Lewis, Megan Mary, Gotch, Travis Bruce, White, Davina Cherie,
'Introduction', in *Allocating water and maintaining springs in the Great Artesian Basin. Volume IV. Spatial survey and remote sensing of artesian springs of the western Great Artesian Basin*, 2013 / Megan M. Lewis, Davina White and Travis Gotch (eds.), Canberra, National Water Commission, Ch. 1 pp.1-11

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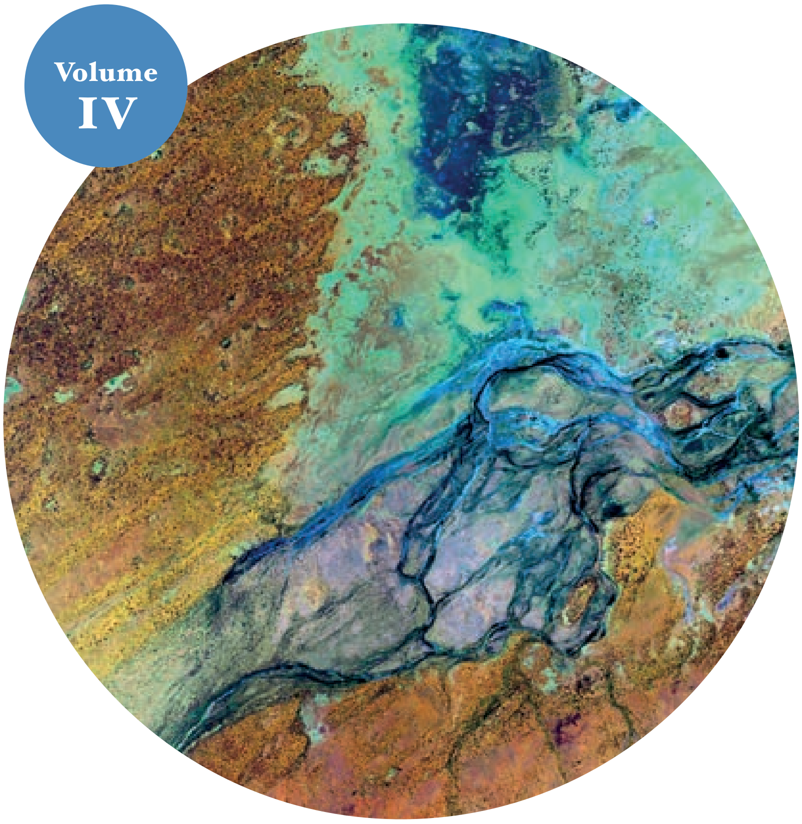
Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

Volume
IV



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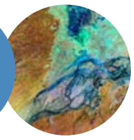

Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

Australian Government
National Water Commission

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South Australia

Northern Territory
Government

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ISBN (volume IV): 978-1-922136-09-1
ISBN (set): 978-1-922136-05-3

Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin, 2013.

Editors: Megan M Lewis, Davina White and Travis Gotch

Published by the National Water Commission
95 Northbourne Avenue
Canberra ACT 2600
Tel: 02 6102 6000
Email: *enquiries@nwc.gov.au*

Date of publication: March 2013

Design, illustration and editing by Ecocreative® <www.ecocreative.com.au>.

This document has been printed on a waterless press under an ISO 14001-certified EMS, onto chain-of-custody, carbon-neutral certified Australian-made paper (made from a mix of sustainably harvested and recycled fibres).

An appropriate citation for this report is:
Lewis *et al.* (eds) 2013, *Allocating Water and Maintaining Springs in the Great Artesian Basin, Volume IV: Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin,* National Water Commission, Canberra.

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About the editors

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Travis Gotch is a Chief Investigator on the AWMSGAB Project. Recognised nationally and internationally as an expert in GAB Springs and highly regarded in this field, Travis has spent the last 13 years working exclusively on the ecology, spatial mapping and management of GAB Springs in South Australia. Currently employed as a Senior Ecologist (GAB) with the South Australian Government, Travis provides expert advice to a wide range of government, industry and community bodies and has been on several advisory panels including the HEVAE Expert Reference Panel and the Queensland Water Commission's Technical Advisory Group for the Spring Impact Management Strategy.

Acknowledgements

This publication is part of a series of works commissioned by the National Water Commission under its Raising National Water Standards Program and its major partners: the Flinders University of South Australia, the South Australian Government, the South Australian Arid Lands Natural Resources Management Board, The University of Adelaide, the Northern Territory Government and the Commonwealth Scientific and Industrial Research Organisation, as part of the Allocating Water and Maintaining Springs in the Great Artesian Basin (AWMSGAB) project.

This work was undertaken on behalf of the Commission by our partner organisations:

- South Australian Arid Lands Natural Resource Management Board (SAALNRMB)
- Department for Environment, Water and Natural Resources (DEWNR)
- Commonwealth Scientific and Research Organisation (CSIRO)
- Finders University of South Australia
- The University of Adelaide.

The scientific editors and authors are grateful to the following people and groups for their assistance in this work, including provision of information and access to land for the collection of data:

- traditional owners and custodians of the South Australian spring country, present and past, particularly the Arrabuna, Dieri, Lower Southern Arrente, Wokangurru and Kuyani peoples and key individuals including Gordon Warren, Marylin Ah Chee and Aaron Stuart. We also wish to specifically thank Mr Dean Ah Chee for guiding us through the Dalhousie Springs Complex on behalf of the traditional owners and native title holders and Mr Reg Dodd for permitting access to Hermit Hill Springs Complex and surrounding Finniss Springs Station
- pastoralists and graziers of the Oodnadatta Track, in particular the Randall Crozier, Norm and Steph Simms, Helen and Trevor Williams, Jim Lomas and Sarah Amy, Col and Jill Greenfield, Rodney and Narrelle Fulton, Margie and Gordon Warren and Bobby Hunter
- Witjira National Park Co-management Board
- Parks SA staff who supported the project over the years, in particular Geoff Axford, Alex Clarke, Dylan Koerner, Tony Magor and Robin Young
- a tireless army of field workers, including Tori Marshall, Adam Kilpatrick, Erika Lawley, Yuot Alaak, Marion Pause, Dr Angela Lausch, Hemi Kerehi and David Ladd for assistance with the remote sensing field campaigns. Karl Newport, Mellissa Farrely, Dylan Koerner and Dan Wohling assisted during the elevation survey
- Graham Green, Mel White and Volmer Berens from DEWNR were of great assistance during the Freeling and Big Blythe campaign, as were Dr Dale McNeil and David Schmarr from SARDI
- Jennie Fluin of DEWNR for her earlier work as project manager
- the entire town of William Creek, specifically Nev and Adrianna Jacobs, Bruce and Mim, Trevor Wright, Tay, Rick, and Ally
- Adam and Lynnie Plate in Oodnadatta for their friendship and assistance

- BHP Billiton for provision of data and access and use of the Borefield Hut facility in Wellfield A, in particular KJ Kovac, Darren Niejalke, Murray Tyler, Tash Bevan and Jane Hosking
- Brian Traeger and Lloyd Sampson from DFW provided important weir gauge data, and Lloyd also assisted with the reconciliation of old water data to new spring survey points
- Mark Raven of CSIRO conducted the X-ray diffraction analysis of the Francis Swamp cores; Dr Cameron Grant assisted with soil sampling and moisture analysis of the Francis Swamp cores; Dr Brad Wolaver (Flinders University of South Australia) and Assoc. Prof. Todd Halihan (University of Oklahoma) provided the salt dilution gauging discharge data
- Australian Research Council Linkage Infrastructure, Equipment and Facilities (LIEF) grant ID:LE989062 consortium for use of FieldSpec spectroradiometer and Dr Tim Munday and Dr Ian Lau of CSIRO loaned their ASD
- Joshua Ryan and Michelle Clark for their dedicated assistance in producing this report
- the Spatial Information Group at The University of Adelaide, in particular Dr Ken Clark and Dr Greg Lyle for their expert advice and support
- The Friends of Mound Springs for their support, particularly Colin Harris, Simon Lewis and Tony Latz for their wealth of historical springs knowledge
- the following companies and agencies for the imagery and data:
    a. HyVista Corporation—HyMap imagery & digital aerial photography and associated image products
    b. Airborne Research Australia—LiDAR & Eagle hyperspectral imagery
    c. Spatial Scientific (Dr Paul Dare)—orthorectification of digital aerial photography
    d. Digital Globe and Sinclair Knight Merz—WorldView-2 and QuickBird satellite imagery
    e. Geoscience Australia—ASTER data, SRTM DEM, Landsat imagery, Australian Geographic Reference Image
    f. MODIS—downloaded free from the Warehouse Inventory Search Tool (WIST) NASA web site

The authors acknowledge and appreciate the thorough and constructive reviews of this volume provided by Dr Simon Benger, Dr Anna Dutkiewicz and Dr Halina Kobryn. Their comments and suggestions have enhanced the quality of this publication.

Background

Photo: Megan M Lewis

Introduction

Increasing efficiency in the use of Great Artesian Basin (GAB) groundwater resources has important economic and environmental benefits for the whole nation. The National Water Initiative (NWI) recognised that lack of water information and scientific knowledge of water systems hampers the ability of authorities charged with water management to fulfil their roles effectively. This is especially true for the GAB.

The National Water Commission, as part of its work to address this limitation, provided funding for the establishment of a research project entitled Allocating Water and Maintaining Springs in the Great Artesian Basin (hereafter referred to as the AWMSGAB Project). The AWMSGAB Project investigated groundwater hydrogeology along the western margin of the GAB (specifically within South Australia and the Northern Territory) and employed the latest technologies in spatial survey and remote sensing to precisely map the locations and elevations of GAB springs, the extent of their wetland vegetation, and their surface characteristics over space and time.

The Great Artesian Basin

The Great Artesian Basin (GAB) is the largest groundwater basin in Australia (and one of the largest in the world), underlying 22% of the Australian continent, including considerable areas of Queensland, New South Wales, the Northern Territory and South Australia. These groundwater resources are of great national and societal significance for Australia.

Groundwater sourced from the GAB supports the iconic GAB springs. The isolated nature of these springs has resulted in the preservation of many endemic, rare and relict species of great ecological, evolutionary and biogeographical significance.

With the exception of the far north and far eastern parts, the GAB largely occurs in the arid and semi-arid interior of central and eastern Australia. Due to the ephemeral nature of surface watercourses in these regions, groundwater from the GAB is often the only reliable water source. Consequently, exploitation of the GAB groundwater resource has played, and continues to play, a vital role in supporting agriculture, mining, industry, civil and cultural communities in Australia (Cox & Barron 1998; Armstrong 1990; Ah Chee 2002; Leek 2002).

The Lake Eyre Basin is a surface water catchment that overlies the GAB. Many springs and lakes within the Lake Eyre Basin are supported by upward leakage from GAB groundwater. This interconnection of groundwater and surface water in the Lake Eyre Basin is largely unexplored and unknown, though is very likely to be of environmental significance.

Geologically, the name GAB refers to a non-marine to marine Triassic-Jurassic-Cretaceous hydrogeological superbasin that covers much of eastern and central Australia. The GAB contains three large epi-continental depressions called the Carpentaria Basin, the Surat Basin and the Eromanga Basin, with the Eromanga Basin being volumetrically the largest. The eastern margin of the GAB abuts the Great Dividing Range and it is from here that the majority of present day groundwater recharge occurs, flowing in a largely westerly and south-westerly direction toward South Australia.

Cultural and historical context

The springs of the GAB are culturally very important to Aboriginal and non-Indigenous Australians. GAB springs were the only reliable water source for Aboriginal people in central Australia for thousands of years and set the boundaries for early European exploration and development through the central inland during the 19th and early 20th centuries.

Since European discovery of the GAB in 1878, thousands of bores have been drilled into the aquifers of the Basin. Currently there are about 3400 artesian bores and over 10 000 sub-artesian bores which access the aquifers of the GAB. Most of the older artesian bores were uncontrolled pastoral bores that flowed freely into open bore drains where more than 95% of the water is lost through evaporation and seepage. These free-flowing bores also cause substantial pressure reductions over much of the basin. Decreases in pressure head have led to diminishing groundwater resources; bores becoming either non-artesian or non-productive, and to either the degradation or extinction of nearby spring-fed natural environments (Cox & Barron 1998; Hassall & Associates 2003; Hovey *et al.* 2008; Kinhill Stearns 1984; Mudd 2000; Reyenga *et al.* 1998).

Government intervention

The need for government intervention to control the extraction of water from the GAB was recognised as early as 1913. Since that time, governments have worked with landholders to control the wastage of GAB water and to reverse the reduction in artesian pressure.
In more recent times, the impact of human exploitation on GAB spring environments has been recognised by both governments and other stakeholders and efforts to remediate past damage and protect what is left have been made (Hassall & Associates 2003; Hovey *et al.* 2008; Reyenga *et al.* 1998). Such recognition culminated in the inclusion of GAB springs under the protection of the Australian Federal Government's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), which aims to protect and manage nationally and internationally important flora, fauna, ecological communities and heritage places (Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) 2011).

Groundwater discharge from the GAB through springs supports natural communities containing a wide variety of endemic species in isolated groundwater-dependent ecosystems surrounded by an otherwise largely waterless landscape. Such environments appear throughout the GAB, but some of the most well-known and best preserved are found within the South Australian portion of the GAB. These springs are also often associated with distinctive mound-shaped accumulations of chemically precipitated freshwater carbonate (either termed 'travertine' or 'tufa') and, to a lesser extent, detrital sediments that build up in the vicinity of the spring vent. Most mounds and spring vents tend to align along faults; in particular, the set of aligned mounds between Marree and Oodnadatta in South Australia is referred to in this and other AWMSGAB Project volumes as the 'Mound Springs Line'.

Economic profile

The contribution of groundwater from the GAB to the Australian economy is difficult to determine but it is considered significant (GABCC 2010). Cox & Barron (1998) estimated the gross value of production of broad-acre farms in the GAB in 1996/1997 to be approximately $2 billion. More recently, GABCC (2010), using auction results for unallocated GAB groundwater licences in New South Wales, estimated the value of groundwater extracted from the GAB on an annual basis at a minimum of $457 million. In relation to non-market values, such as the GAB's contribution to tourism, biodiversity and quality of life, Rolfe (2008) tentatively estimated that improved management of the GAB groundwater resources could be valued as high as $68 million annually. The economic value of the groundwater resource is expected to increase with future developments, particularly with respect to the petroleum and mining industries slated for the area (SAALNRMB 2009).

