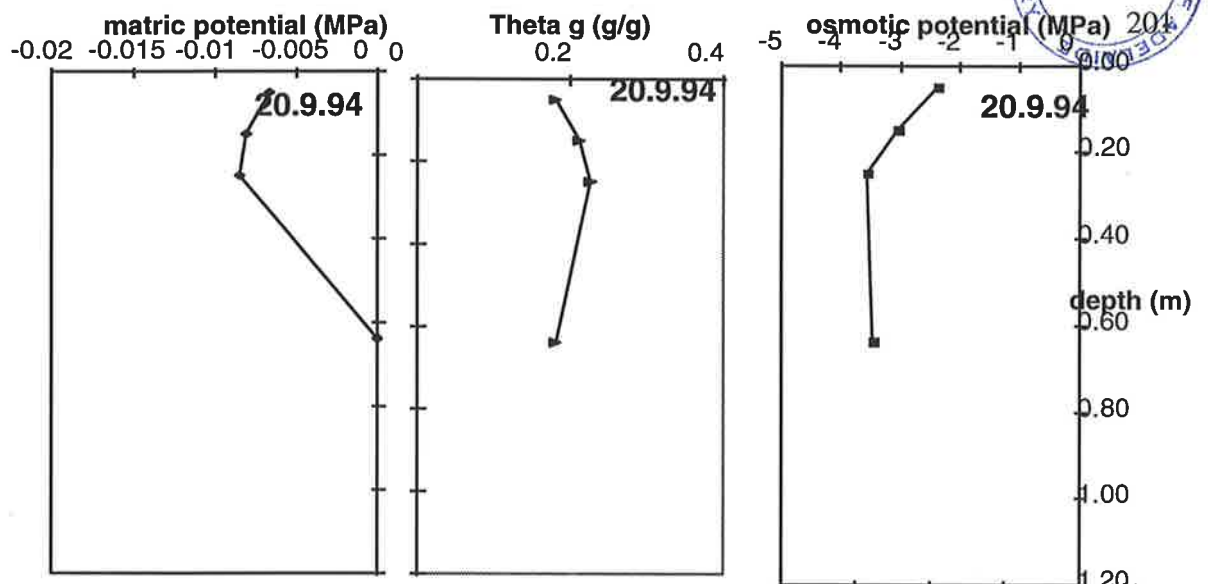
(e)



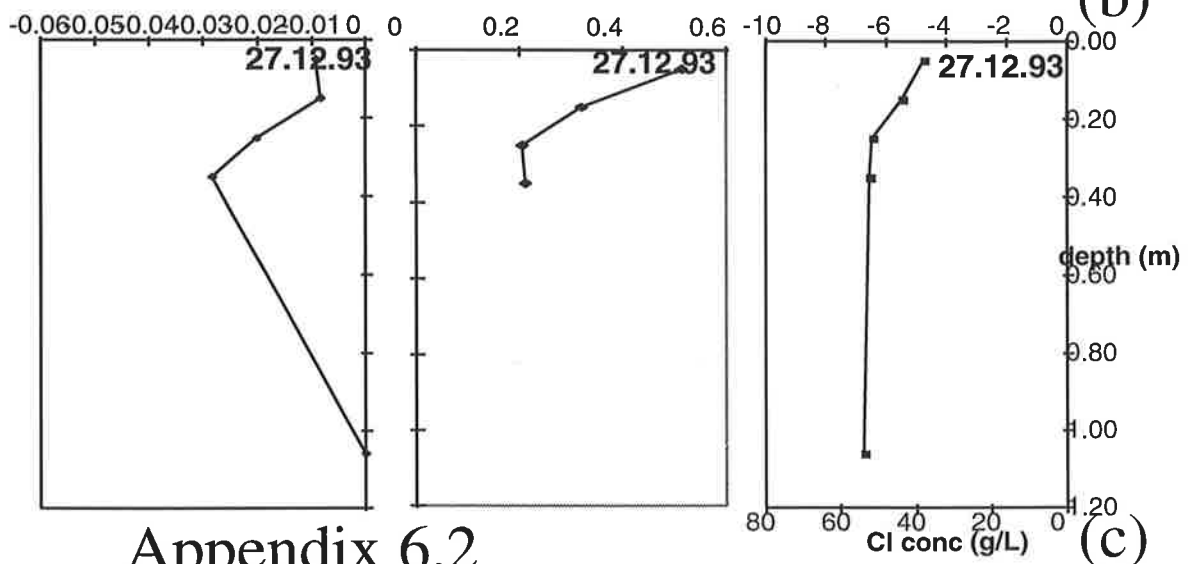
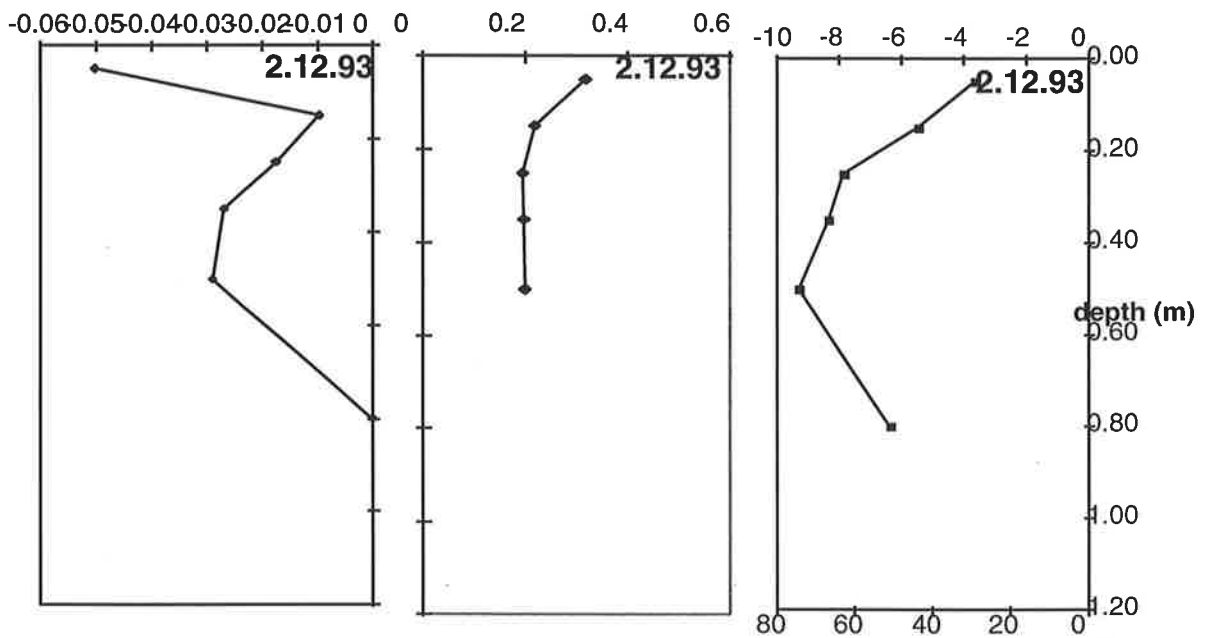
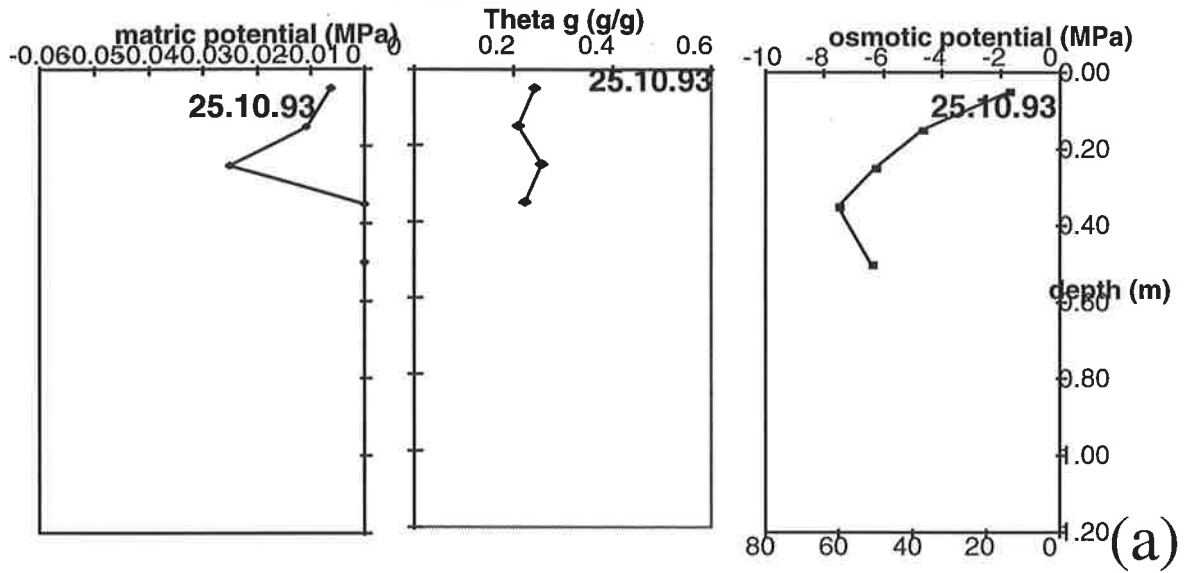
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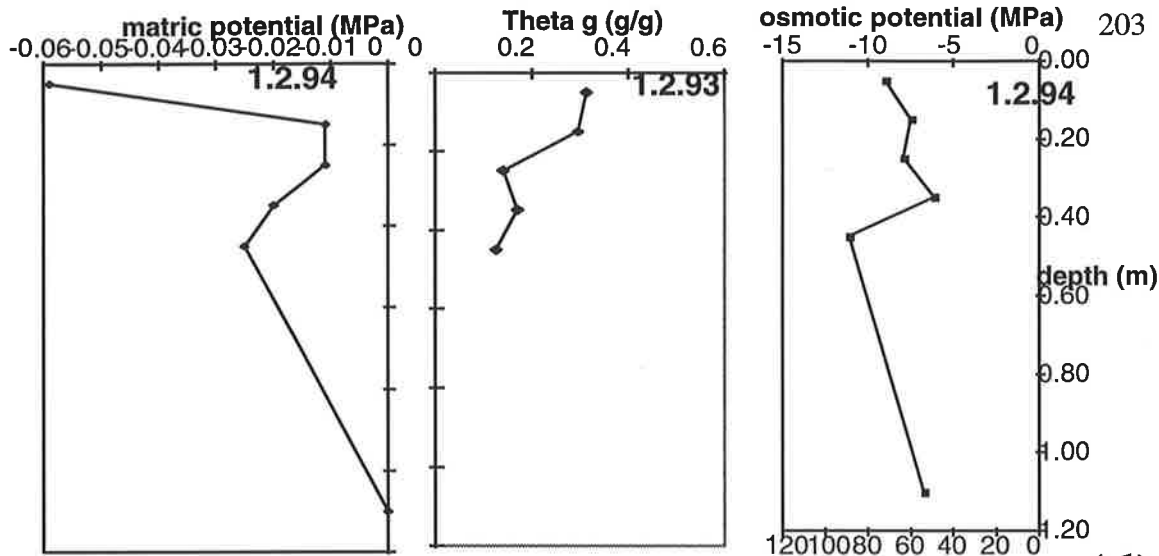


(i)

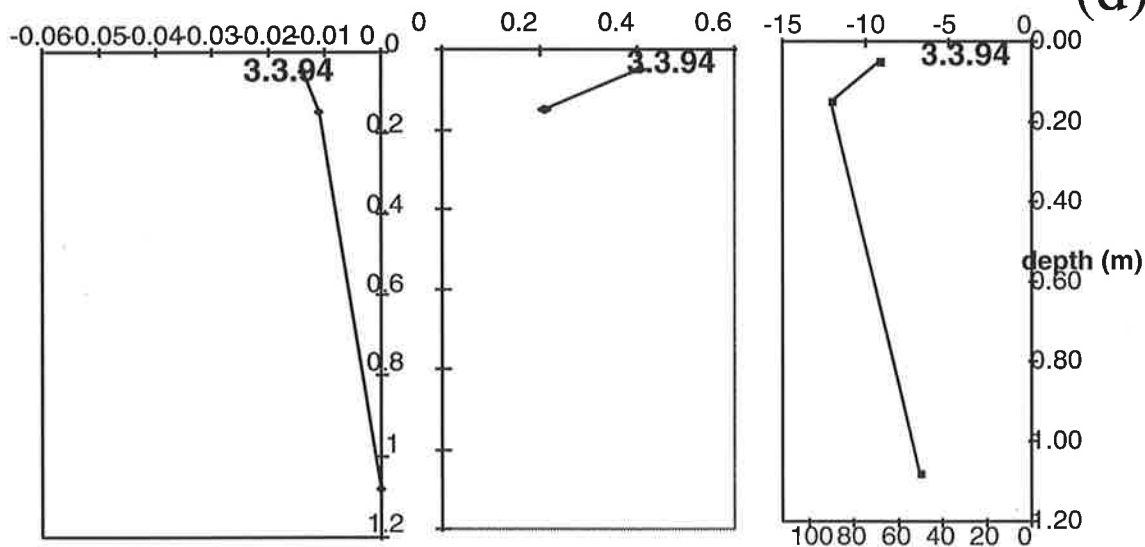


Lesron

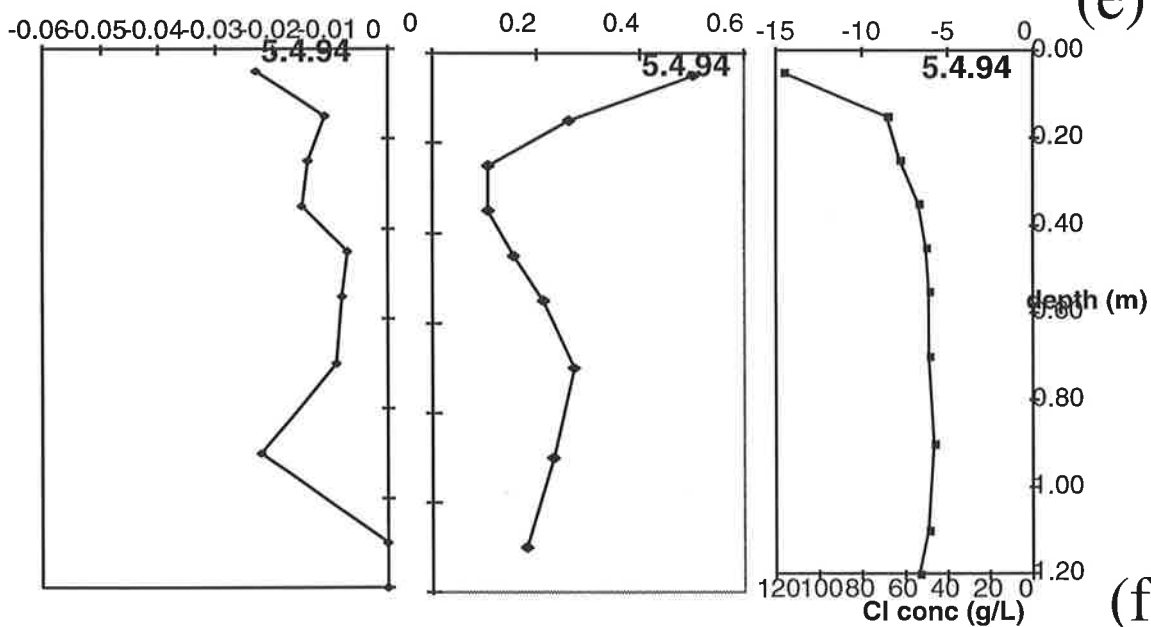




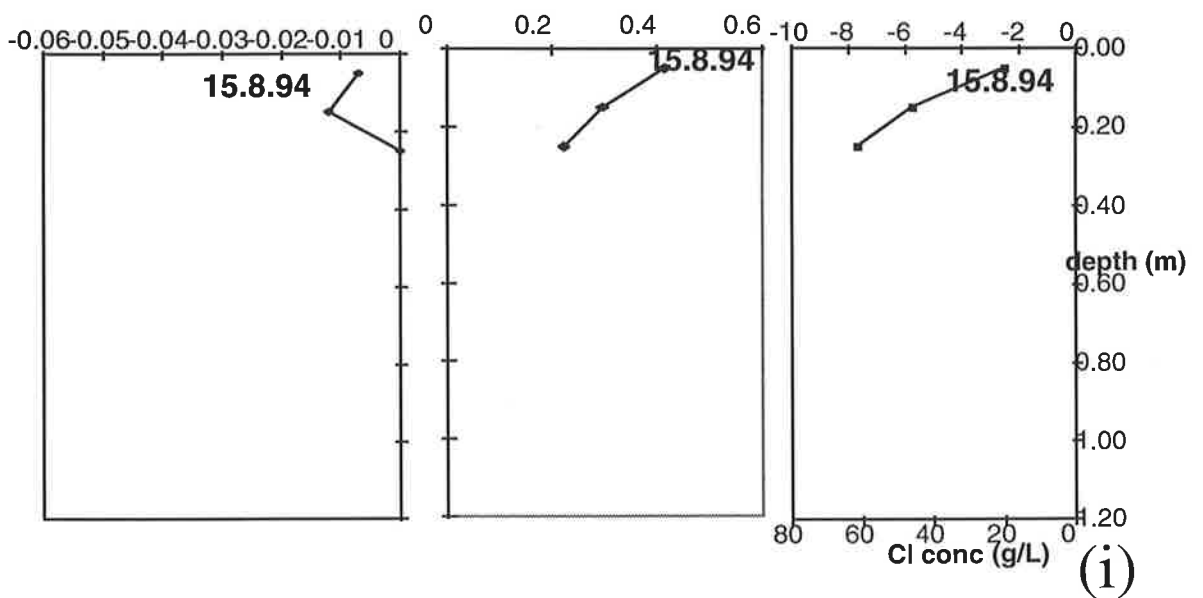
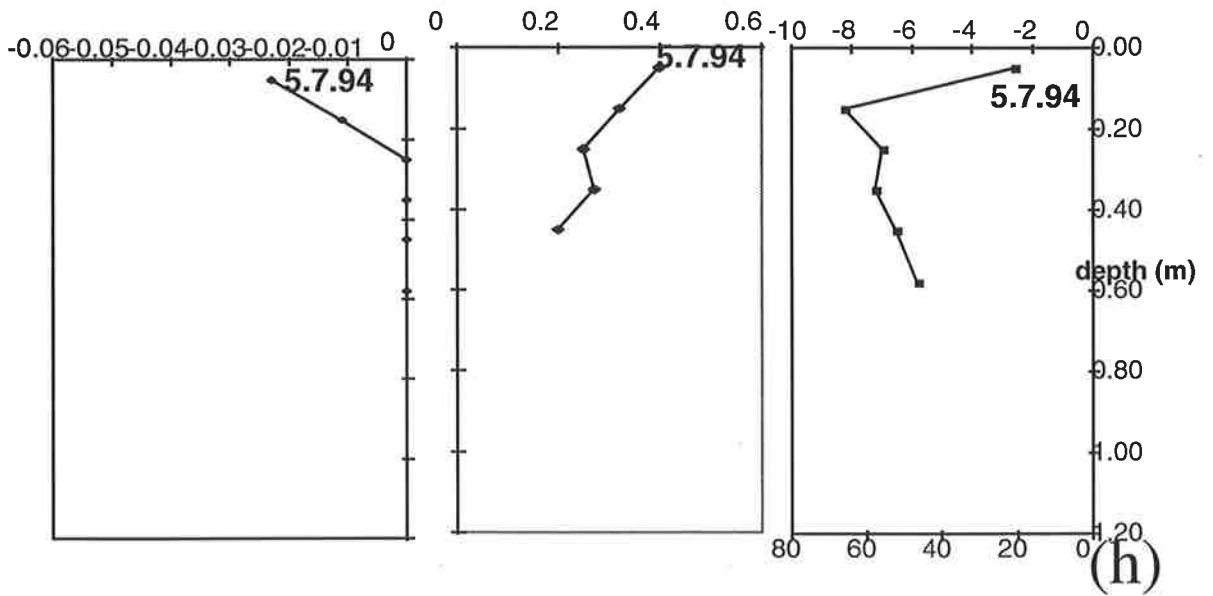
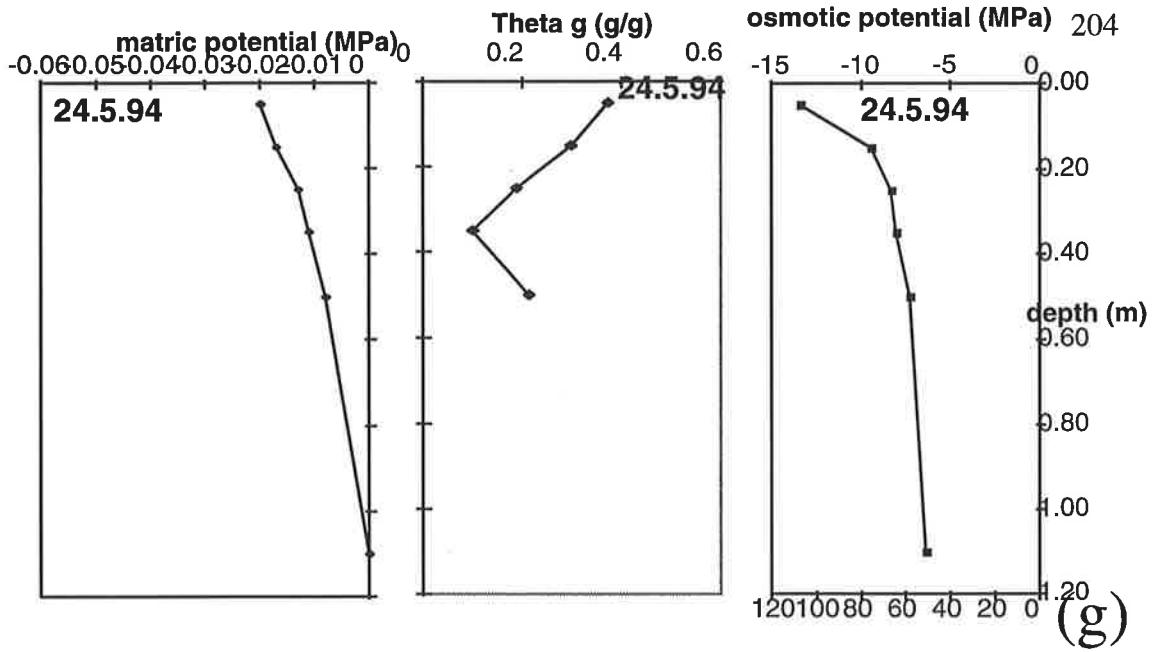
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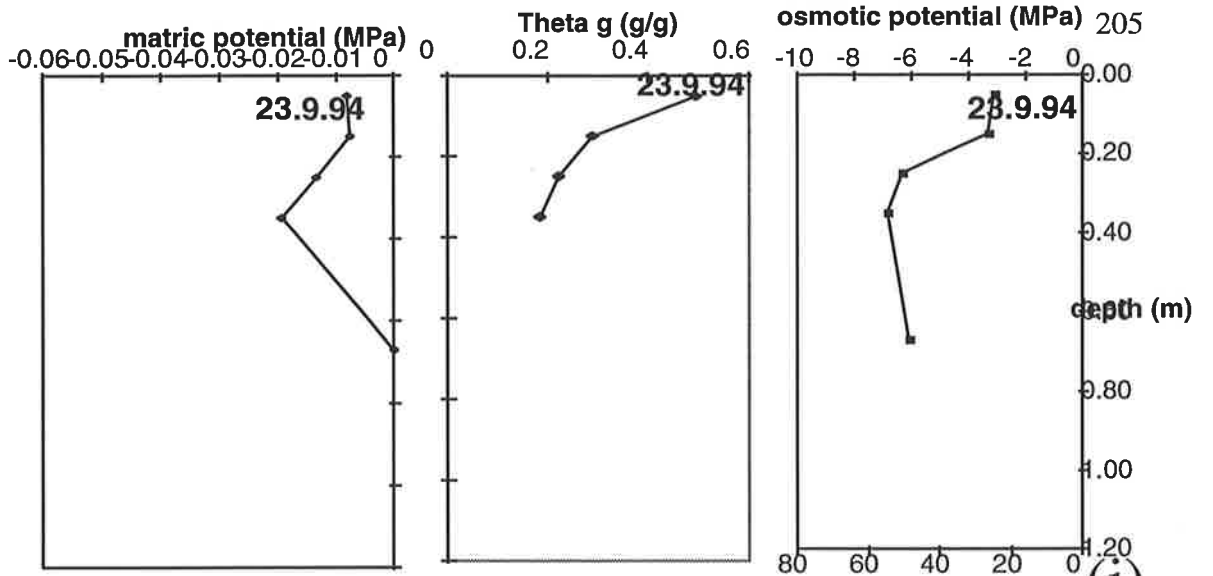


(e)