The AWMSGAB project

The AWMSGAB study area

The AWMSGAB hydrogeological studies were undertaken in the South Australian and Northern Territory portion of the GAB. The groundwater-dependent ecosystem studies (including the spatial mapping, remote sensing and risk assessment) were undertaken in the South Australian portion of the GAB.

Project aim

Between April 2008 and June 2012, the AWMSGAB Project was undertaken in order to obtain a greater understanding of the complex hydrogeological and ecological systems in the western margin of the GAB.

Project partners

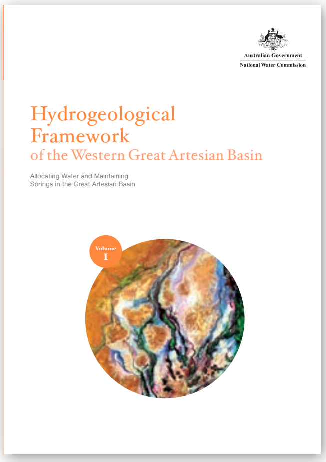
The AWMSGAB Project was funded by the National Water Commission and undertaken with the following project partners:

- South Australian Arid Lands Natural Resources Management Board
- Flinders University of South Australia
- The University of Adelaide
- South Australian Department for Environment, Water and Natural Resources
- Northern Territory Department of Natural Resources, Environment, the Arts and Sport
- Commonwealth Scientific and Industrial Research Organisation.

The Project also attracted a number of national and international scientific collaborators, including the University of New Mexico, University of Bern, Oklahoma State University, Argonne National Laboratory at the University of Alberta, and Bureau of Economic Geology, University of Texas.

The report volumes

The Allocating Water and Maintaining Springs in the Great Artesian Basin Project (the AWMSGAB Project) is one of a series of projects commissioned by the National Water Commission under its Raising National Water Standards Program.



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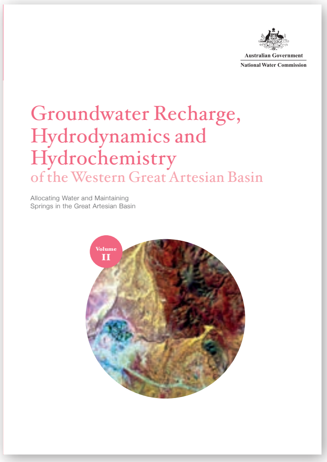
Hydrogeological Framework
of the Western Great Artesian Basin

Allocating Water and Maintaining Springs in the Great Artesian Basin

Volume I

Volume I: Hydrogeological Framework of the Western Great Artesian Basin presents a summary of background knowledge of the climate, physiology, geology and hydrogeology of the western margin of the GAB that can support the work of managers, scientists and risk assessors in relation to the GAB resource and its associated extractions.

Volume I



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Groundwater Recharge, Hydrodynamics and Hydrochemistry
of the Western Great Artesian Basin

Allocating Water and Maintaining Springs in the Great Artesian Basin

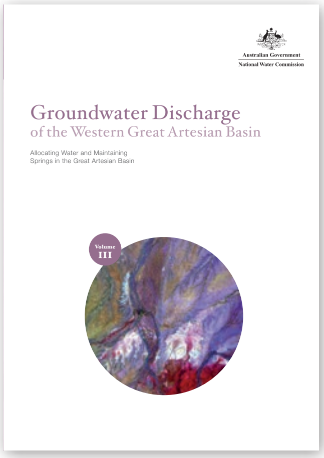
Volume II

Volume II: Groundwater Recharge, Hydrodynamics and Hydrochemistry of the Western Great Artesian Basin examines three forms of groundwater recharge processes in the western margin of the GAB: ephemeral river recharge, diffuse recharge and mountain block recharge. It presents when and how recharge currently occurs and concludes that present day rates of groundwater recharge are much less than in the past.

Volume II

Volume
III

Volume III: Groundwater Discharge of the Western Great Artesian Basin bridges a number of knowledge gaps in the understanding of groundwater discharge in the GAB, presenting research relating to the source and origin of spring water, the formation and evolution of the mound springs, the formation of acid sulfate soils, the hydrogeology of Dalhousie Springs, and the results of the first successful Uranium-series dating on GAB spring travertine deposits.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Groundwater Discharge
of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

Volume
III

Volume
IV

Volume IV: Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin advances knowledge of GAB springs and wetlands through the application of a range of advanced land survey and remote sensing technologies. It provides new spatially-explicit information about the location, elevation and distribution of GAB springs, their surface characteristics and how these vary over time. This information provides a foundation for future monitoring of the ecological and hydrogeological condition of springs in the western GAB and beyond.


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Spatial Survey and Remote
Sensing of Artesian Springs
of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

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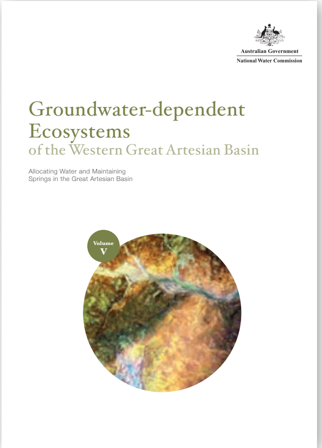
IV

Volume
V

Volume V: Groundwater-dependent Ecosystems of the Western Great Artesian Basin presents the results of several research studies which explored palaeo-ecology, genetic and floristic diversity of the springs as well as a comprehensive review of the function of *Phragmites australis* and on-ground works to enable the return of environmental flows in the western GAB.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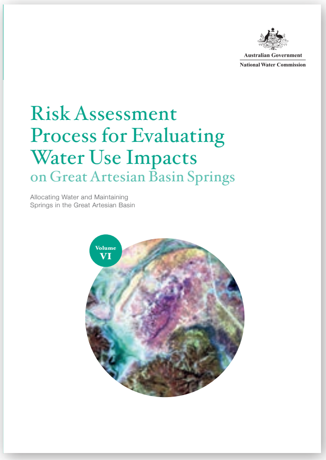
Groundwater-dependent
Ecosystems
of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

Volume
V



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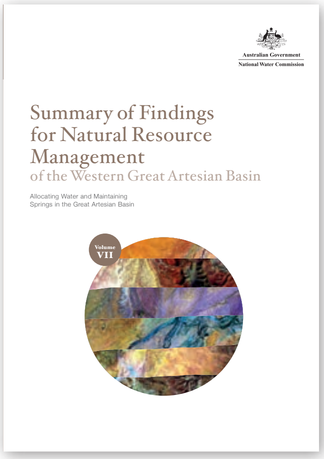
Risk Assessment Process for Evaluating Water Use Impacts on Great Artesian Basin Springs

Allocating Water and Maintaining Springs in the Great Artesian Basin

Volume VI

Volume VI: Risk Assessment Process for Evaluating Water Use Impacts on Great Artesian Basin Springs provides a clear and transparent process to analyse and evaluate risk factors associated with reductions in groundwater pressure in the GAB. The risk assessment process has been developed using the information generated by all components of the AWMSGAB Project.

Volume VI



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Summary of Findings for Natural Resource Management of the Western Great Artesian Basin

Allocating Water and Maintaining Springs in the Great Artesian Basin

Volume VII

Volume VII: Summary of Findings for Natural Resource Management of the Western Great Artesian Basin presents a summary of each of the volumes and outlines the key tools, methods and information arising from the research.

Volume VII

Executive summary

This report advances knowledge of Great Artesian Basin (GAB) springs and wetlands through the application of a range of advanced land survey and remote sensing technologies. This research was undertaken because, despite the scientific and ecological importance of the GAB springs, they have been poorly documented to date. There is a need for objective information about the distribution, character and status of the western GAB springs and their associated wetlands.

The objectives of this report are to:

- map the location and elevation of western GAB springs using high-precision global positioning systems (GPS)
- compile baseline information on the flow status, condition and ecological value of the mapped springs, from which future changes can be established
- develop and evaluate new methods for remote sensing image-based mapping and monitoring of the surface characteristics of western GAB spring-fed wetlands and surrounding environments
- use these remote sensing methods to document the distribution and extent of wetland vegetation and associated environments and to provide information about vegetation community composition and its variation in space and time.

Spring survey

Field survey-standard GPS and baseline information of spring condition and ecological value was collected for all spring complexes, groups and the majority of individual springs in the western GAB; in total 4516 spring vents in 103 spring groups were surveyed. This is the most comprehensive and accurate survey of spring vent position and elevation ever undertaken in the GAB. The record of springs that were flowing or extinct in February 2012 provides an objective baseline against which to monitor any future changes in spring flows. A standardised classification and nomenclature system for springs, spring groups, complexes and supergroups was developed and implemented.

The network of Permanent Survey Marks established across the western margin of the GAB will provide reference locations for future spatial surveys.

Remote sensing: characterisation of wetlands

New spatially explicit information about the current status of the western GAB springs, in particular the extent and floristic composition of spring-fed wetland vegetation, was obtained from analysis of satellite and airborne images coupled with field studies. For Dalhousie, Francis Swamp, Hermit Hill and Mt Denison complexes this report presents the first thorough documentation and baseline mapping of the geomorphic context and surface expression of the springs, their associated wetlands and environments.

Case studies illustrate use of this baseline data for a range of applications, such as monitoring the influence of bore capping on springs in Mt Denison Springs Complex, and the use of surface water delineation to estimate native fish populations and their risk of invasion by Mosquito Fish.

Remote sensing: wetland change over time

Analysis and interpretation of moderate spatial resolution, high temporal frequency satellite imagery documented seasonal growth cycles of the dominant wetland vegetation types. Different wetland communities have characteristic seasonal phenological patterns of greening and drying, distinct from those of dryland and intermittent watercourse vegetation. This information can be used to recommend appropriate timing of image and field data collection for future spring monitoring.

Changes in wetland area for Dalhousie and Hermit Hill complexes were documented over the past decade with fortnightly time steps. Seasonal fluctuations are underlain by decade-long trends in changing wetland area, strongly influenced by total rainfall in the preceding 6–12 months.

Very high spatial resolution satellite images of vegetation greenness provided highly detailed delineations of the extent of spring-fed wetland vegetation. In addition, high spectral resolution airborne images of selected spring groups acquired in 2009 and 2011 enabled comparisons of dry and wet antecedent conditions. Spectral mapping techniques revealed changes in the extent and species composition of spring-fed wetland vegetation and surrounding wetted area and diffuse discharge.

Area of wetland vegetation as a surrogate for spring flow

The detailed mapping of wetland extent was used to develop a strong linear relationship between spring-fed wetland extent and spring flow rates at Dalhousie and Mt Dension spring complexes. This relationship enables spring-fed wetland area to be used as a surrogate for spring flow volume, providing an objective and cost-effective means of monitoring GAB spring response to aquifer changes.

Remote sensing tools and methodologies

The project applied and evaluated a wide range of forms of remote sensing, spatial information and field measurements for spring characterisation, assessment and monitoring. These methods were tested over a range of spring contexts, spatial and temporal scales. Based on the outcomes of the research, protocols and methods are recommended for future studies to monitor GAB spring status and condition. The report provides recommendations for future spring survey and documentation, monitoring and baseline assessment priorities.

1

Introduction

Megan M Lewis School of Earth and Environmental Sciences, The University of Adelaide
Travis Gotch Department of Environment, Water and Natural Resources, Government of South Australia
Davina White School of Earth and Environmental Sciences, The University of Adelaide

1. Introduction

This volume presents two components of the Allocating Water and Maintaining Springs in the Great Artesian Basin (AWMSGAB) Project: an extensive and comprehensive survey of the geographic locations and status of all springs in the south-western margin of the Great Artesian Basin (GAB) in South Australia, and studies using remote sensing technologies that document the spring-fed wetlands, their characteristics, composition and variation in space and time.

The results presented address the need for more comprehensive knowledge of the distribution, characteristics and status of the springs in this part of the GAB, and for quantitative, robust and repeatable methodologies to determine their sensitivity to water allocation, thus improving the capacity of water planners and managers to make informed allocation decisions.

The GAB spring ecosystems are ecologically varied, widely dispersed and have not been well documented to date. The locations and condition of most springs have been poorly recorded, with many remaining unknown to current natural resource managers. Direct monitoring of flow from springs has been limited in extent and duration and is logistically difficult in these remote and disparate locations. Mapping and monitoring of vegetation has been confined to selected springs in the south-western margin of the GAB and has relied on methods which are costly, time-consuming and limited in their ability to differentiate wetland communities. These methods consisted of visual interpretation and classification of aerial photography combined with a considerable amount of fieldwork.

The research presented in this volume advances knowledge of spring vegetation and environments by exploiting the potential of a range of advanced survey and remote sensing technologies for improved land cover location, discrimination and monitoring of change over time. The underlying premise is that the extent of perennial wetland vegetation is an indicator of the long-term flow from spring groups; hence the research developed advances methods for documenting and monitoring vegetation using appropriate remote sensing technologies which have not been applied to this task before.

Specific objectives of the research were to:

- map GAB springs in South Australia at survey-grade GPS levels of precision. This included mapping flowing and extinct spring vents to establish a baseline record of spring activity status for future evaluation of water allocations. Spring elevations relative to the potentiometric head are a critical factor in evaluating the potential impacts of water allocation from the GAB, thus high levels of accuracy and precision are integral in developing robust evaluation methods
- provide a baseline inventory of spring resource condition and ecological values against which future changes can be monitored
- provide spatial and survey support to other studies within the AWMSGAB Project
- develop and evaluate remote sensing approaches coupled with ground validation data to detect, map and monitor GAB spring-fed wetlands and associated environments. Specific goals were to develop methods for

Photograph on facing page: Davina White mapping the distribution and extent of the wetland vegetation and provide information about vegetation community composition and variation in space and time.

The ground-based spatial survey of springs included all the spring complexes, groups and the majority of springs in the western margin of the GAB. The remote sensing studies focused on four spring complexes: Dalhousie, Francis Swamp, Mt Denison and Hermit Hill (Figure 1.1). The complexes were prioritised for their ecological and conservation importance and potential sensitivity to artesian water allocation, grazing and management. They were chosen because they are representative of the diversity of spring forms and vegetation communities present in this part of the GAB (Figure 1.1).

1.1. Study components

Table 1.1 outlines the study components, focal spring complexes and volume structure. The spatial survey component of this volume presents the outcomes of several years of real-time kinematic differential GPS (RTK DGPS) survey work (Chapter 2). It provides a detailed baseline survey of spring condition and a large dataset to enable future monitoring and evaluation of water allocations in the western margin of the GAB.