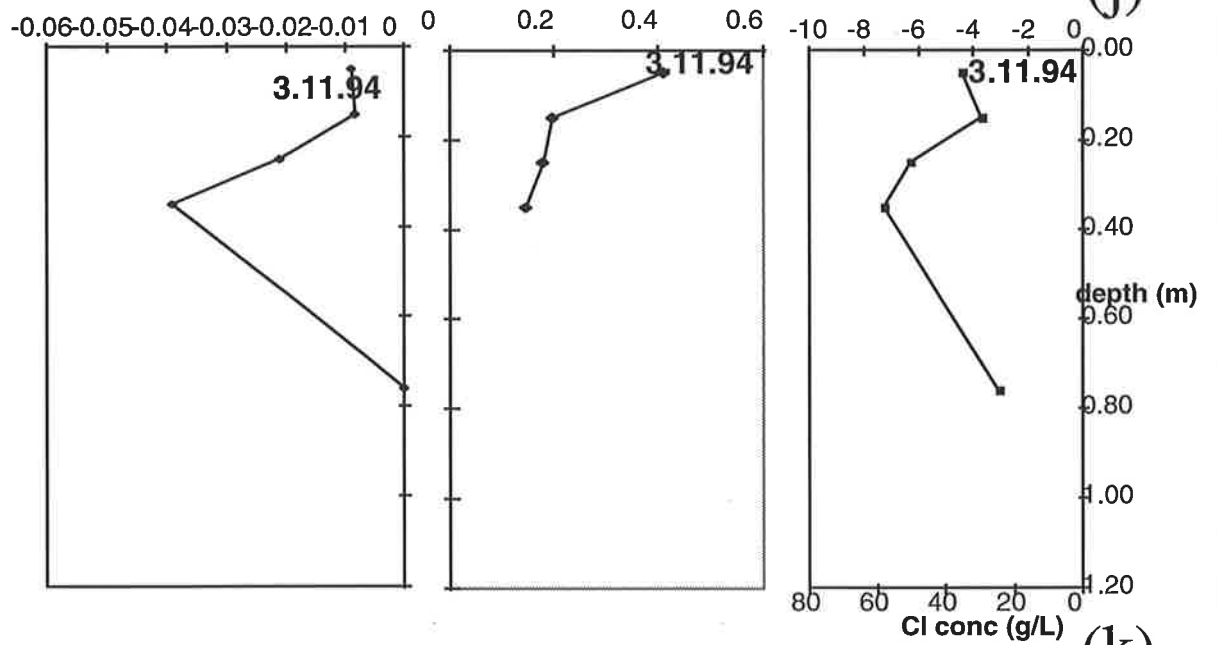


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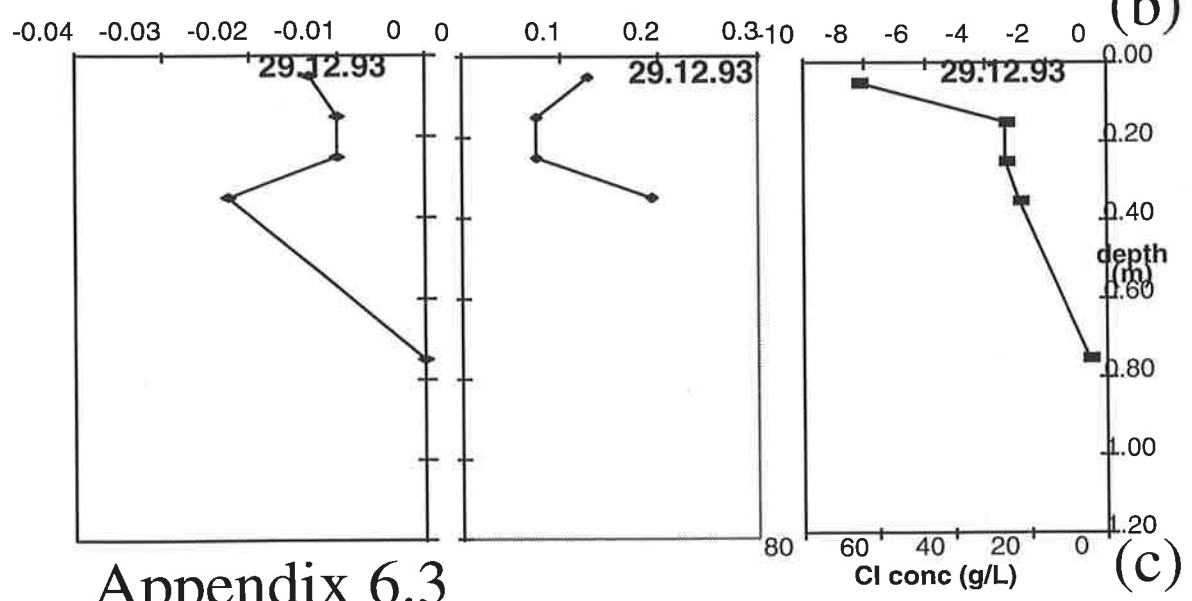
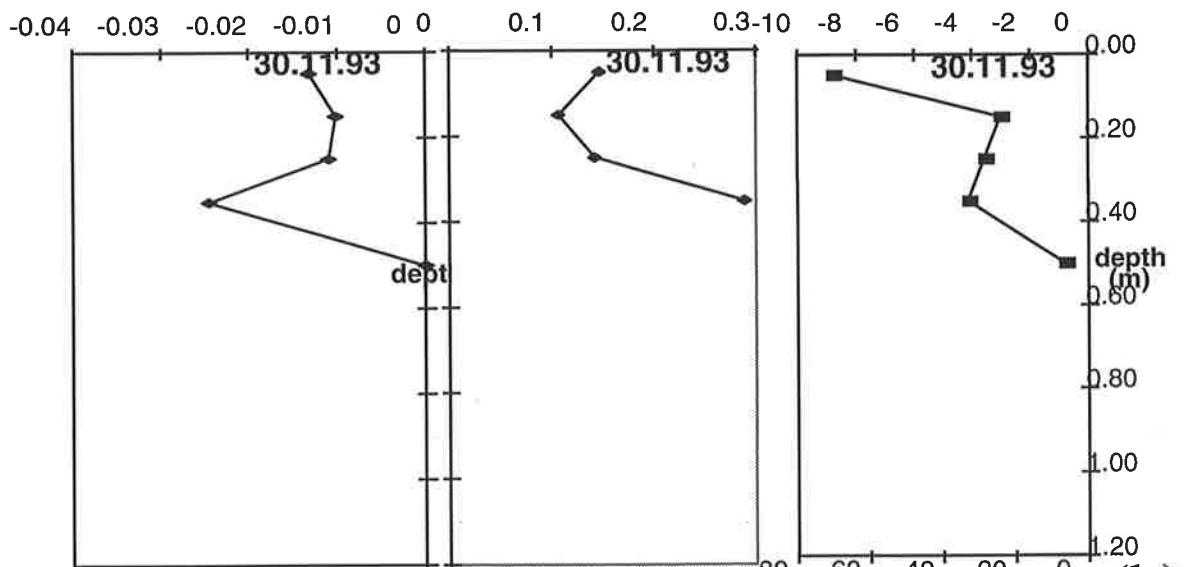
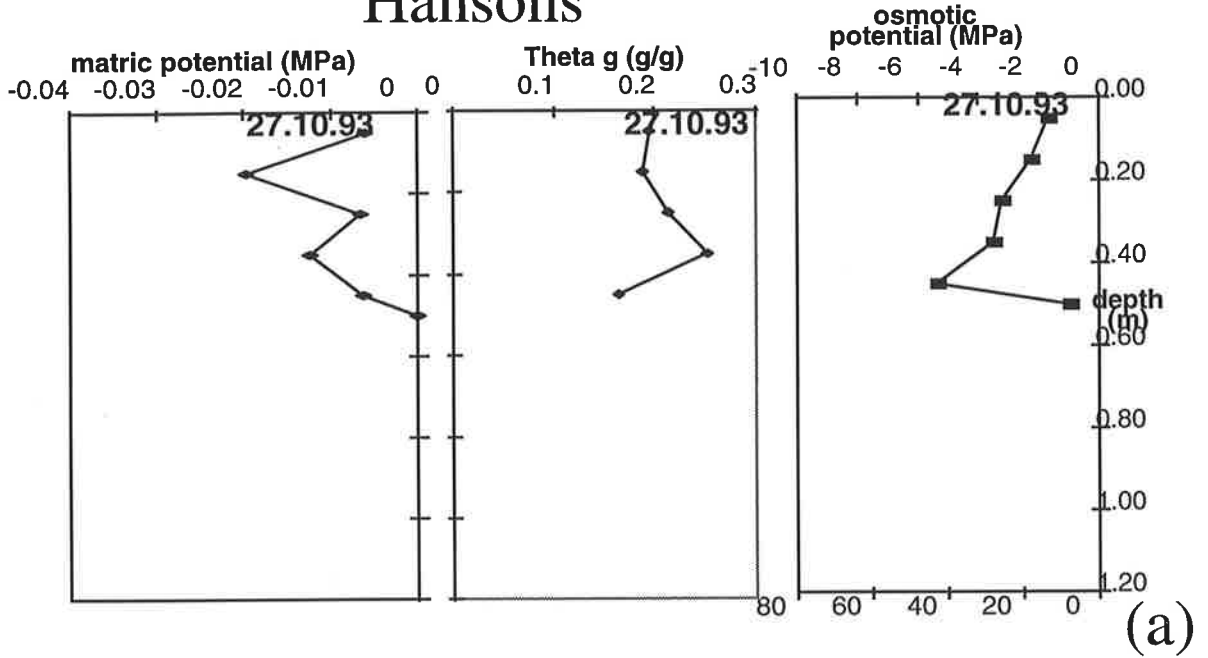


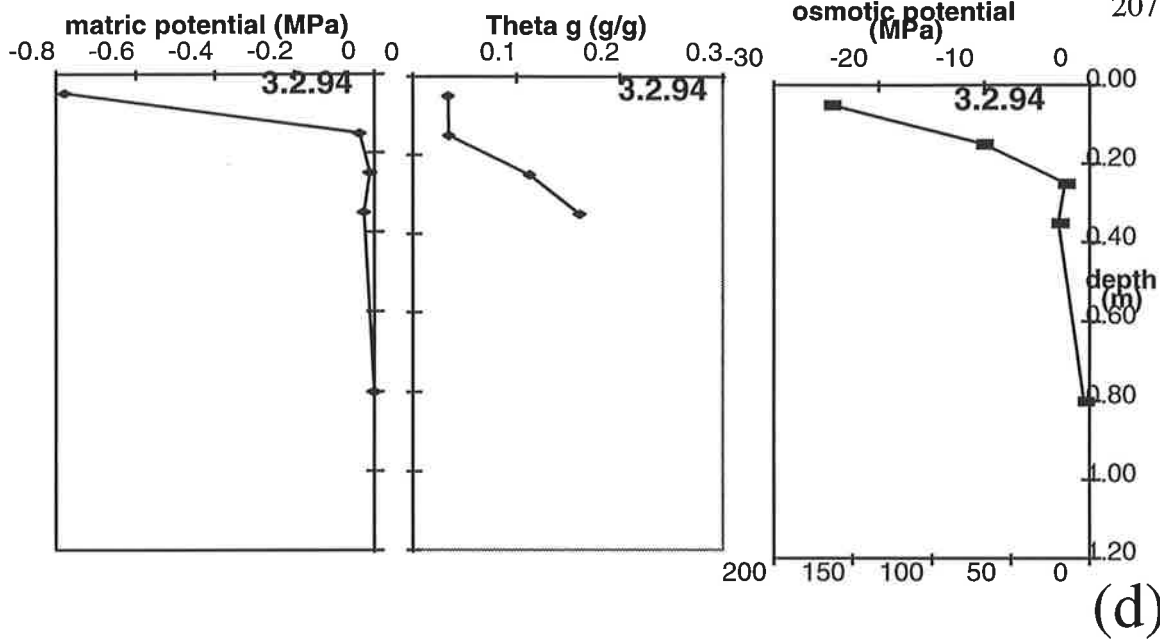
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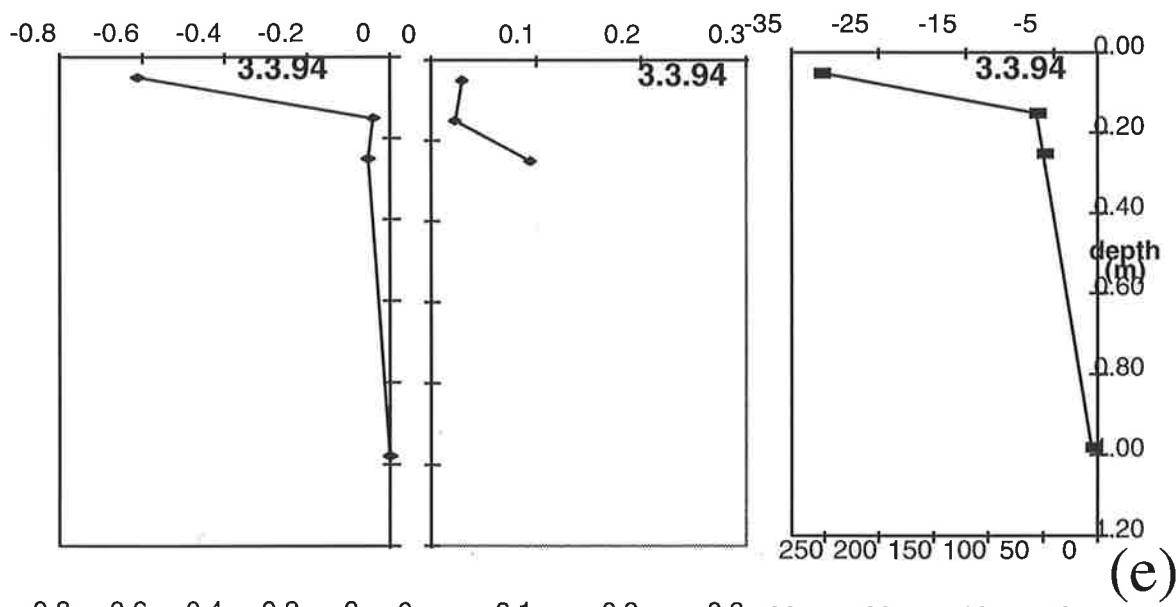
(k)