For the focus spring complexes and groups, this volume presents the first baseline mapping and spatially comprehensive characterisation, drawing on the latest remote sensing technologies, analysed and interpreted in combination with field studies. Although some of these spring groups have been described in previous natural history, ecological and hydrological literature, none have been mapped, nor their spatial characteristics documented and quantified to this extent. Image-based maps and detailed inventories are presented in Chapter 3 and include, for selected spring groups, geomorphic and landscape setting, topography, distribution and extent of wetland vegetation, selected dominant plant species and communities, wetted area, diffuse discharge and associated evaporite minerals.

While this new characterisation of the spring wetlands and surroundings presents baseline information against which future changes can be assessed, spring flows and wetland communities are not static. It is important to understand the extent and nature of this variability in space and time to fully interpret monitoring records and assess the significance of observed changes. Chapter 4 presents studies of the dynamics of selected spring groups within and between years, drawing on time-series and comparisons of remotely sensed imagery. The seasonal patterns of growth and senescence of dominant wetland vegetation species are characterised and differentiated from those of dryland and watercourse vegetation and related to climatic influences.

Longer term changes in wetland area and development at Dalhousie and Hermit Hill complexes are traced over the past decade with fortnightly time-steps, providing the first detailed understanding of the temporal dynamics and trends of wetland vegetation of these communities. These longer-term time sequences provide context for detailed studies of spatial changes in wetland vegetation, wetted area (which includes spring wetlands and the surrounding zone of surface moisture) and diffuse surface discharge for several spring groups and complexes for selected dates in recent years. These high-resolution comparisons of the springs for selected periods provide new insights into the nature and drivers of change in the spring environments (Chapter 4).

For this improved ability to assess and monitor wetland vegetation to translate into reliable tools for monitoring spring flow, the relationship between wetland vegetation and spring flow must be established. Such a relationship was proposed in an early study of Dalhousie Spring

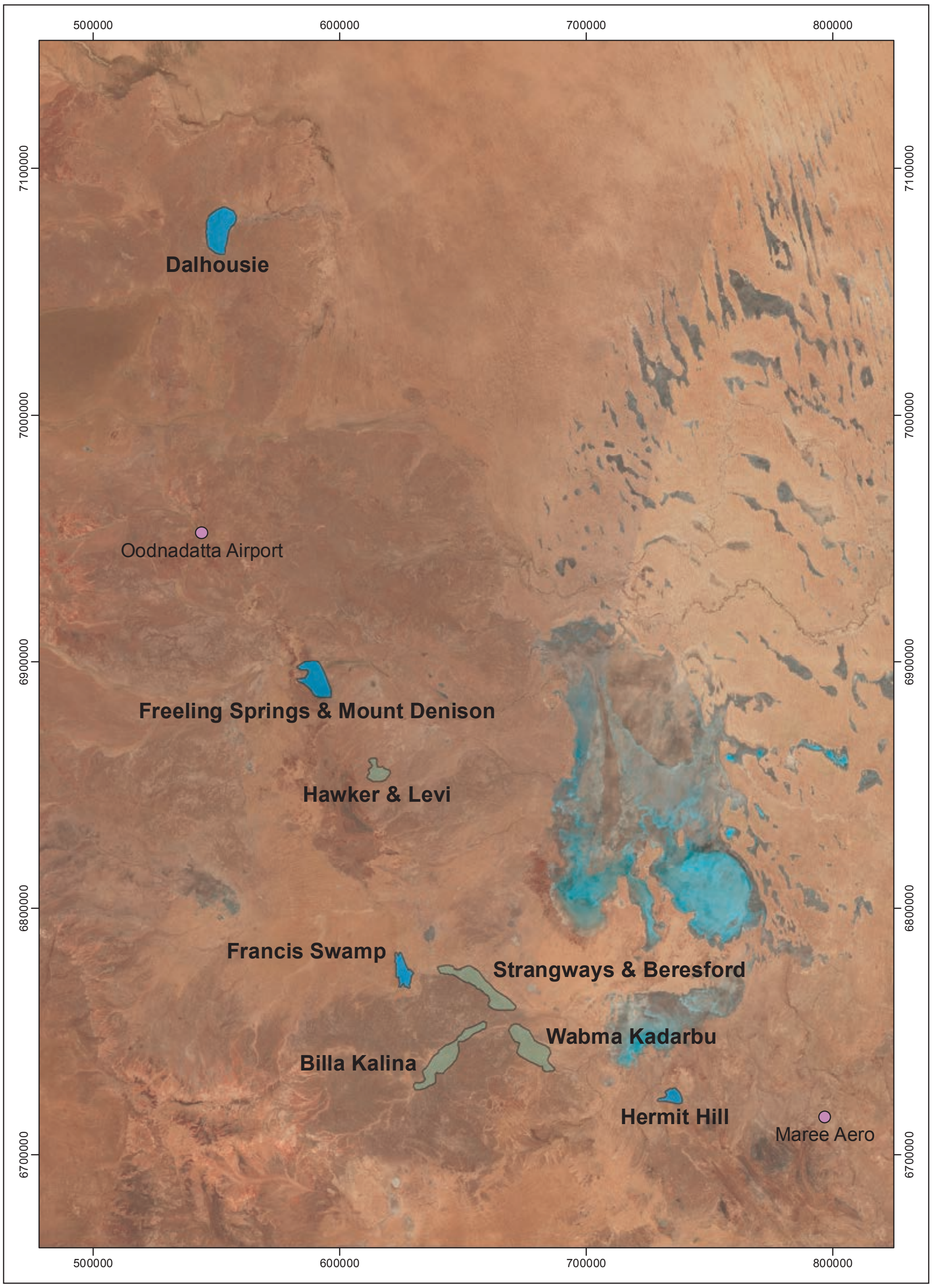


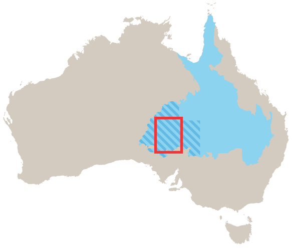
Figure 1.1: Location of study spring complexes in the western GAB, highlighting the four complexes on which this volume focuses

Spring Complex

🟦 Focal Spring Complex
🟩 Other Spring Complex
● Meteorological Station

0 50 100
Kilometres
N

Background image: Landsat, true colour, 2006.
Produced by The University of Adelaide School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: February 2012



Complex using in-situ flow measurements and wetland area crudely measured from black-and-white aerial photos (Williams & Holmes 1978). This report has quantified this relationship using digital analysis of the latest high spatial resolution satellite imagery to delineate spring wetland extent and associating this with ground measurements of spring flow volume. This work has been conducted over a wider range of spring types and sizes using far more precise measurements of wetland area (Chapter 5).

This volume also evaluates a wide range of sources of remote sensing, spatial data and techniques that have been developed to map and monitor the GAB springs for the first time; recommendations are presented on the most appropriate approaches for spring assessment and monitoring in differing contexts and scales.

Several components of this report have been published in scientific journals and conference proceedings (Gotch & Green 2010; Lewis & White 2012; Petus *et al.* 2012a; Petus *et al.* 2012b; White & Lewis 2009; White & Lewis 2010a, 2010b, 2010c, 2011, 2012). The scope of these in relation to the study components, focal spring complexes and chapters of this volume is indicated in Table 1.1.

In-situ measurement of spectral reflectance.
Photo: Erica Lawley

The nature of hyperspectral imagery: the detail is in the spectra

Plants, soils and minerals have distinctive reflectance characteristics, often called spectral signatures, in the visible to near-infrared part of the spectrum. These are caused by differential absorption, scattering and reflection of light by the molecules and structures that make up the materials. Hyperspectral remote sensing is able to record these spectral signatures and can be used to provide information about land surfaces, including vegetation condition and types, soil variations, minerals and moisture.

Hyperspectral data contain many narrow wavebands, usually more than 100, within the visible to near-infrared parts of the spectrum.

One ground-based and two airborne sensors were used in this study:

- HyMap airborne sensor (450–2500 nm)
- ASIA Eagle airborne sensor (400–970 nm)
- Analytical Spectral Devices (ASD) full-range FieldSpec® 3 spectroradiometer (400–2500 nm).

The extensive suite of collected hyperspectral data provides new insights into the characteristics of spring vegetation distribution and composition as well as substrate and saline surfaces. Field spectra was collected to assist with and validate hyperspectral image analysis for mapping of spring characteristics, as well as providing new spectral information about the GAB springs.

The rapidly growing field of hyperspectral remote sensing is a valuable tool for mapping GAB springs because:

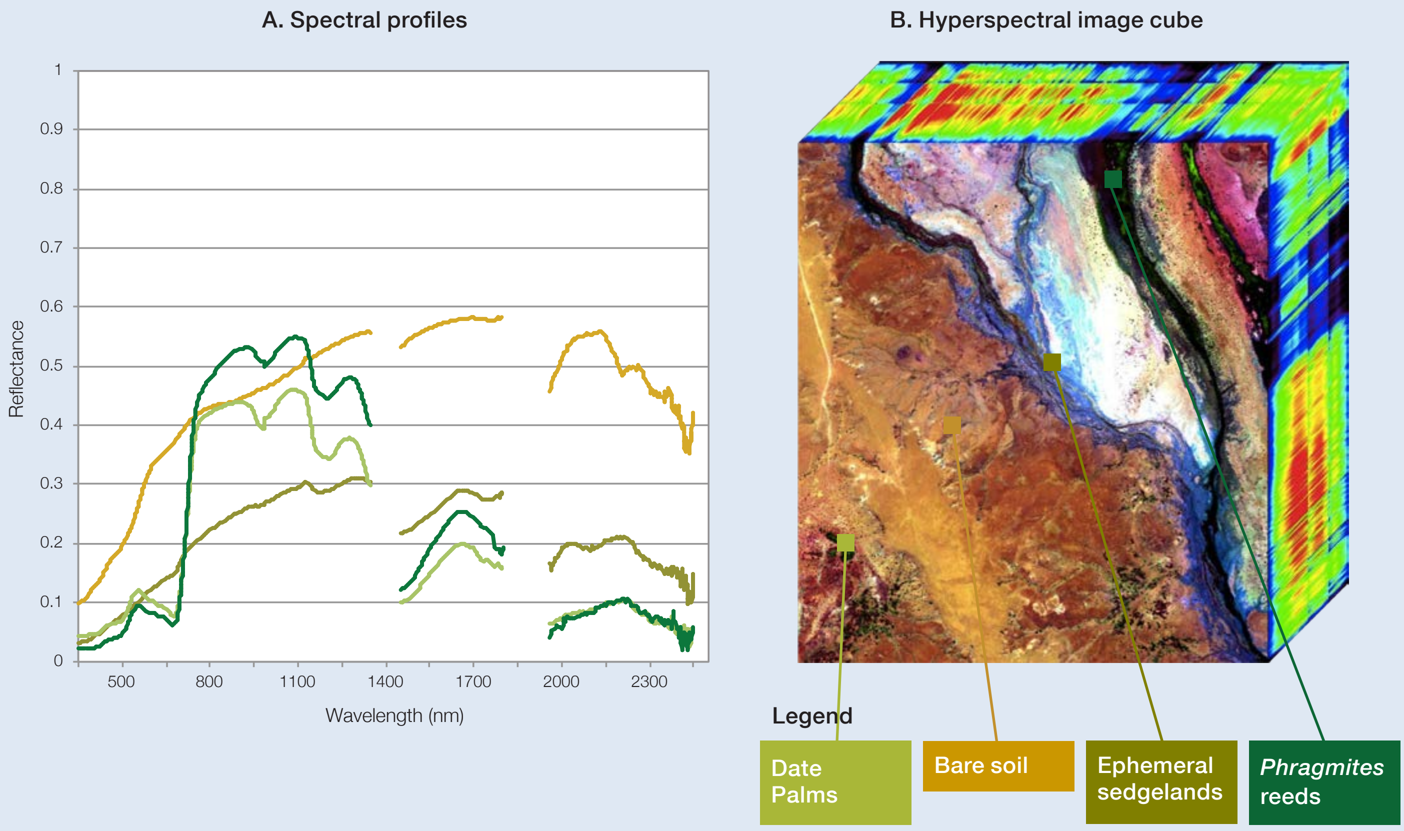
- the rich spectral detail (many narrow wavebands) enables discrimination of different vegetation communities and types, which were found to have unique spectral characteristics that could be differentiated at the spring-group scale
- spectral signatures also enabled discrimination of surface water, minerals and substrate surface expressions
- two epochs of hyperspectral image capture enable changes in the characteristics of the springs and their surroundings to be investigated at an unprecedented level of detail.

1.2. Data and approaches

The spring elevation survey was undertaken using high-precision DGPS. This included static baselines and AUSPOS (online tool for post-processing GPS data) solutions for the control network, while all spring vents were surveyed using RTK DGPS. Existing survey data was collated from South Australian Arid Lands Natural Resource Management Board (SAALNRMB), Department for Environment, Water and Natural Resources (DEWNR) and BHP Billiton and used in addition to the survey data collected during the AWMSGAB Project.

Baseline data of spring condition was collected during the survey including flow, flora and fauna diversity, grazing impacts, weeds and other threats, as well as basic water quality parameters such as pH and conductivity. More detailed explanations of the approaches used during spring survey and the spring groups surveyed are included in Chapter 2 and Appendix 1.

The forms and sources of remote sensing, spatial and ground-based data used in these studies are summarised in Table 1.2. Fuller technical specifications are detailed in Appendix



A. Spectral profiles

B. Hyperspectral image cube

A. Examples of spectral signatures of GAB wetland plants measured with field spectroradiometer and corresponding features in HyMap airborne hyperspectral imagery (Dalhousie, March 2009).

B. The image cube illustrates both the spatial and spectral detail achievable with this type of imagery: every pixel in the high-resolution image is recorded in 126 spectral bands, highlighted in rainbow colours behind the colour image.

2. The new understanding of GAB springs presented in this volume is underpinned by a very wide range of satellite and airborne imagery that was specifically commissioned and acquired for this work. Low spatial resolution, high temporal frequency Moderate Resolution Imaging Spectrometer (MODIS) vegetation greenness sequences from 2000–2011 were used to document inter- and intra-annual wetland vegetation dynamics at Dalhousie and Hermit Hill spring complexes. Targeted acquisitions of very high resolution QuickBird and WorldView-2 multispectral satellite imagery were used to document detailed changes in wetland area and distribution over time and to develop relationships with spring flow rates.

Several specialised forms of airborne remote sensing were central to this study. Extensive sets of hyperspectral imagery were acquired for nine spring groups representing the diversity of spring settings and forms in the western GAB in South Australia. The rich spectral information contained within this data has been exploited for detecting and mapping wetland area, plant species, surface moisture, diffuse discharge and evaporite minerals. Repeat acquisitions over focus study sites were used to document changes in spring surface expressions. Trials were conducted with different hyperspectral sensors to compare their performance for spring wetland mapping, and airborne LiDAR (Light Detection And Ranging) was evaluated as a source of information about vegetation structure that may enhance spectral mapping. Very high resolution visible and infrared aerial photography was acquired simultaneously with the hyperspectral imagery and was a valuable source of ground truth information, and was used widely to assist validation of features derived from image analyses.

The Shuttle RADAR Topography Mission Digital Elevation Model (Australian 2010 release) was used in terrain analyses to delineate spring-fed wetlands from surrounding streams at Dalhousie Springs Complex, and provided insights into surface features and trends for Francis Swamp Springs Complex.

The full potential of remote sensing approaches is only realised when linked to appropriate on-ground environmental measurements of surface properties. Extensive field sampling campaigns were conducted as close as was feasible to the timing of airborne image acquisitions, using methods designed specifically for the spatial scale of vegetation communities and imagery. Field surveys included extensive sampling of vegetation cover and composition in plots, spectral characterisation of survey plots, wetland plant species and land surfaces, near-surface soil moisture measurements and measurements of spring flow rates. Fuller details of field sampling and survey methods are presented in Appendix 2.

Ground-based vegetation survey data was widely used to provide training and validation areas for image-based digital analysis and mapping and to develop site-specific calibration relationships between image vegetation indices and percentage of plant cover within survey plots. Field spectral measurements were used to assess the potential for spectral discrimination of wetland plant types and as references for hyperspectral image analyses. Measurements of flow from selected springs were used to develop calibration relationships with corresponding image-derived wetland vegetation areas for Dalhousie and Mt Denison complexes.

Publications and presentations of aspects of this volume

A Gotch, TB & Green, G 2010, 'GAB spring classification and risk assessment', *Proceedings Groundwater 2010 Conference: The Challenge of Sustainable Management*, Canberra, Australia.

B Lewis, MM & White, DC 2012, 'Multi-sensor synergies provide new understanding of Great Artesian Basin wetlands', *Proceedings XXII Congress, International Society of Photogrammetry and Remote Sensing*, Melbourne, Australia.

C Petus, C, Lewis, MM & White, DC 2012a, 'Using MODIS Normalised Difference Vegetation Index to monitor seasonal and inter-annual dynamics of wetland vegetation in the Great Artesian Basin: A baseline for assessment of future changes in a unique ecosystem', *Proceedings XXII Congress, International Society of Photogrammetry and Remote Sensing*, Melbourne, Australia.

D Petus, C, Lewis, MM & White, DC 2012b, 'Monitoring temporal dynamics of wetland vegetation at Dalhousie Springs Complex in Australia using MODIS Normalised Difference Vegetation Index (NDVI)', *Ecological Indicators,* in review.

E White, DC & Lewis, MM 2009, 'Mapping the spectral and spatial characteristics of GAB mound spring wetland vegetation: Initial findings and exploration of an unsupervised PCA approach', *Proceedings of National Water Initiative Workshop: Allocating Water and Maintaining Springs in the GAB: Australian Society for Limnology Annual Congress*, Alice Springs, Australia.

F White, DC & Lewis, MM 2010a, 'An expedient method for monitoring great Artesian Basin spring flow rates using very high resolution QuickBird satellite imagery', *Proceedings Groundwater 2010 Conference: The Challenge of Sustainable Management*, Canberra, Australia.

G White, DC & Lewis, MM 2010b, 'Mapping the spectral and spatial characteristics of mound spring wetland vegetation in South Australia: A novel spectrally segmented PCA approach', *Proceedings of American Society for Photogrammetry and Remote Sensing Annual Conference*, San Diego, USA.

H White, DC & Lewis, MM 2010c, 'Mapping the spectral and spatial characteristics of mound spring wetland vegetation: A novel integrated hyperspectral approach', *Proceedings 15th Australasian Remote Sensing and Photogrammetry Conference,* Alice Springs, Australia.

I White, DC & Lewis, MM 2011, 'A new approach to monitoring spatial distribution and dynamics of wetlands and associated flows of Australian Great Artesian Basin springs using QuickBird satellite imagery', *Journal of Hydrology*, vol. 48, pp.140–152.

J White, DC & Lewis, MM 2012, 'Mapping the wetland vegetation communities of the Australian Great Artesian Basin springs using SAM, MTMF and spectrally segmented PCA hyperspectral analyses', *Proceedings XXII Congress, International Society of Photogrammetry and Remote Sensing*, Melbourne, Australia.

Table 1.1: Study components, focal spring complexes, groups and volume structure

Study components A-J: publications reporting this research	Spring complexes and groups			
	Dalhousie	Francis Swamp	Freeling	Hermit Hill
Chapter 2: Spatial survey of springs				
Control point survey	●	●	●	●
RTK DGPS spring survey	● A	● A	● A	● A
Spring inventory		●	●	
Chapter 3: Characterising spring groups				
Wetland vegetation distribution and extent	● I	●	●	●
Dominant species and communities distribution from hyperspectral analysis and field data	● E G H J		● J	● J
Variations in wetland vegetation greenness	●			
Near-surface moisture distribution from hyperspectral analysis	●		●	●
Near-surface moisture distribution from thermal imagery and field sampling		●		
Diffuse evaporative discharge distribution from hyperspectral analysis	●		●	●
Evaporite mineral distribution from hyperspectral analysis		●		
Terrain and elevation analysis & interpretation	●	●		
Chapter 4: Temporal dynamics of spring complexes				
Seasonal growth in relation to environmental influences	● C			● C
Decade of changes and trends in wetland vegetation growth in relation to rainfall	● C D			● C D
Detailed changes in distribution and area of:				
Wetland vegetation	● F I		●	●
Near-surface moisture	●		●	●
Diffuse evaporative discharge			●	●

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Table 1.1: Study components, focal spring complexes, groups and volume structure

Study components A-J: publications reporting this research	Spring complexes and groups			
	Dalhousie	Francis Swamp	Freeling	Hermit Hill
Chapter 5: Associating wetland extent and spring flow rates				
Image vegetation index related to field measures of % cover	● F I		●	
Wetland area related to spring flow	● F I		●	
Chapter 6: Evaluation of remote sensing approaches				
Differentiation of wetland vegetation species with reflectance measurements	● E G H I	●	●	●
Evaluation of remote sensing technologies and methods: relative merits and limitations for GAB spring mapping and monitoring	● B C D E H I J	● B	● B	● B
Recommendations for future monitoring	●	●	●	●
Appendices: Data and methods				
Spring spatial hierarchy and RTK DGPS survey Control point survey Remote sensing data technical specifications	All sites A			
Field data collection methods Vegetation sampling Spectral measurements	Standardised for all sites E F G H I			
Image and data analysis methods	All sites			
	B C D E F G H I J		J	J

More detailed technical specifications are presented in Appendix 2.

Table 1.2: Remote sensing, spatial and field data used in this report

Data	Spring complexes and groups								
	Dalhousie	Beresford and Warburton	Billa Kalina	Francis Swamp	Freeling	Hawker and Levi	Hermit Hill	Strangways	Wabma Kadarbu
RTK DGPS spring survey data	●	●	●	●	●	●	●	●	●
Remotly Sensed Data									
Low resolution, high temporal frequency satellite imagery									
MODIS Normalised Difference Vegetation Index 2000–2011	●						●		
Moderate resolution satellite imagery									
ASTER Visible–Infrared–Thermal				●					
Very high spatial resolution satellite imagery									
QuickBird/WorldView-2 2006	●								
QuickBird/WorldView-2 2009	●								
QuickBird/WorldView-2 2010	●								
QuickBird/WorldView-2 2011					●		●		
Airborne hyperspectral imagery									
HyMap 2009	●	●	●	●	●	●	●	●	●
HyMap 2011	●				●		●		●
Eagle 2011	●								
Very high resolution aerial photography									
2009 (Visible)	●	●	●	●	●	●	●	●	●
2011 (Visible, near-infrared)	●								
Airborne LiDAR (Riegel)	●								
Digital elevation models									
Shuttle Imaging RADAR Digital Terrain Model	●	●	●	●	●	●	●	●	●
High-resolution DEM and DSM from UltraCam aerial photography	●								

Table continued on next page >

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Table 1.2: Remote sensing, spatial and field data used in this report

Data	Spring complexes and groups								
	Dalhousie	Beresford and Warburton	Billa Kalina	Francis Swamp	Freeling	Hawker and Levi	Hermit Hill	Strangways	Wabma Kadarbu
Field sampling									
Vegetation plots (number of samples)									
2009	11	3	9		5		6	8	2
2010			12				8		
2011					18		32		33
Near-surface soil moisture									
2010				78					
Soil mineralogy									
X-Ray Diffraction				12					
Wetland plants and soils: Reflectance spectra (visible/near-infrared)									
2009	●	●		●	●		●	●	●
2010			●				●		
2011					●		●		●
Spring flow rates									
Weir gauges (1997–2010)	●								
Salt dilution July 2009	●								
2011					●		●		

Volume IV: Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin

Allocating Water and Maintaining Springs in the Great Artesian Basin

2

Spatial survey of springs

Travis Gotch Department of Environment, Water and Natural Resources, Government of South Australia

2. Spatial survey of springs

2.1. Introduction

Historically, Great Artesian Basin (GAB) springs have been important features in the landscape of arid Australia. Permanent fresh water has meant that the general locations of springs have been recorded since the first humans arrived in the region. However, this has been haphazard and, until the Allocating Water and Maintaining Springs in the Great Artesian Basin project (AWMSGAB Project), no complete survey of spring vent locations had been undertaken in South Australia.

The first people to map the springs were the ancestors of the current Aboriginal peoples of the region. Petroglyphs at a number of sites indicate, to those who can interpret them, that water is nearby. The locations of spring groups were also 'mapped' as part of the oral history and songlines of the people that inhabited these areas. Songlines are integrally linked to the landscape and progress as people move through the country. To be 'sung into country' is to be introduced to the cultural and ancestral history of the area and to be given a road map of the features in the area, springs included.

The earliest Europeans to see and map the springs along the western margin of the GAB were part of BH Babbage's 1858 expedition to map 'the country west of Lake Torrens and the eastern shore of Lake Gairdner, and thence northwards' (Babbage 1858). Babbage was later joined by Warburton and soon followed by John McDouall Stuart, each of whom mapped many more springs. Several more surveying expeditions set out to map the important features of the area, but the first comprehensive spring survey did not occur until work investigating the GAB to provide water for the Olympic Dam mine commenced in the early 1980s (Australian Groundwater Consultants 1982; 1984). These studies focused mainly on springs in the Hermit Hill Complex and many spring vents were surveyed not only for position but also for elevation. Since this survey was undertaken by surveyors and hydrogeologists, only vents with noticeable flow were included, while vents that only supported wetland vegetation were ignored. Several biological and cultural surveys were undertaken that included some limited mapping but none were to a survey standard (Greenslade *et al.* 1985; Hercus & Sutton 1985; Kinhill Stearns 1985; McLaren *et al.* 1985; Zeidler & Ponder 1989).

Photograph on facing page:
Erika Lawley

A number of real-time kinematic differential GPS (RTK DGPS) surveys on South Australian springs have been undertaken (Table 2.1) prior to the AWMSGAB project, though all of them focused on specific areas. The first survey was conducted by Gotch (unpublished data), investigating the role of flooding in the dispersal of GAB spring wolf spiders. This was expanded when WMC (Olympic Dam Corporation) undertook a RTK DGPS survey of springs within the impact zone of Wellfield A (WMC (Olympic Dam Corporation) Pty. Ltd. 2003) and later initial surveys for the Olympic Dam 3rd Expansion Pre-feasibility Study. It was during this time that other agencies began to realise the importance of high-precision elevation data in managing GAB springs.

The former Department for Environment and Heritage (DEH) undertook a detailed study of springs in Wabma Kadarbu Conservation Park in 2005 (Graham 2005). This included RTK DGPS survey, as well as detailed flora, fauna and hydrochemical inventory. Unfortunately, the base stations were not properly linked during the survey. As a result, the accuracy of some of the spring positions and elevations may be reduced (Graham, A & Ferguson, R pers. comm. 2005). Despite this, the detail and quality of the attribute data collected in this survey was of a high standard and demonstrated that there is significant value in collecting physical and biological data along with positional data.

RTK DGPS surveys continued in an opportunistic manner by the Arid Areas Catchment Water Management Board (AACWMB) and later the South Australian Arid Lands Natural Resource Management Board (SAALNRMB), until the AWMSGAB Project commenced in 2008.

The work presented in this volume directly links the ecological and hydrological components of the AWMSGAB Project. The spatial and inventory data collected have provided a baseline for future monitoring and have been used to provide specific surveying support to the other components of the AWMSGAB Project.

Table 2.1: History of RTK DGPS surveying in South Australian GAB springs

Date	Title	Surveyor	Notes
1858	Northern explorations: Reports from Messrs Babbage and Warburton, and Police Trooper Burtt, on exploration into the north and north-western interior of South Australia	BH Babbage	
1984	Olympic Dam Water Supply, Wellfield A investigation	Australian Groundwater Consultants	
2000–2002	Spring elevation survey (PHD) data	TB Gotch	First Real Time Kinematic Surveys
2003	WMC: Mound spring monitoring of the Lake Eyre South region	TB Gotch	
2004-2005	WMC 3rd Expansion pre-feasability study	TB Gotch & P Crettenden	
2005	Wabma Kadarbu Conservation Park GAB springs inventory	A Graham	PSM not correctly located may warrant future re-survey
2005–2009	AACWMB/SAALNRMB spring elevation surveys	TB Gotch	
2008–2011	AWMSGAB Project	TB Gotch	

Table 2.2: Spring classification hierarchy and definitions

Classification	Definition and description
Supergroups	Clusters of spring complexes; there are 13 supergroups across the GAB with three found in South Australia
Complexes	Clusters of spring groups that share similar geomorphological settings and broad similarities in water chemistry
Groups	Clusters of springs that share similar water chemistry and source their water from the same fault or structure
Spring	Individual wetlands comprising one or more vents and tails joined together by permanent wetland vegetation
Vents	Individual point discharges of water from the GAB, varying in size and structure: some are discrete discharges of water as if coming from a pipe, while others may be several metres across with no clear point of discharge within the region—the spring vent is the minimum unit used when describing the number of springs from a legislative perspective and in accordance with water allocation planning
Tails	Wetlands associated with flow away from the vent

2.2. GAB spring spatial hierarchy and nomenclature

Habermehl (1982) identified springs clustered into 11 large groups around the margins of the GAB. Ponder (1986) coined the term ‘supergroups’ to distinguish these from smaller aggregations of springs, which he termed ‘complexes’ and ‘groups’, respectively. Additionally, Cape York Supergroup was recognised in 1998 (Great Artesian Basin Consultative Council 1998) and the Mitchell-Staaten Rivers Supergroup was identified by Fensham and Fairfax (2003)—bringing the total to 13 supergroups. Within the western margin of the GAB there are three supergroups, 22 complexes (Figure 2.1) and 169 groups (Appendix 1).