Hansons

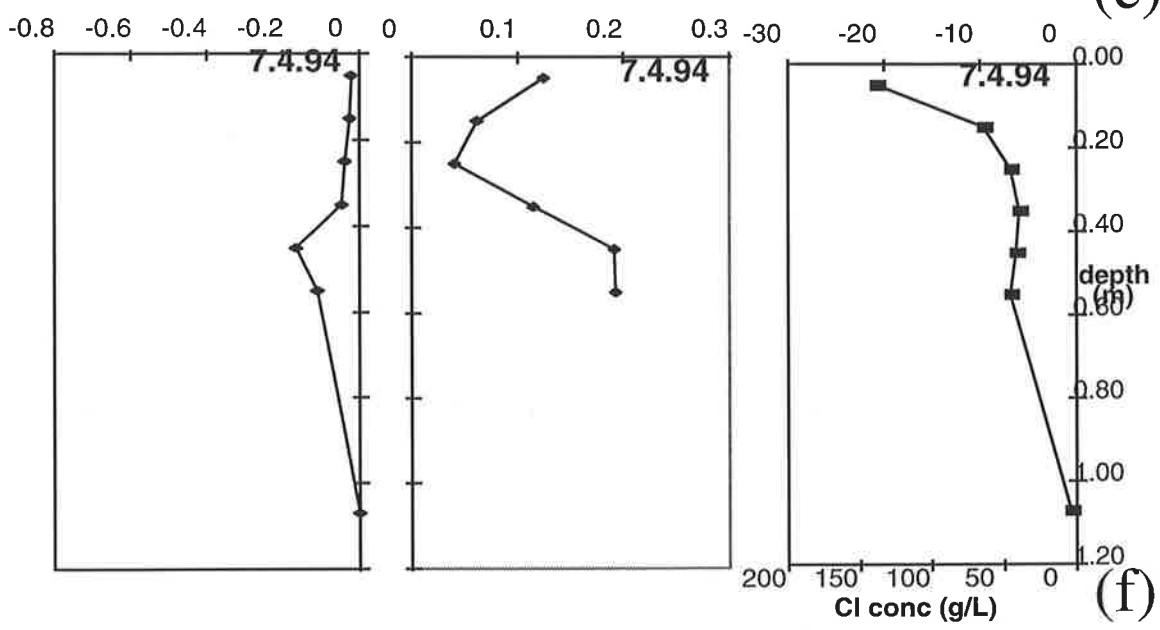




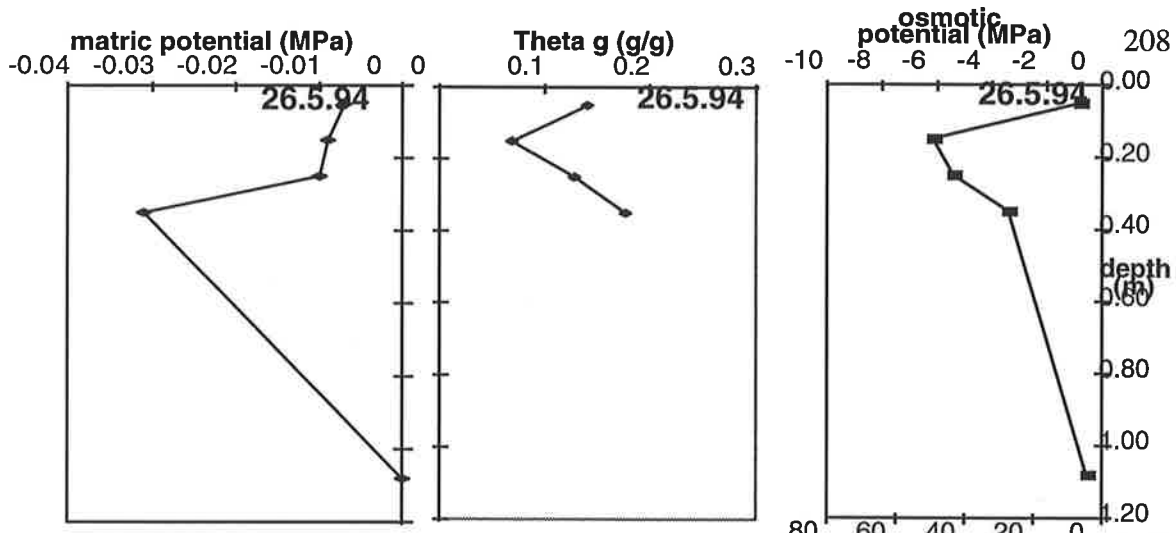
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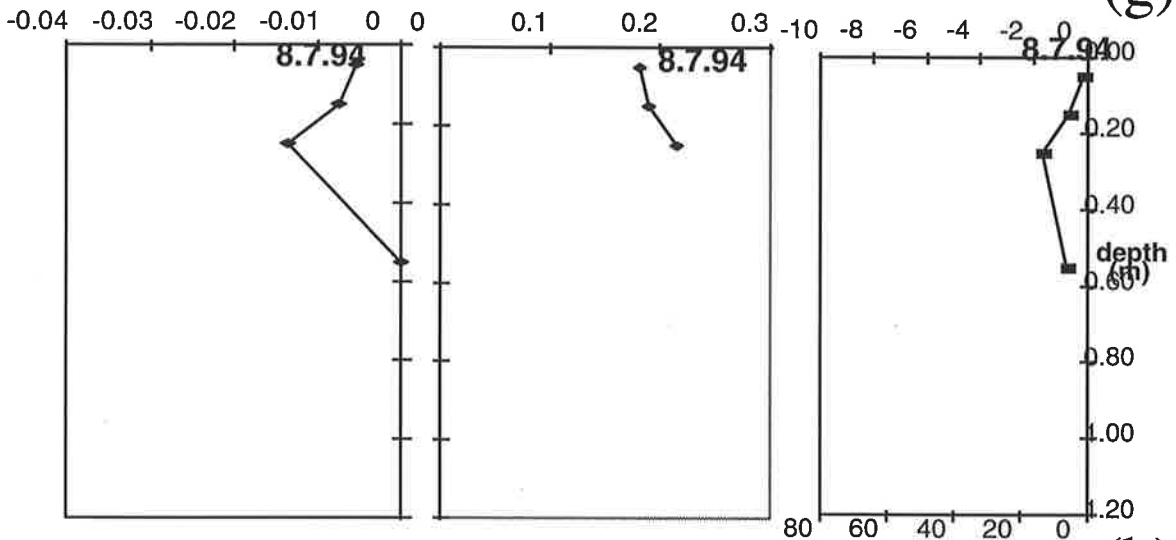
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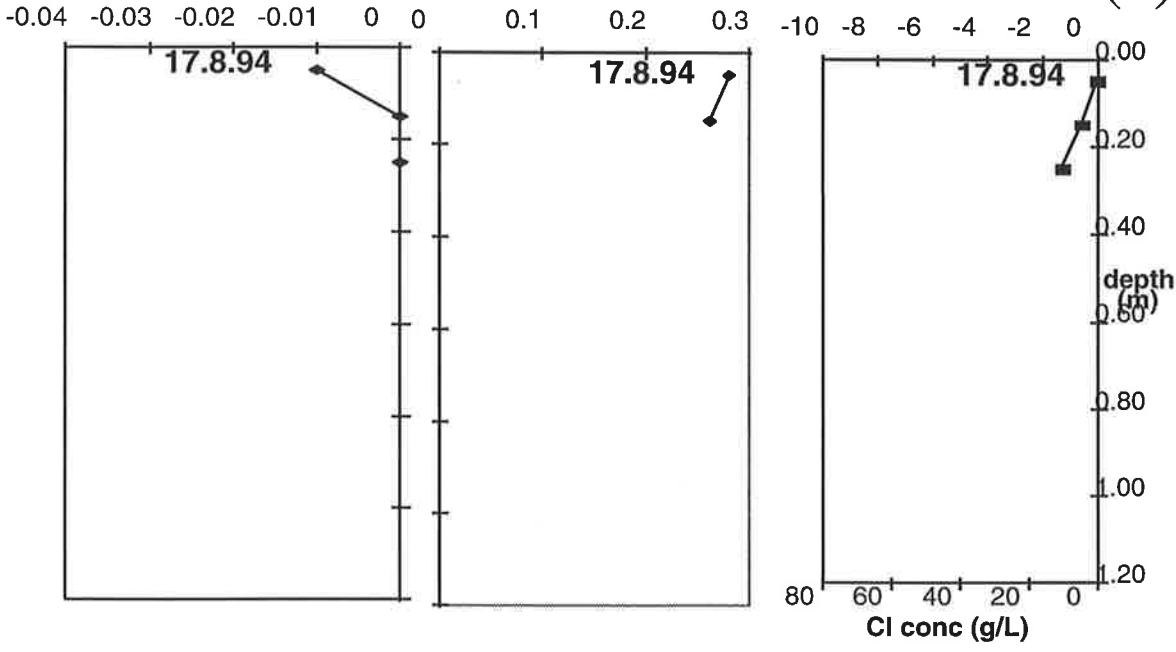