The terminology used to describe GAB springs established by Ponder (1986) was further refined to include hydrogeological parameters by Fatchen and Fatchen (1993) and this is the system used in South Australia. This definition is explained in Table 2.2, as well as terms used to describe individual springs and wetlands.

Another definition based on Ponder (1986) and developed by Fensham and Fairfax (2003) emphasises spatial organisation and distance. These definitions are:

- spring group: clusters of springs no further than 1 km apart and sharing a similar geomorphic setting.
- spring complex: clusters of spring groups no further than 6 km apart and sharing a similar geomorphological setting.
- supergroup: a major regional cluster of spring complexes.

There are two main differences between these approaches, both of which are relatively minor. The first is the use of hydrogeological parameters to assist in the classification of groups in South Australia and the second is the use of a distance limiter in Queensland. Many South Australian spring complexes do not fit the distance units identified in Fensham and Fairfax (2003). Some complexes have groups that are closer than the 1 km delimiter (Hermit Hill Complex) while many other complexes have groups spread further than 6 km apart. This is especially common in the Lake Eyre Supergroup. Other than this, the two systems are essentially the same and can be relatively easily interchanged.

Figure 2.1: GAB spring supergroup and complex distribution in South Australia

Spring Complex

- Beresford Hill
- Billa Kalina
- Coward Springs
- Dalhousie
- Francis Swamp
- Hermit Hill
- Lake Blanche
- Lake Cadibarrawirracanna
- Lake Callabonna
- Lake Eyre
- Lake Eyre South
- Lake Frome
- Marree
- Mt Denison
- Mt Dutton
- Mt Margaret
- Neales River
- Peake Creek
- Petermorra
- Reedy
- Strangways
- Wangianna

Spring Supergroup

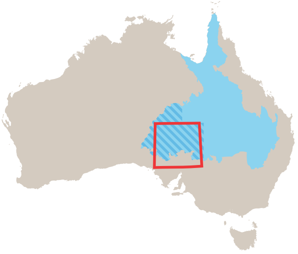
- Dalhousie
- Lake Eyre
- Lake Frome

Legend

- Oodnadatta Track
- Primary Road
- Secondary Road

0 50 100 150
Kilometres
N

Background image: Landsat, True Colour, 2000
Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: January 2012



Another significant definition in Fensham and Fairfax (2003) is around 'recharge' and 'discharge' springs. These are not addressed in the AWMSGAB Project, as there are no active recharge springs on the western margin of the GAB.

Because of the large number of spring vents, groups and complexes, many different naming conventions have arisen amongst various studies (Zeidler & Ponder 1989; Fatchen & Fatchen 1993; Kinhill Engineers Pty Ltd 1997; Graham 2005). Sites were named with ad hoc and individual naming conventions by investigators in these previous studies. This has resulted in great difficulty for managers and researchers interrelating the various studies. It has also caused some confusion in spring names. For example, there is often confusion between two Welcome Spring groups (KWS and WWS), located at Anna Creek and Callana Stations respectively, and between Margaret Springs (FMS) and Billa Kalina Springs (KBK) because the latter is located adjacent to Margaret Creek. In the past, attempts have been made to standardise the naming of spring vents, but with the exception of the unit number assigned in the SA Geodata database, no consistent system has been applied across the South Australian portion of the GAB. Unfortunately, the unit number system is not intuitive, nor does it offer any information on the relationship between the vent and the group.

The spring vent numbering protocols originally used by environmental scientists associated with the Olympic Dam Mine project give clear indications of how a vent fits in the broader spatial hierarchy. The system consists of a six-digit alphanumeric code with the first letter indicating the complex, the second pair of letters defining the group and the subsequent three numbers defining the vent number. For example HWF037 is Hermit Hill Complex (H), West Finniss Spring Group (WF) and vent number 37. This protocol was adopted by the GAB Springs Project (AACWMB and SAALNRMB) and applied to all springs in South Australia. The AWMSGAB Project represents the first complete data set of spring vent locations named using a consistent and informative naming convention in South Australia.

2.3. Survey methods

Because of the broad area covered by the ground-based survey, it was impractical to attempt the survey with conventional surveying methods. DGPS surveying enables fast and accurate collection of points over large areas. This is particularly appropriate in GAB spring surveys where loop closure distances could exceed 150 km.

DGPS is a surveying method that uses two or more GPS receivers to simultaneously collect data, which are then processed together to remove common errors. The result of this processing is a three-dimensional vector between the receivers, known as a baseline. When one of the receivers is located over a known point, the baseline can be added to the known coordinates to derive a relative position for the other receiver. There are two main techniques used to derive accurate and precise positions: static DGPS and RTK DGPS.

Static DGPS is the most accurate of the two methods, but requires the receivers to occupy the points for relatively long periods of time (two hours plus one minute per kilometre of baseline). Faster solutions can be achieved using 'fast static' methods; this results in slightly less accurate solutions, but with more productive workflow.

RTK DGPS involves data from a fixed base being sent by radio to a rover receiver and processed in real time to produce a three-dimensional vector that then gives the derived position at the rover. It has the advantage of short occupation times for the rover and rapid work flow. The disadvantage is that it is not as accurate as static DGPS.

The AWMSGAB Project used a combination of these methods for the survey, depending on the application. The equipment used included Trimble RTK DGPS, GNSS R8 Receivers, Trimble TSC2 Controller and Trimble Data Radios. This system gives minimum static accuracy of 3 mm + 0.1 ppm Root Mean Square (RMS) in the horizontal and 3.5 mm + 0.4 ppm RMS in the vertical and minimum kinematic surveying accuracy of 10 mm +1 ppm RMS in the horizontal and 20 mm +1 ppm RMS in the vertical. Post-processing was carried out initially using Trimble Geomatics Office and later with Trimble Business Centre software.

Other equipment used during the survey included TPS water meters for measuring pH, conductivity, temperature and dissolved oxygen, and digital cameras to record pictures of vents and springs at the time of survey.

2.4. Control point survey

A control point network was created from static observations derived from zero-order horizontal and third-order vertical survey benchmarks supplied by the Office of the Surveyor General of South Australia (Table 2.3). Static baselines to locate the control network were used according to the manufacturer's recommendations and in accordance with the Intergovernmental Committee on Surveying and Mapping (ICSM 2007). There was one other permanent survey mark (PSM) used, located near Pump Station 1. This point did not have any coordinates recorded in the Surveyor General's Office, so was used as a mark to be incorporated into the control network after a static position was derived from BM 1730.

Due to logistical and time constraints, some of the control points were derived using AUSPOS. AUSPOS is an online tool produced by Geoscience Australia to enable the rapid post-processing of carrier phase and RINEX data, giving sub-centimetre accuracy from a single receiver. While not as accurate as static baselines, it is a very useful method for sites that are difficult to access and has the advantage that RTK DGPS surveys can be carried out simultaneously with the correction applied later via Trimble Business Centre. AUSPOS control points were collected with five-second epochs for a minimum of six hours.

Table 2.3: Survey benchmarks used to develop control point network

		Benchmark	
		BM 3125	BM 1730
	Site	Anna Creek	Coward Springs
	Mark number	6140/1057	6293/1051
Horizontal detail	Easting	614198.042	669867.028
	Northing	6802365.650	6752818.155
	Datum	MGA94	MGA94
	Zone	53	53
	Order	0	0
Vertical detail	Elevation	95.718	26.200
	Datum	AHD	AHD
	Order	3	3

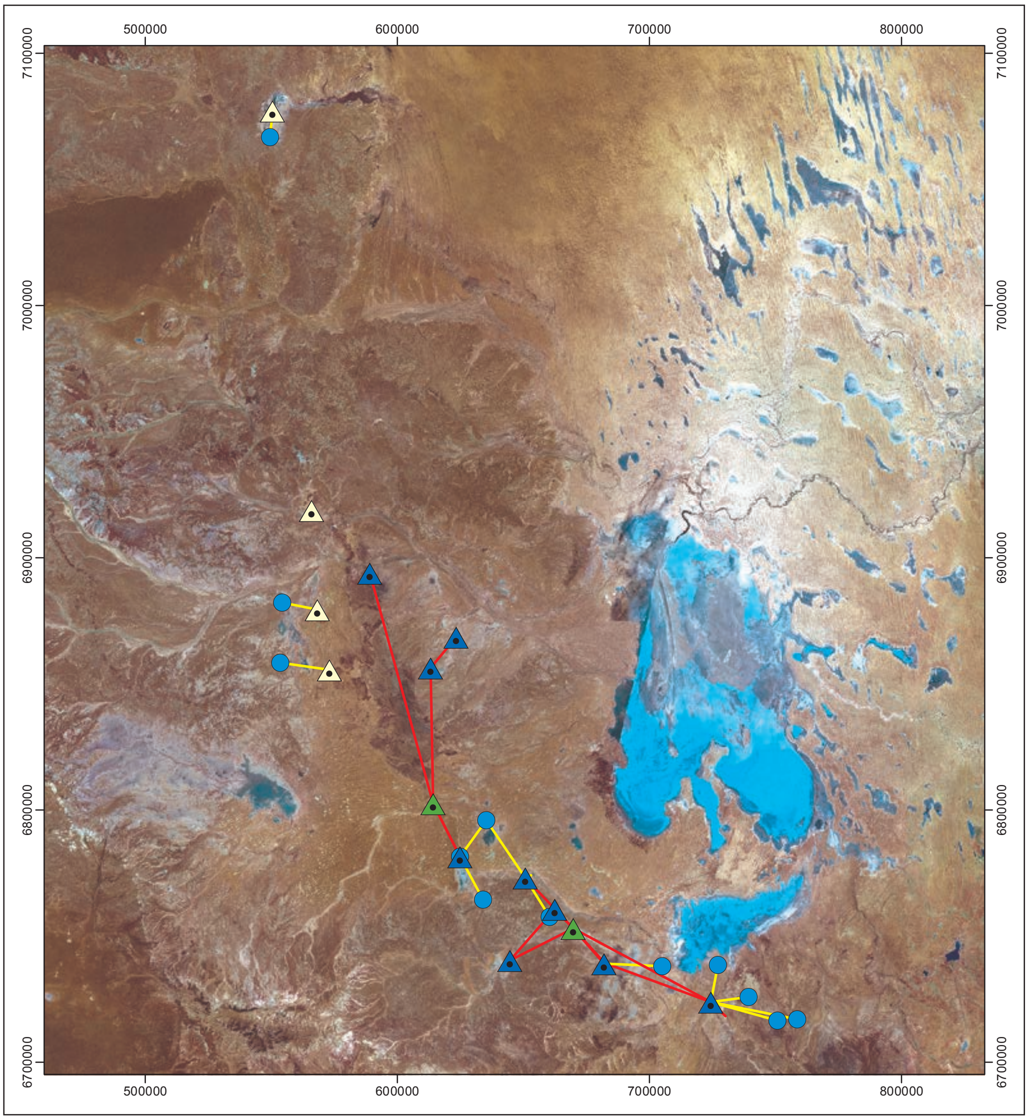


Figure 2.2: Permanent Survey Mark control network

Survey Benchmarks

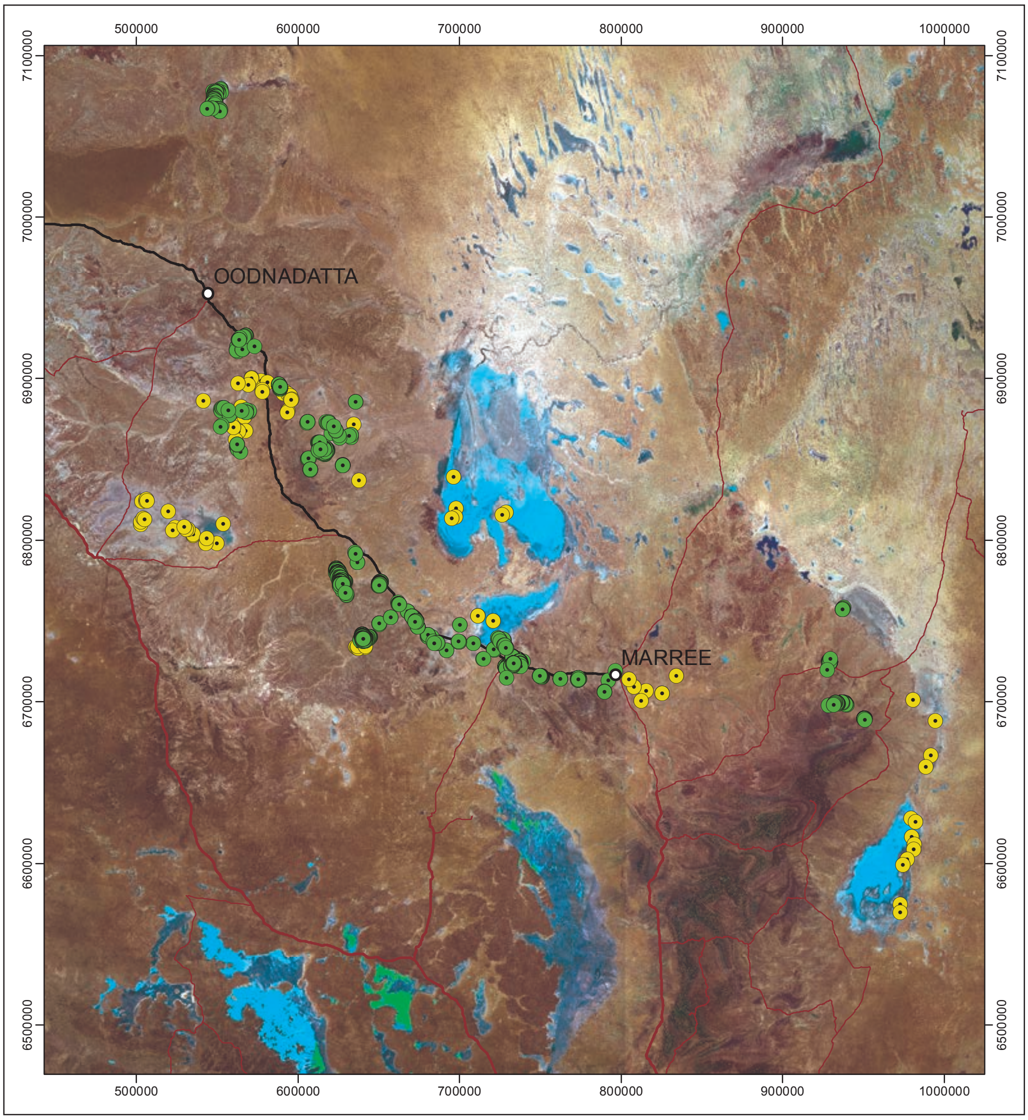
- ▲ Survey Benchmark
- ▲ Static Observation
- △ AUSPOS Observation
- ● Observed Control Point

Baseline Vectors

- — Observed Control Point
- — Static

Background image: Landsat, True Colour, 2000.
Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: January 2012

Figure 2.3: Distribution of surveyed and unsurveyed spring vents in South Australia



Background image: Landsat, True Colour, 2000.
Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
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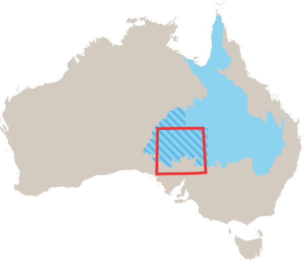
Date: January 2012



The control point network of PSMs established on the western margin of the GAB includes the Lake Eyre and Dalhousie supergroups (Figure 2.2). A separate control network established by Haines Surveying Pty Ltd was used for the Lake Frome Supergroup, but this was not part of the study and has not been included here. A total of 12 PSMs were installed alongside the three existing marks. In addition, another 12 control points were created by driving a star dropper into the ground as far as possible and then cutting it off close to ground level. The centre was then marked with a centre-punch. These points are listed in Appendix 1.

The development of the control network ensures spring elevations are set to a consistent datum (horizontal GDA94 and vertical AHD). The surveys are also consistent between sites, which enables regional assessments to be undertaken. It also ensures future survey works have a local control point, enabling accurate comparisons and georegistration with this work.

2.4.1. RTK DGPS spring survey

Spring vents were surveyed using RTK DGPS. Bases and rovers were set up in accordance with Trimble operating manuals. A single radio was used for smaller spring groups close to the base, but a second radio repeater was used for larger areas and in locations where the terrain resulted in high RMS errors. Occupation time for vents was five seconds, with one update per second. Baseline lengths varied from site to site but the majority were within 15 km of the base. Longer baselines were used when shooting forward and in these situations a repeater radio was used. When shooting forward, longer occupation times were required, typically a minimum of 180 epochs. All survey loops were closed to within acceptable tolerances.

Spring vent elevations were recorded at the highest point where water was visibly discharging from the ground or at the highest point wetland vegetation was recorded. If the vent had no visible water or wetland vegetation then the elevation of the highest point of the extinct or dry mound was recorded. Many spring vents were heavily vegetated with Common Reed (*Phragmites australis*), which presented challenges in identifying the vent. However, *Phragmites* flowers more densely over fresh water and by interpreting the vegetation height and density of flower spikes, the approximate location of the vent could be determined. It was then necessary to dig down through the leaf litter (sometimes in excess of 2 m) to find the vent. Other species of vegetation, while densely growing, did not pose such difficulty in identifying the vent location. Care needs to be taken at springs in the Dalhousie Complex as *Phragmites* occasionally rafts over deep vent pools. This can result in the surveyor falling into deep water that is difficult to get out of due to the thickness of the vegetation.

A total of 4516 spring vents have been surveyed to centimetre-accuracy across 103 spring groups. Due to record rainfall events across much of the region during the AWMSGAB Project, 66 spring groups remain unsurveyed (Figure 2.3). A summary of the spring complexes, groups and number of vents, with names following the standard nomenclature, is included in Appendix 1. This survey was conducted with a high degree of positional accuracy with a mean horizontal plane error of +8.4 mm on the horizontal plane and +14.8 mm in the vertical plane.

Surveyed spring locations are stored within SA Geodata; access to the data can be obtained by application to the SAALNRMB. This data is an important resource for managers, spatial scientists, ecologists, hydrogeologists and industry. Equally, this work has been integral to the delivery of many other parts of the AWMSGAB Project overall. Using the spring elevation data and the revised potentiometric surface for the GAB, excess head measurements have been calculated for the springs of the western margin, enabling the development of a risk framework for water allocations on springs

(Volume VI: Risk Assessment Process for Evaluating Water Use Impacts on Great Artesian Basin Springs (Green *et al.* 2013)).

Spring coordinates and vent codes have been reconciled with existing water data stored within SA Geodata, greatly expanding the value of this resource. Historical water records, some dating back more than 100 years, have been linked to these spatial coordinates. This incorporation and reconciliation of historical water quality measurements with high-accuracy spatial locations provides a powerful view into the past and a window into how GAB springs have responded since the first bores were drilled in the region.

2.4.2. Spring inventory

In addition to the spatial locations of spring vents, several other attributes were measured (Table 2.4). These were recorded on a TSC2 Controller as a feature code library attached to each vent record.

Most attributes are self explanatory, however spring flow was assessed both quantitatively and qualitatively. Where possible, exact flow rates in L/sec were recorded, but due to technical limitations and the time and effort required to do this, most spring vents could not be assessed this way. When quantitative measurements could not be recorded, a set of qualitative classes were used (Table 2.5).

Table 2.4: Spring inventory attributes

Attribute	Description
pH	Standard measurement of acidity/alkalinity
Conductivity	Measured in µS
Flow	Free water and tail; free water; saturate; damp; dry; extinct
Substrate	Sand; silt; gravel; organic; travertine
Grazing	Heavy; moderate; light; nil
Pugging	Heavy; moderate; light; nil
Flora	Wetland-dependent flora with dominant vent vegetation listed first
Fauna	Significant species and endemics observed
Date Palms	Present/absent
Threats	Any other observed threats including ferals, excavation, tourism impacts etc.
Notes	Any other noteworthy features including aboriginal artifacts, old troughs and yards etc.

Table 2.5: Spring inventory flow classes and definitions

Flow status	Definition
Free water and tail	Vents with free water at the vent and flowing wetland tails; this can also include springs with vent pools
Free water	Vents where free water is observed either at the top of the mound or in the form of a vent pool but flow is insufficient to create a wetland tail
Saturated	Spring vents that have saturated substrate such that depressing them will cause water to form in the hollow
Damp	Spring vents that support actively growing wetland vegetation but the substrate is moist to dry and does not release water when depressed
Dry	Spring vents that either have dead or dormant wetland-dependent vegetation or actively growing species that are associated with drier conditions such as *Sporobolus virginicus* or *Cyperus gymnocaulis*; substrates are also dry to touch
Extinct	Spring vents that are clearly no longer flowing and do not support any wetland vegetation

2.5. Conclusions

Baseline flow data have been collected for a total of 1785 springs, while 1055 spring vents have had a more comprehensive baseline survey. These data expand and complement existing datasets such as that collected by Niejalke from 1996 to 2005.

The elevation survey of GAB springs conducted here represents the culmination of many years of work and field surveying. The data collected as part of this survey are one of the most important datasets for spring managers and researchers and will significantly advance the capacity for management of springs along the western margin of the GAB.

The establishment of a baseline of flowing and extinct springs is invaluable to those who will need to monitor the impacts of drawdown in the future. Without knowledge of the current status of springs, the ability to assess and monitor impacts is significantly retarded. With this information, future spring extinctions can be quantified with no uncertainty as to when the extinction took place.

The survey data have also been used with the remotely sensed imagery and associated field data presented in subsequent chapters of this report (refer to Appendix 2 for further details on the methods involved). Briefly, survey data are useful for:

- precisely locating vegetation survey plots within the remotely sensed imagery for deriving values from analysed image outputs of vegetation indices and mapped outputs of dominant vegetation types and substrate surface features; these image values were subsequently used for regression analyses, calibration purposes and for input into further image analyses
- contextual information for delineating individual spring wetland vegetation extents from the high spatial resolution multispectral satellite
- ground validation of image mapped products
- locating core samples of soil moisture
- providing comprehensive technical descriptions of the sites investigated.

3

Characterising spring groups

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3. Characterising spring groups

3.1. Introduction

New spatial technologies and sources of information were used to characterise and map several major spring groups and complexes that have been poorly described to date. This chapter draws on results of the spring survey (Chapter 2), analyses of airborne and satellite imagery and digital elevation models, combined with vegetation sampling to provide new descriptions and mapping for complexes and groups representative of the diversity of springs in the western GAB. The descriptions and accompanying maps present new quantifiable baseline information regarding land surface features, including:

- geomorphic setting and terrain
- spring vent distribution and flow status
- distribution and extent of wetland vegetation
- distribution of dominant wetland vegetation species
- distribution of zones of near-surface moisture (wetted areas)
- distribution of surface salinisation associated with diffuse evaporative discharge of groundwater.

3.2. Overview of methods

Specialised airborne image surveys and satellite image acquisitions provided the basis for delineation of wetland vegetation and surface indicators of diffuse discharge, as summarised in Table 1.2. Most of the spatial distributions and descriptions of surface characteristics presented here are based on analysis of HyMap airborne hyperspectral imagery acquired in March 2009 and April 2011, supported by near-simultaneous ground measurements of vegetation cover, composition and spectral signatures. Very high spatial resolution multispectral QuickBird and WorldView-2 satellite images acquired in May 2009 and October 2010 and an archived image (December 2006) (Table A2.1, Appendix 2) were also used to study variations in plant growth within the Dalhousie Springs wetlands. This high spatial resolution multispectral satellite imagery was also acquired in May 2011 at Freeling springs within the Mt Denison Complex to map and quantify wetland vegetation extent. ASTER thermal imagery from December 2009 was used to identify surface temperature variations at Francis Swamp.

The distribution and extent of wetland vegetation was derived from the Normalised Difference Vegetation Index (NDVI), an indicator of plant photosynthetic activity (greenness), cover and biomass, applied to red and infrared wavelengths of multispectral satellite or hyperspectral airborne imagery. Thresholds to distinguish wetland vegetation from halophytic and arid plant communities were established through calibration relationships with field measurements of plant cover.

Dominant wetland species, areas of surface salinisation and evaporite mineral concentration were identified and mapped using spectral analysis of hyperspectral images. In general, these methods compared image spectral reflectance values with reference signatures of target species, surfaces and minerals, identifying areas of strongest similarity across the study regions. Methods included spectral angle mapping, mixture-tuned matched filtering, spectral matching, and red-edge position analysis (Hestir *et al.* 2008; Becker *et al.* 2007;

Photograph on facing page: Megan M Lewis

Andrew & Ustin 2008). Selection of appropriate reference signatures was guided by preliminary image analysis to identify ‘pure’ samples with distinctive spectra, records from ground samples and interpretation of very high resolution digital aerial photography.

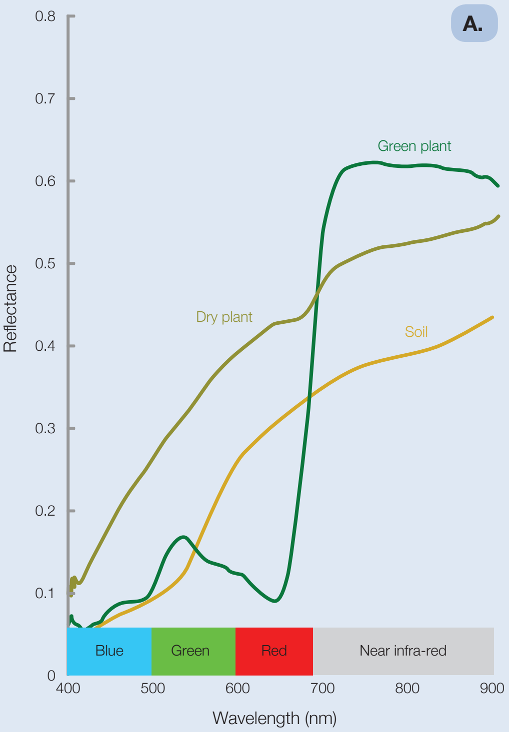
The location and extent of standing surface water at Freeling Springs within the Mt Denison Complex was mapped using the Modified Normalised Difference Water Index (Xu 2006; Lei *et al.* 2009) applied to visible and near-infrared bands of HyMap imagery. Areas of high surface moisture, termed wetted areas, were identified and mapped using a Normalised Difference Soil Moisture Index (Haubrock *et al.* 2008) applied to the hyperspectral imagery. The index is based on spectral absorptions in short-wave infrared wavelengths associated with clay minerals and water, and included wetted areas within vegetated wetlands as well as areas of high soil moisture resulting from spring or other groundwater seepage. Salinised areas of diffuse groundwater discharge and evaporation were identified by their distinctive signatures and spectral analysis of airborne hyperspectral imagery.

The Normalised Difference Vegetation Index: A measure of vegetation greenness

The Normalised Difference Vegetation Index (NDVI) provides a quantitative measure of vegetation greenness which can be derived from visible to near-infrared satellite and airborne imagery. Actively growing green plants have a distinctive reflectance signature, with strong absorption by chlorophyll pigments in the red wavelengths and high reflectance in the near-infrared as light is scattered and reflected by internal leaf cells and structures. Dry, senescent plants and soils have quite different signatures over this wavelength range (**A**).

The NDVI exploits this strong contrast between red and infrared reflectance (R) displayed by healthy vegetation and takes the form:

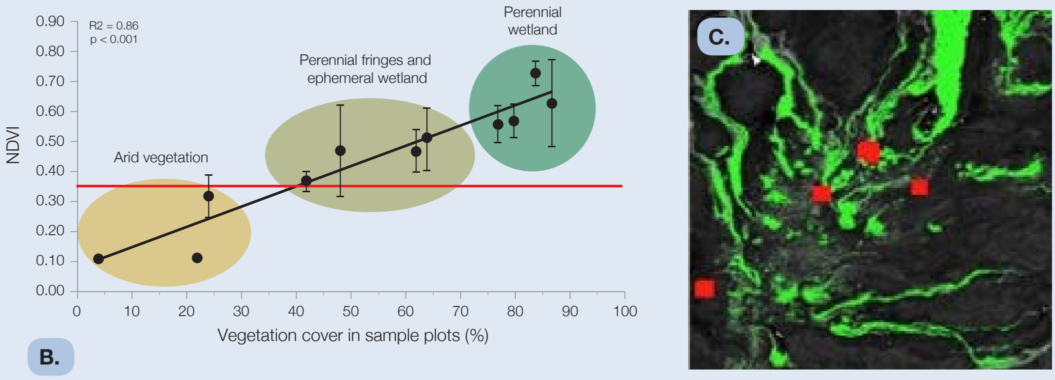
$$\text{NDVI} = \frac{R_{\text{Infrared}} - R_{\text{Red}}}{R_{\text{Infrared}} + R_{\text{Red}}}$$



Distributions of vegetation and surface features derived from image analyses were verified with reference to records of plant species composition and percentage cover from ground sample plots, field reconnaissance and interpretation of very high resolution aerial photography. The ground-based field sampling and aerial photograph acquisition coincided with the timing of airborne hyperspectral and satellite image capture.