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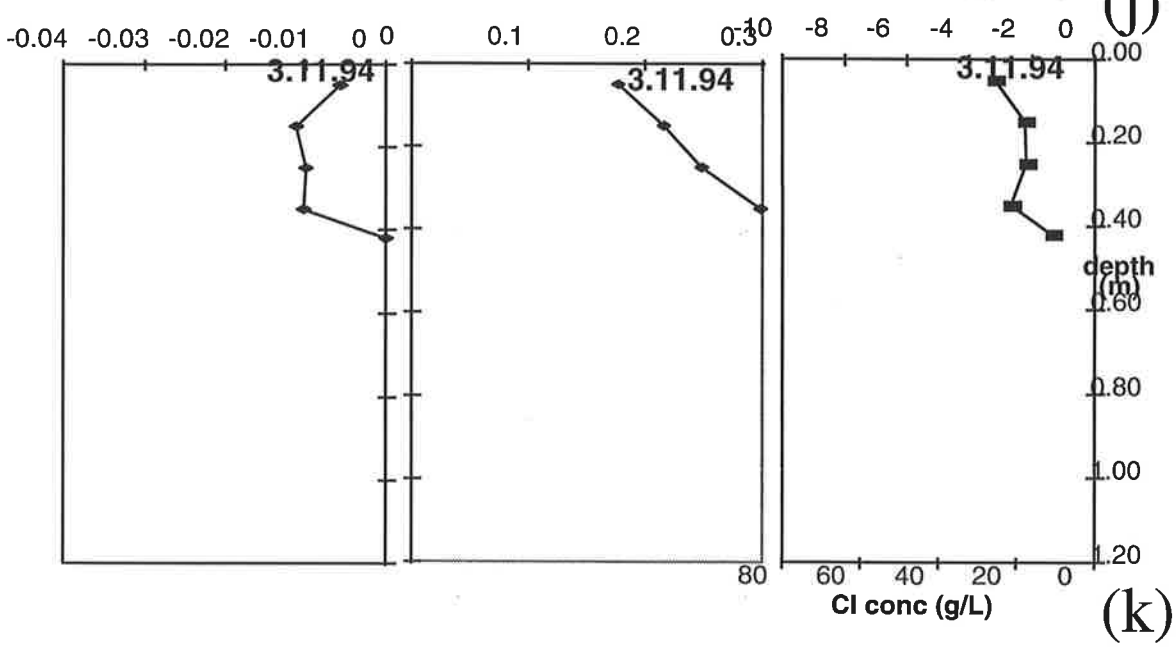
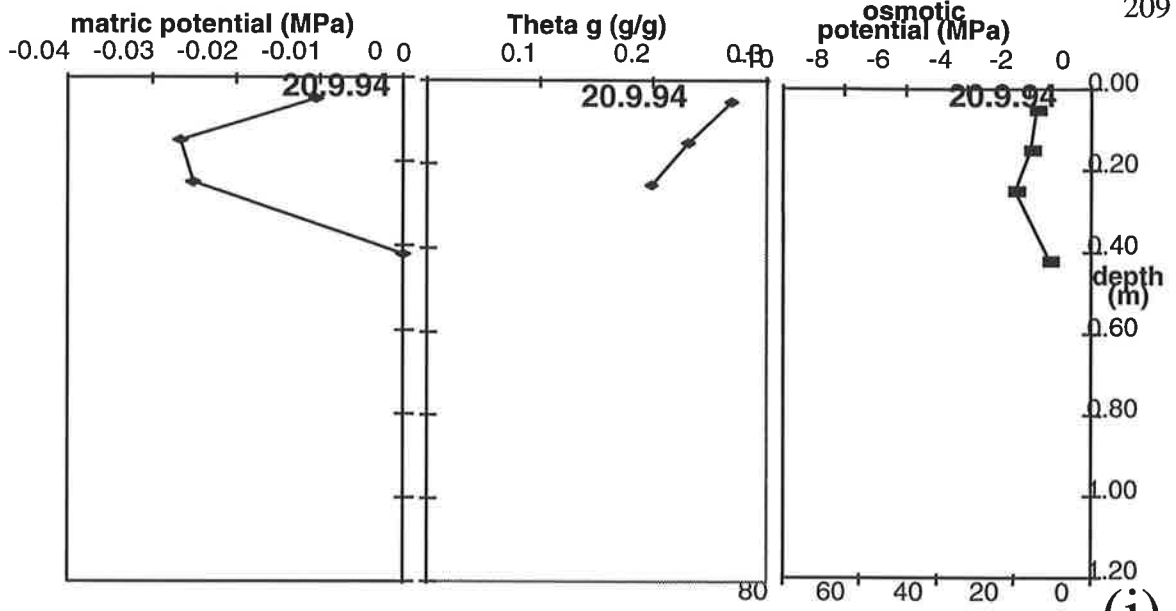
(g)



(h)

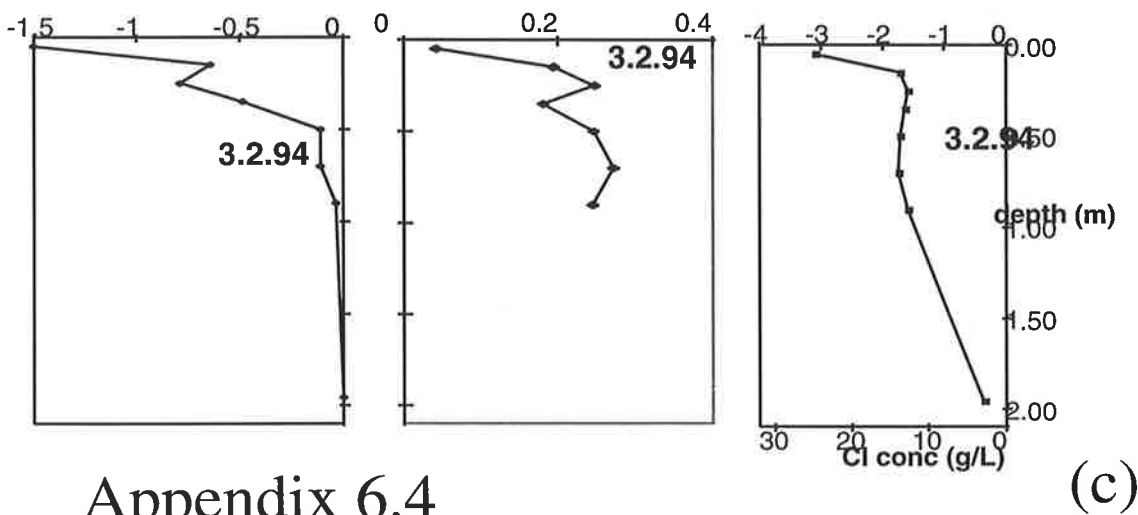
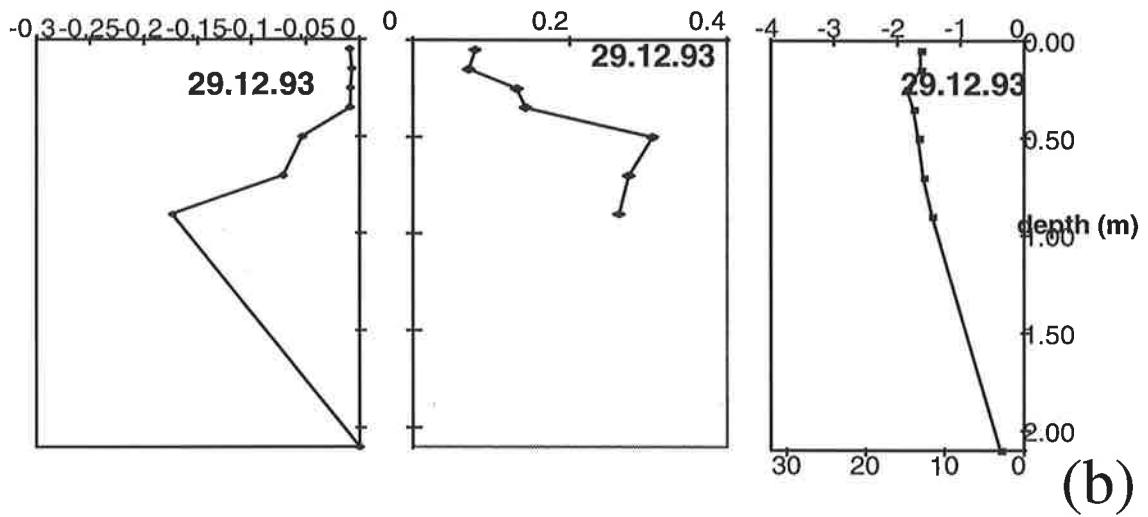
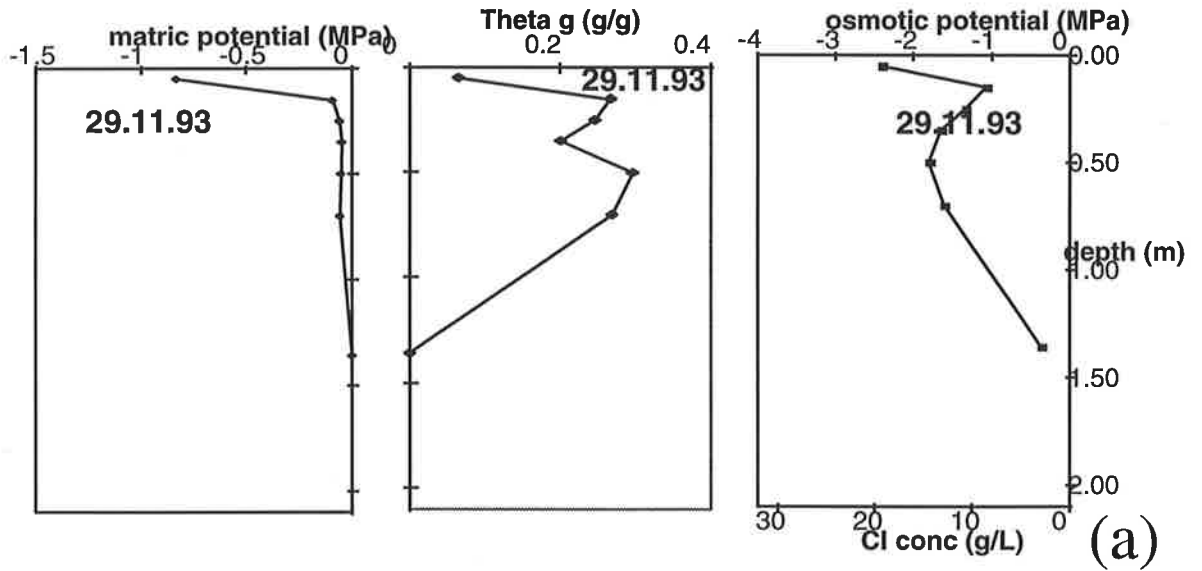