Analysis and interpretation of the Shuttle RADAR Topography Mission Digital Elevation Model (Australian 2010 release) provided valuable understanding of terrain for some spring complexes. For Dalhousie Springs Complex, analysis of flow paths and localised catchments using the digital elevation model provided an objective basis for delineating a zone containing spring-fed flows from rain-fed streams and uplands. At Francis Swamp Spring Complex, the digital elevation model revealed subtle trends in the swamp surface, associated with zones of spring activity.

More detailed information on data and methods is presented in Appendix 2.



B. Regression relationship between NDVI image values and field vegetation cover from sample plots representative of vegetation types at Dalhousie Springs Complex, and **C.** example of wetlands delineated by NDVI threshold of 0.35. Sample plots shown in red.

Different red and infrared bands were used in the NDVI analyses according to the differing band configurations and widths of the multispectral and hyperspectral sensors (refer to Appendix 2).

High NDVI is associated with actively photosynthesising vegetation, with dense canopy cover or high biomass. Lower NDVI is associated with dry, senescent plants, lower levels of plant cover or increased soil exposure.

A relationship was established between image NDVI and levels of cover of vegetation within ground sample plots.

This served several purposes:

- to provide a means of calibration between the NDVI derived from satellite or airborne sensor measurements and vegetation cover as measured using on-ground methods
- to allow differentiation of spring wetlands from the surrounding dryland vegetation using an NDVI threshold.

This method of deriving image-based NDVI and relating image values to vegetation cover on the ground can be used as a means of mapping the spring wetland vegetation in the GAB (details in Appendix 2).

3.3. Climate and weather

The spring complexes in the western margin of the GAB lie within the most arid part of the Australian continent. Average annual rainfall is less than 200 mm per annum and is highly variable between years. On average, rainfalls of greater than 1 mm occur on less than 15 to 20 days per annum, with higher falls tending to occur between December and February (Figure 3.1). There is a gradient of increasing temperature from south to north; average daily maximum temperatures range from 27°C south of Lake Eyre to over 30°C near Dalhousie Springs Complex in the north. Summer average temperatures for the region range from a minimum of 20°C to maxima over 36°C, while winter average temperatures range from 5°C to 22°C (Figure 3.2).

Meteorological records from Oodnadatta Airport, Hamilton Station and New Crown Station in the north of the study area and from Maree, south-east of Lake Eyre, indicate long-term rainfall patterns in the region, which provide context for the environmental information presented in this report.

At Oodnadatta, the closest meteorological station to the Dalhousie Springs Complex and Freeling Springs, above average annual rainfalls were recorded from 2000 to 2003, with much lower totals in 2004, 2006 and 2007 and returns to very high totals in 2010 and 2011. At Marree, closer to the southern spring complexes of Hermit Hill and Francis Swamp, very high annual totals occurred in 2000 and 2001, followed by below average annual totals from 2002 to 2009, and very high falls in 2010 (Figure 3.3).

Airborne imagery flown in March 2009 was used for most of the hyperspectral analyses presented here, unless otherwise indicated. At the time, most of the western GAB had experienced below average rains for around five years.

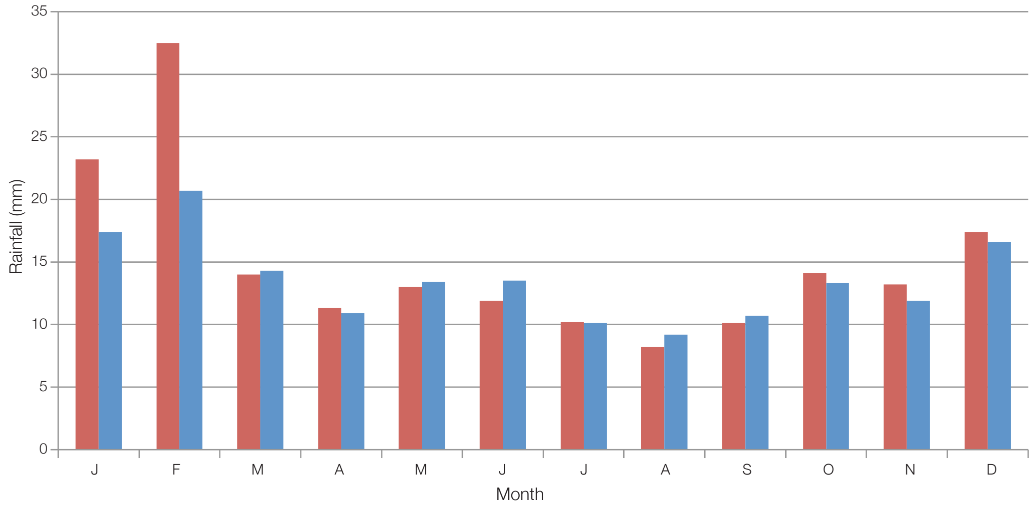


Figure 3.1: Mean monthly rainfall for Oodnadatta Airport and Marree meteorological stations

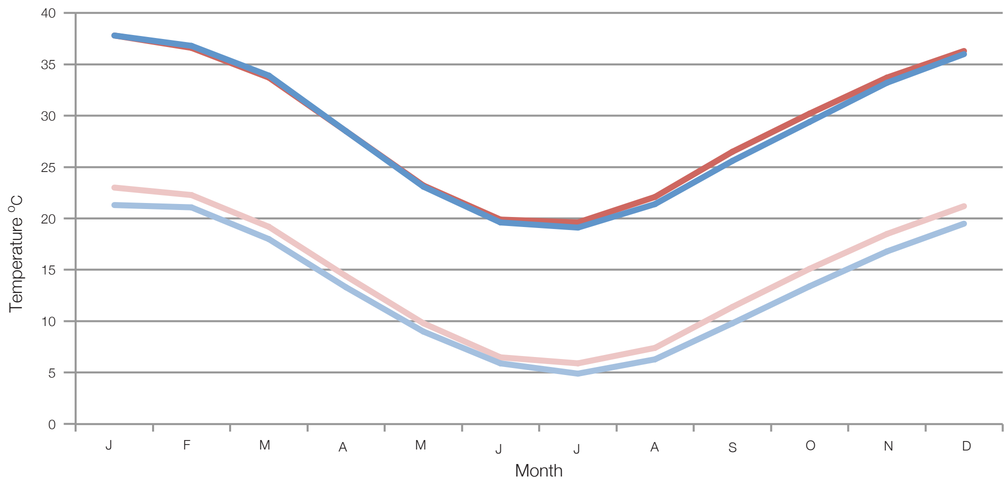


Figure 3.2: Mean monthly temperatures for Oodnadatta Airport and Marree

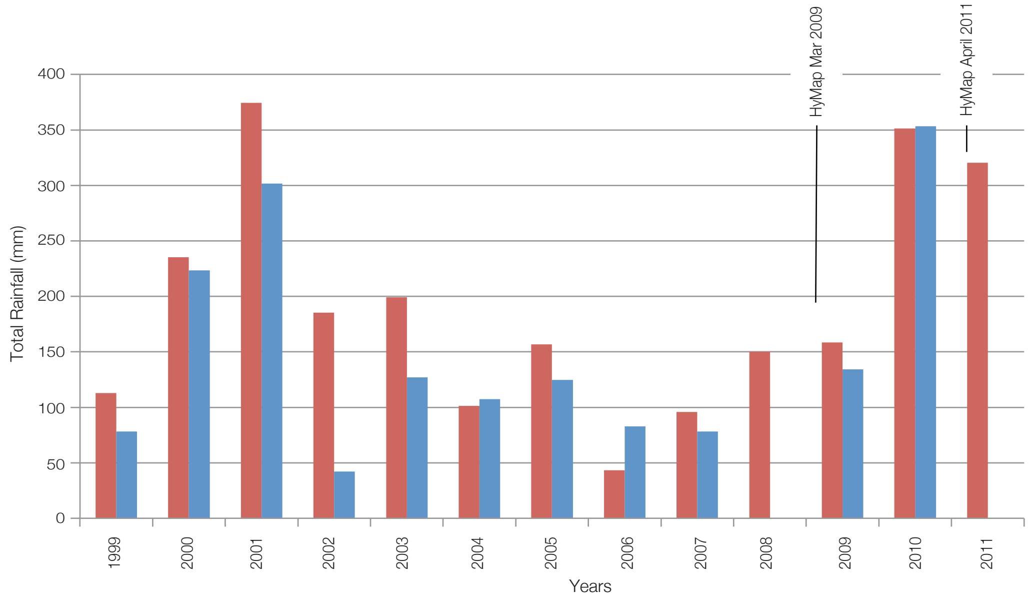


Figure 3.3: Total annual rainfall for Oodnadatta and Marree 1999–2011, and dates of image acquisitions

3.4. Dalhousie Spring Complex

Dalhousie is the largest and best developed of the spring complexes on the south-western margin of the GAB in South Australia. It is situated at latitude 26.45°S and longitude 135.51°E, lying within the Breakaways sub-region of the Interim Biogeographic Regionalisation for Australia (IBRA) (Australian Government 2012). The surrounding landforms comprise tablelands of broken silcrete and plains covered in gibber desert pavement, supporting sparse, low open chenopod shrublands, with some low woodlands of Gidgee (*Acacia cambagei*) and Coolabah (*Eucalyptus coolabah*) lining intermittent stream beds. The spring complex and surrounding land are protected within the Witjira National Park and are included in the Australian Government Register of the National Estate and the National Heritage List.

The spring complex covers approximately 19 000 ha, with flows dispersing across plains lying some 30 m below the surrounding plateau and residual silcrete-capped mesas, based on interpretation of digital elevation models and RTK DGPS measurements of representative points. Analysis of the Shuttle RADAR Topography Mission Digital Elevation Model (Australian 2010 release) provided flow paths, flow accumulation and localised catchments. These outputs were used to define a boundary which delineates spring-related groundwater flows from rain-fed streams and upland areas for the entire complex (Figure 3.4). This boundary was used in later studies (Section 4.4) to provide an objective basis for discriminating spring-fed wetlands from other vegetation, and a consistent basis for comparing changes over time in wetland area for Dalhousie Springs Complex.

There were 145 surveyed springs within the complex, distributed across 10 groups (Table 3.1). The springs are in the core of the breached Dalhousie Anticline (Krieg 1989). The combination of upwarping that produced the anticline and erosion into its upper layers has brought the waters of the GAB close to the ground surface. Pressure from the anticline has created a series of vertical faults, which have allowed water to reach the surface and form springs (Krieg 1985). The spring vents are aligned along the faults, with the majority of the largest flowing springs in the northern-most spring groups. A zone of low potentiometric head corresponds to an area of higher elevation across the centre and slightly to the west of the central axis of the spring group. Springs in this zone tend to have lower flow rates. Springs on the northern, southern and eastern sides of this dome typically have higher potentiometric heads and correspondingly higher flow rates.

Dalhousie Springs Complex is one of the highest complexes relative to sea level in South Australia. The difference in elevation from highest to lowest vent in the complex spans 32.3 m (Figure 3.4). Despite this, it has the largest flowing discharge of spring complexes in the arid zone, second only to spring groups in the far north of Cape York. Spring groups in the northern half of the complex tend to form classical mounds, while the southern-most groups tend more to seeps with some terracing. Spring groups in the northern half of the complex have greater variation across their elevation profile than do the springs further south. This implies greater susceptibility to changes in flow for the springs on the southern margins of the Dalhousie Springs Complex (Table 3.1).

The wetlands at Dalhousie Springs are the most extensive and diverse of the spring complexes in South Australia, covering approximately 1000 ha, as measured from analysis of high-resolution satellite imagery (Figure 3.5). Most radiate from the central zone of springs' interbraided multiple channels which often disperse into extensive fans. Because the wetlands follow lines of outflow from the numerous spring vents, most are linear in form, extending up to five and even 10 km from source.

Table 3.1: Spatial characterisation of Dalhousie Spring Complex

Spring group code	Spring group names	Aboriginal spring group name	Number of vents	Elevation (m above MSL)				
				Mean	Maximum	Minimum	Range	Standard deviation
DAA	Kingfisher	Idnjundura	12	117.804	129.748	112.363	17.385	5.555
DBA	Banana's, Airstrip	Irunpakanha Kwatja	4	116.511	129.259	107.111	22.148	9.246
DCA	Main Pool	Irrwanjira	15	121.621	135.761	110.969	24.792	9.199
DCB	Witcherre Mound	Inkintja	10	124.819	134.100	113.754	20.346	6.528
DCC	Ilpikwa	Ilpikwa	10	127.982	132.831	120.497	12.334	4.272
DCD	Loveheart	Irrumulanha	13	124.974	136.825	116.437	20.388	6.040
DDA	Errawanyera	Unknown	4	132.623	133.819	131.756	2.064	0.864
DDB	Dalhousie Proper	Kirki	16	130.230	134.688	125.074	9.614	3.187
DEA	Dinner, Blind Fish	Ura-alapa	17	129.742	134.183	125.112	9.070	2.787
DFA	Warrarrinna, Cadni Dreaming	Unknown	9	128.185	132.517	122.000	10.517	3.902
DGA	Donkey Flat	Unknown	9	121.336	125.125	115.091	10.034	3.725
DGB	Frog Dreaming	Unknown	22	106.848	109.187	104.499	4.687	1.798
DHA	Mt Jessie	Unknown	4	121.487	123.478	119.139	4.339	1.830

The largest springs occur in the northern part of the complex, feeding extensive wetlands along flow lines to the north, north-east and east, with many confluences of flow paths (Figure 3.5). Wetlands associated with the more southerly springs extend along outflows to the south and south-east. To the south-west, an isolated group of small springs near the old Dalhousie Station ruins support wetlands extending to the west. Although the densest stands of vegetation occur close to the vents, fanning outflows support widespread and dispersed wetlands towards the northern and southern extremities of the complex.

Within the wetlands, analysis of satellite and airborne imagery reveals considerable variation in vegetation growth and species composition. For example, the transition from actively growing, dense perennial vegetation near spring vents to sparser and drier plants in the spring tails was detected through changes in visible/near-infrared reflectance signatures as recorded by WorldView-2 satellite imagery (Figure 3.6 and Appendix 2).