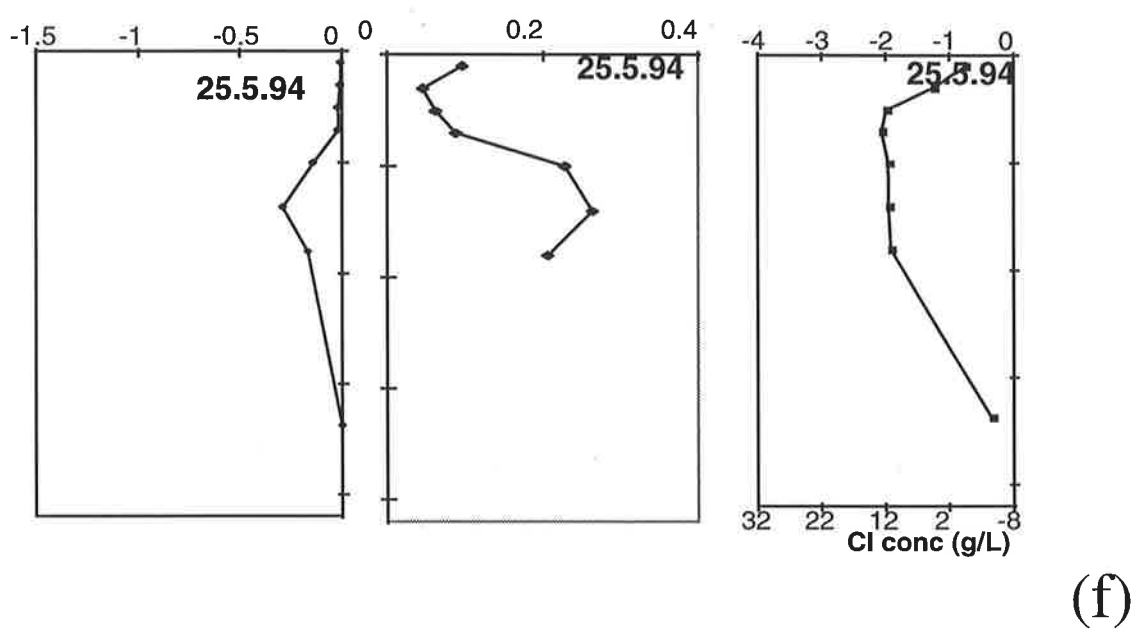
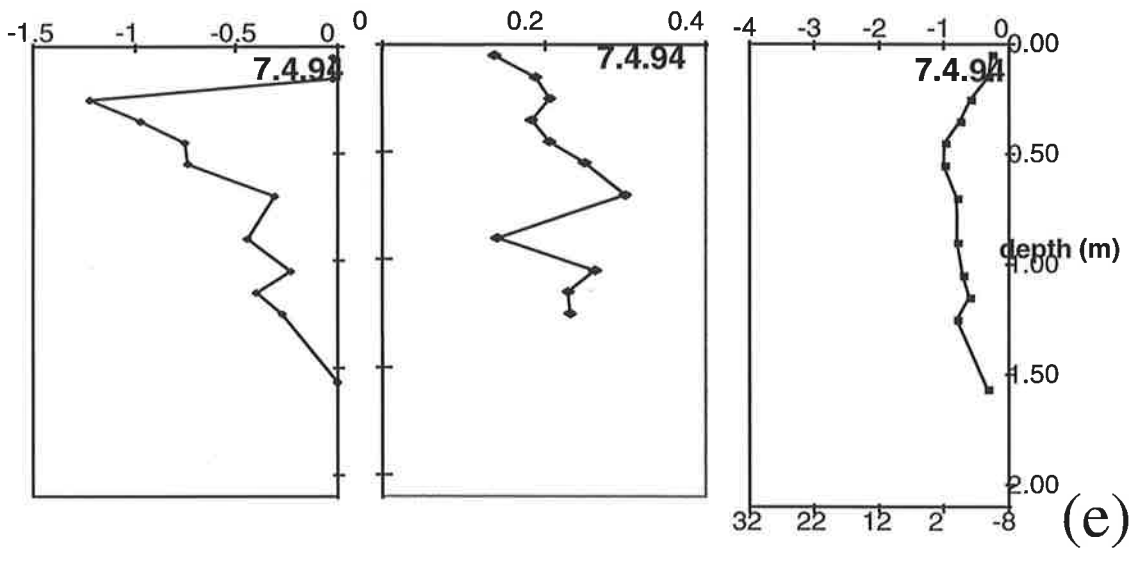
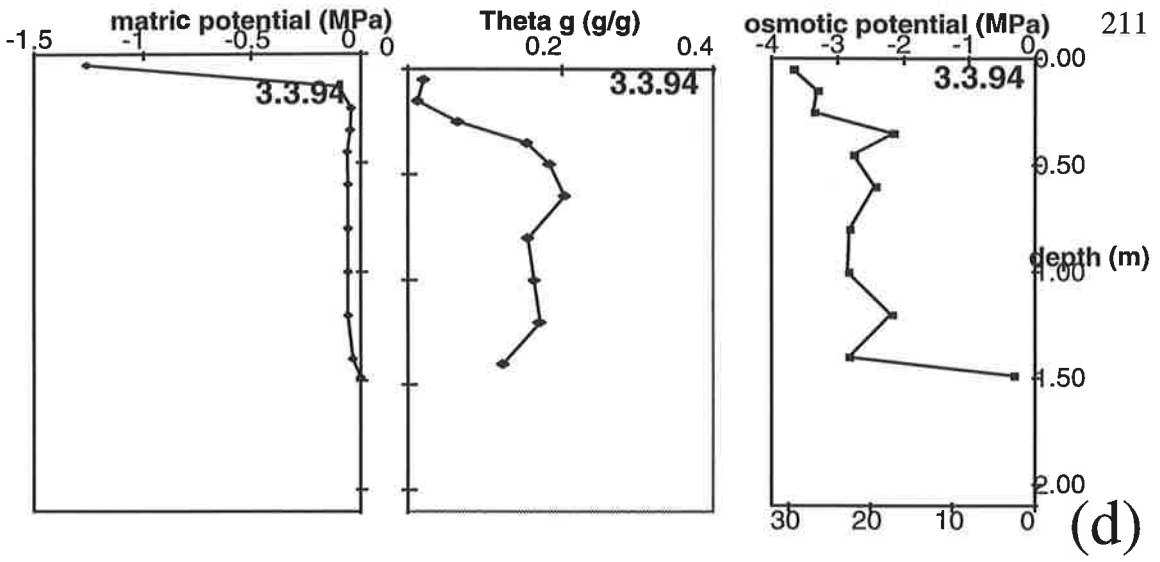
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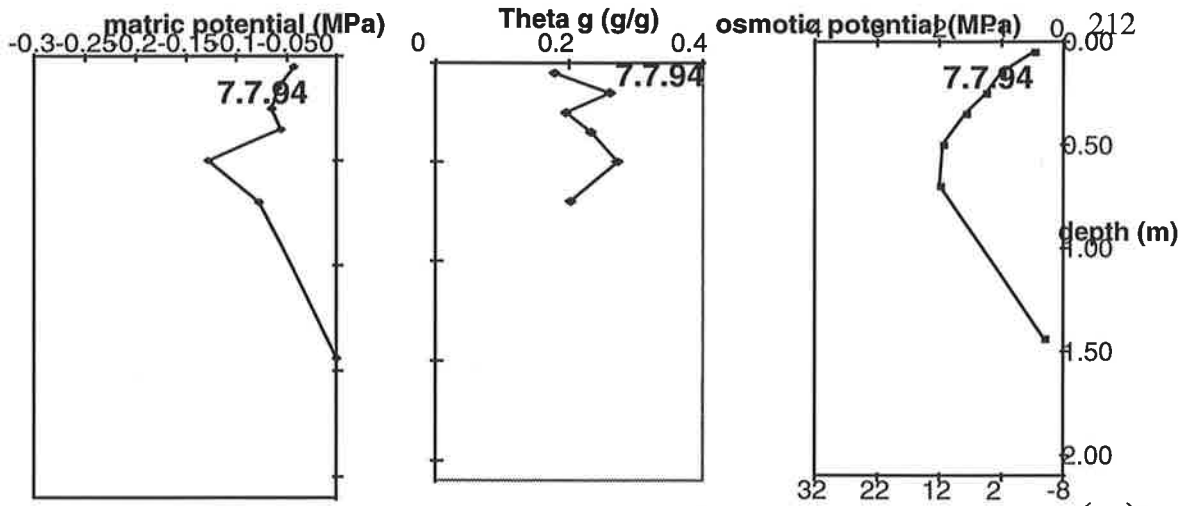


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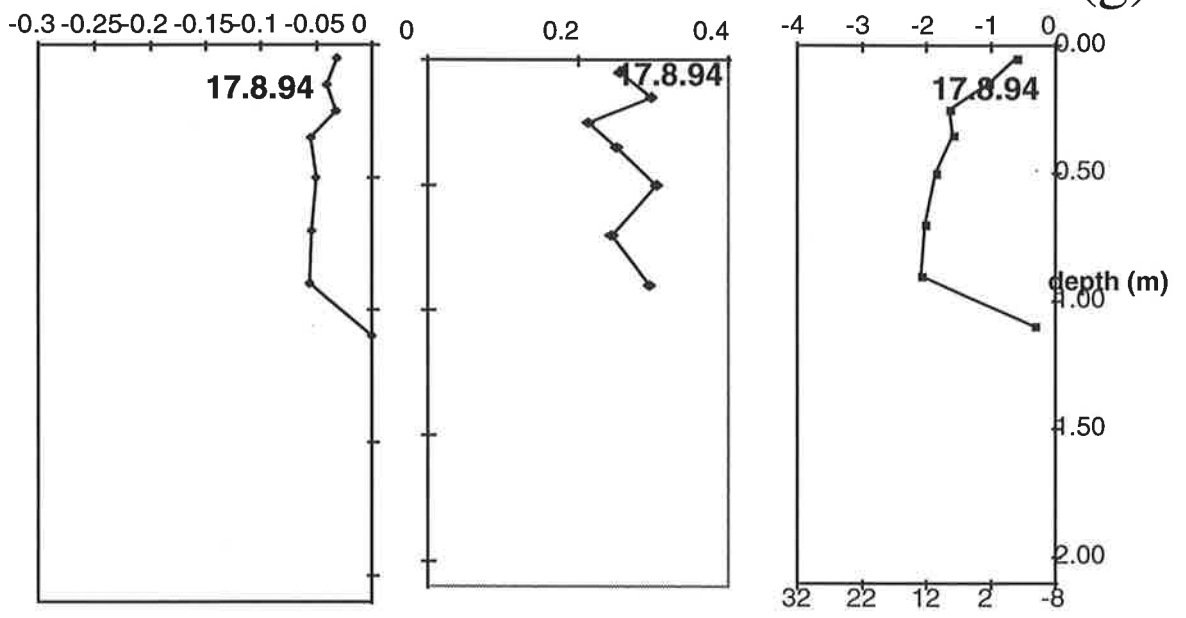
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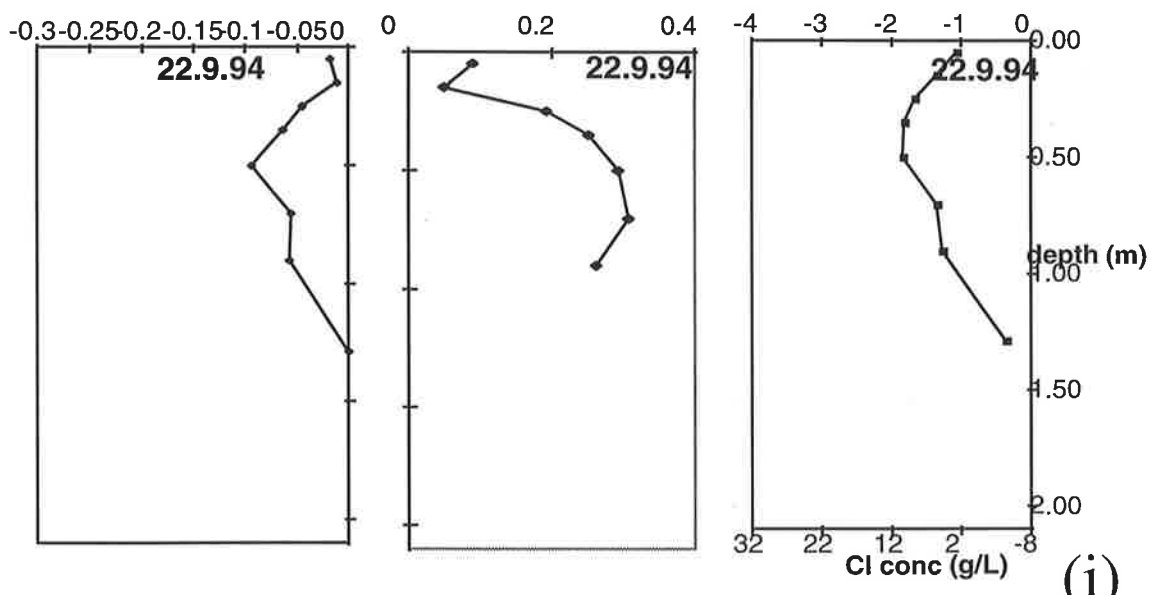




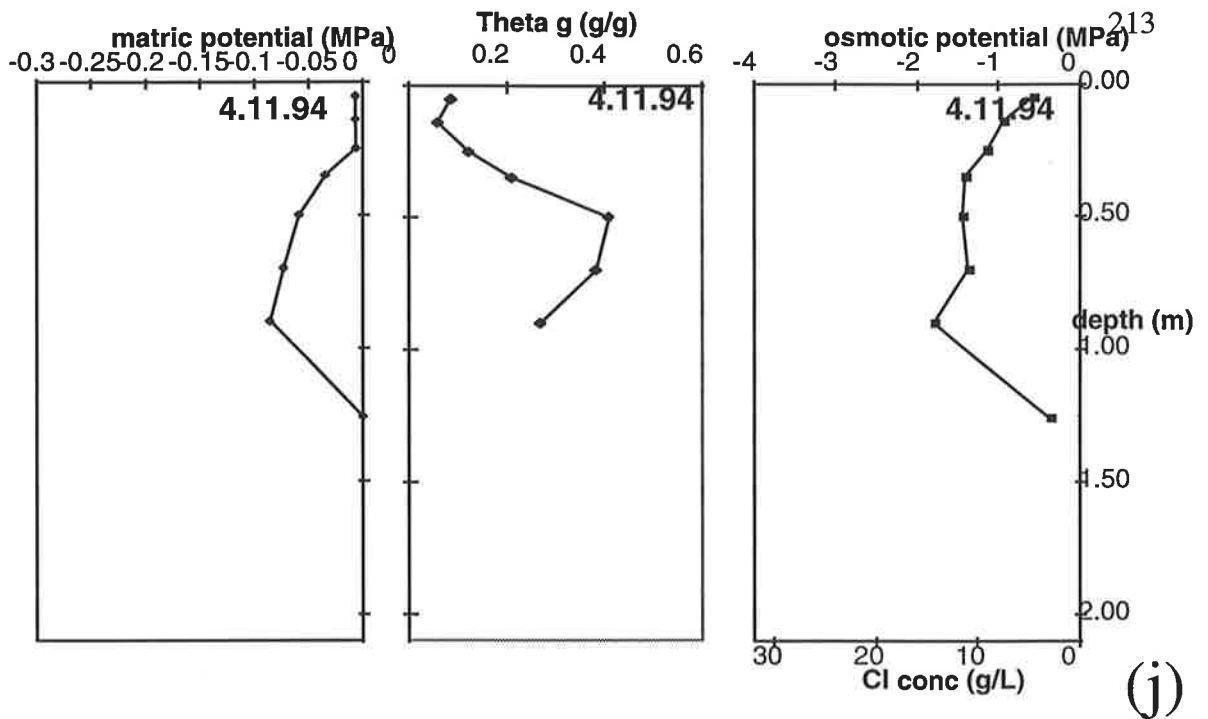
(g)



(h)



(i)



(j)

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