The plant species composition and distribution is complex. Previously, 44 plant communities had been identified (Mollemans 1989) of which White Tea Tree (*Melaleuca glomerata*) open forests and woodlands are the most conspicuous,

and reedbeds of Common Reed (*Phragmites australis*) the most prevalent spring-related vegetation. Date Palm (*Phoenix dactylifera*) is a notable invasive species. The distribution of these dominant species and communities was mapped using spectral analysis of airborne hyperspectral imagery, providing new information about their distribution and abundance. *Melaleuca glomerata* stands occur primarily in association with spring vents, in a line extending north–north-east to south–south-west along the central zone of springs (Figure 3.7). *Phragmites australis* reedbeds are particularly extensive, in some cases extending several kilometres from spring vents in dense, almost impenetrable, mono-specific stands up to 3–4 m high (Figure 3.7). *Phoenix dactylifera* is now restricted within the complex, having been largely eradicated in recent intensive management programs. Remaining stands and isolated trees remain near the Dalhousie ruins, and have been successfully discriminated from other vegetation types through hyperspectral image analyses.

Extensive zones surrounding surface spring flows and wetland vegetation are influenced by diffuse discharge and evaporation of artesian groundwater. These areas are characterised by high levels of near-surface moisture and salinisation, often with evaporite minerals forming a surface crust. The wetted area was delineated using the Normalised Difference Soil Moisture Index (NDSMI) applied to airborne hyperspectral imagery (Figure 3.8 and Appendix 2). This zone generally radiates north and southward from the concentration of spring vents in the centre of the spring complex. Within these areas, concentrations of surface salts indicative of evaporative discharge are identifiable by their distinctive surface reflectance. The diffuse discharge areas vary in levels of surface moisture from near saturation to quite dry and are generally poorly vegetated with sparse halophytic low shrublands and grasses. Conspicuous areas of salinisation occur at the southern end of the complex in association with a large spring tail, but also more disparately on the northern boundary of the complex.

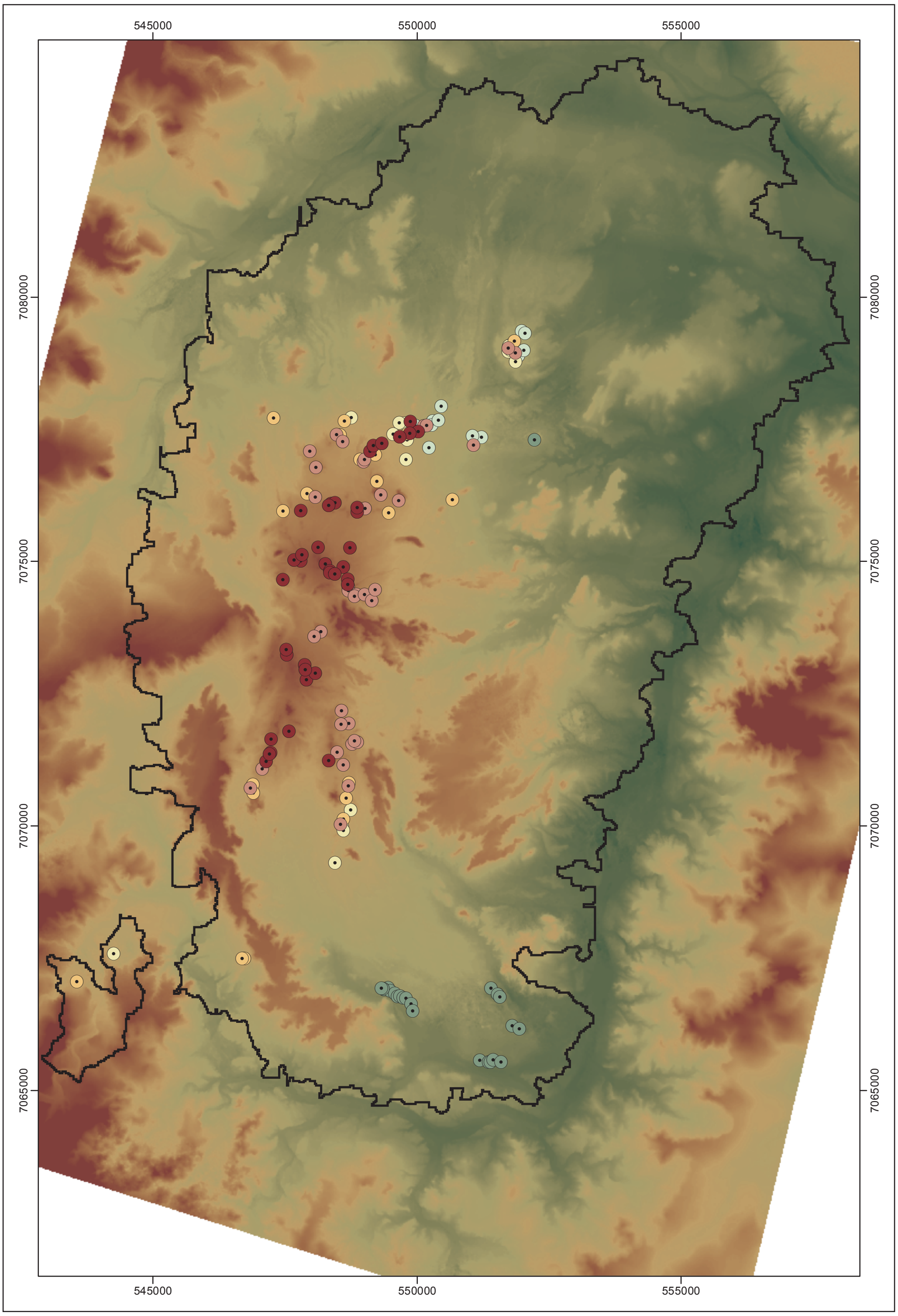


Figure 3.4: Elevation of Dalhousie Springs Complex and surrounding terrain

Derived from UltraCam digital orthophotography, and spring complex groundwater discharge-based boundary produced from Shuttle RADAR Topography Mission Digital Elevation Model (Australian 2010 release).

Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: January 2012

Figure 3.5: Distribution of wetland vegetation in Dalhousie Springs Complex, from NDVI analysis of WorldView-2 multispectral satellite imagery

Legend

🟩 Wetland Vegetation

▢ Spring Discharge Boundary

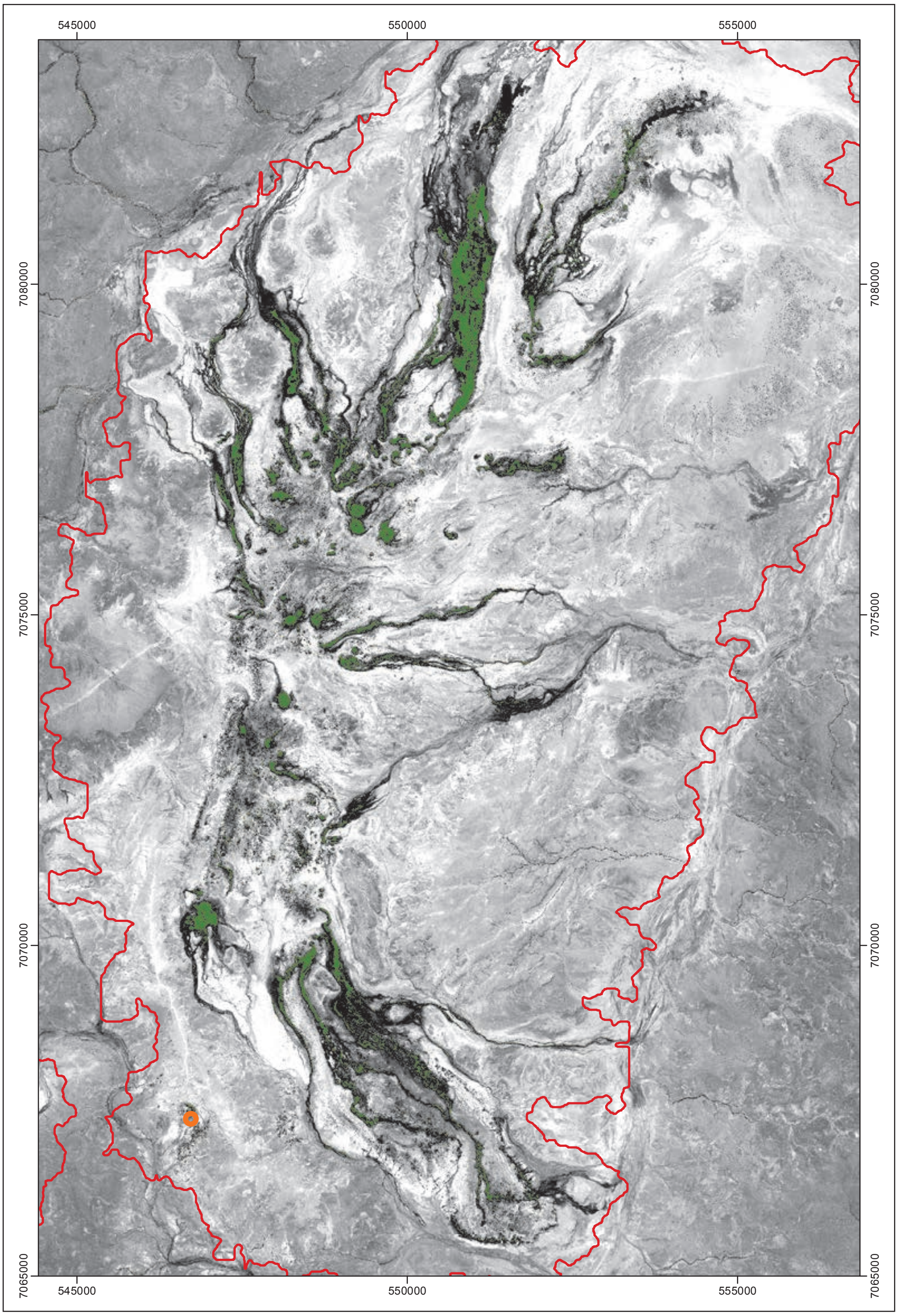
◉ Old Dalhousie Station Ruins

0 1 2 3

Kilometres

N

Background image: HyMap, 665.7 nm, March 2009.
Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: January 2012



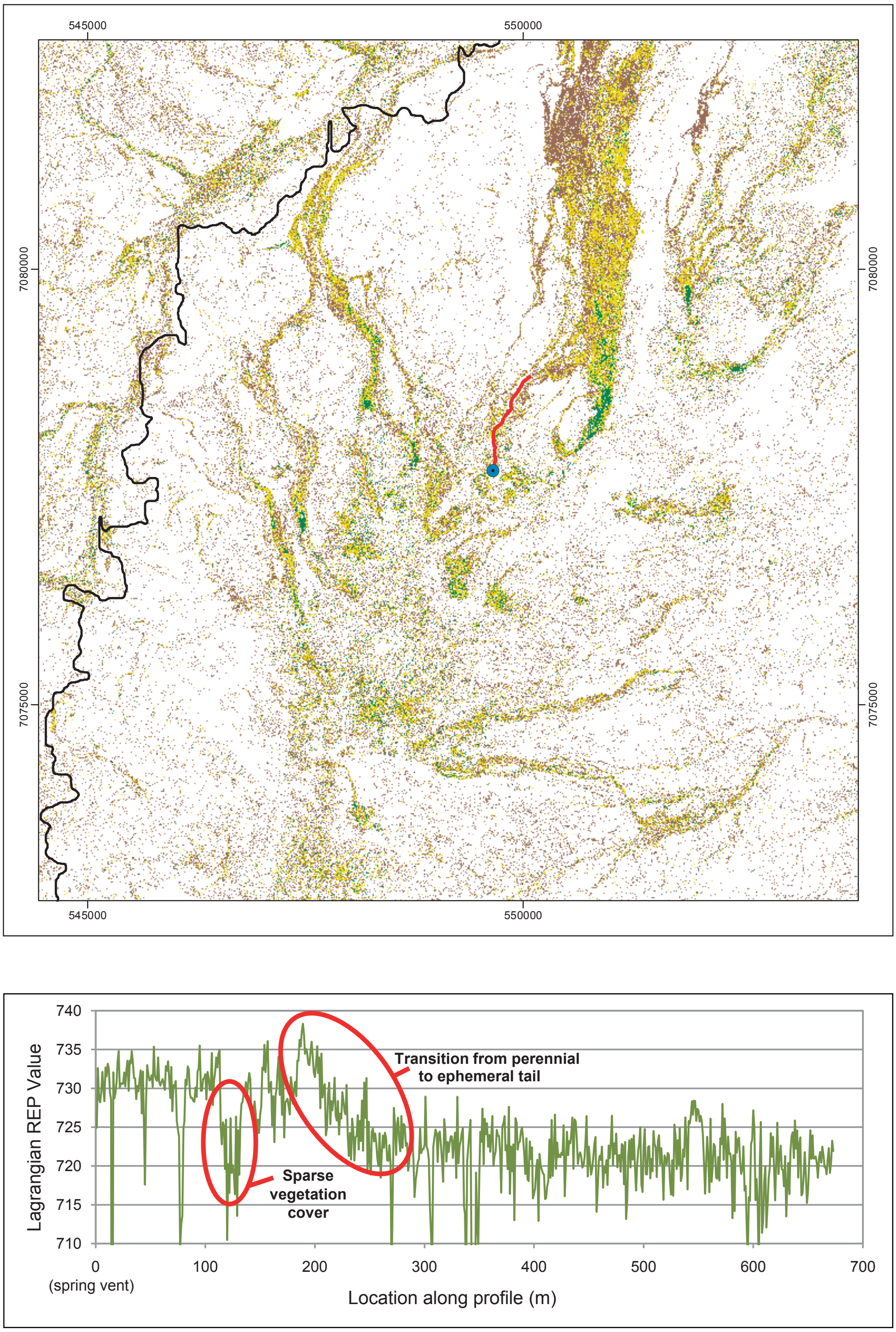


Figure 3.6: Gradients of wetland vegetation greenness and density revealed through red-edge analysis of WorldView-2 multispectral satellite imagery

Inset: Profile of red-edge position along a transect traversing from spring vent to tail

Red Edge Position

🟩 Dense actively growing vent vegetation (738 - 729 nm)
🟨 Transition, empemeral vegetation (728 - 721 nm)
🟫 Sparse drier tail vegetation (720 - 710 nm)

Legend

Spring Discharge Boundary
Profile Trajectory from Spring Vent
● Spring Vent

0 1 2
Kilometres
N

Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum Geocentric: Datum of Australia 1994
Date January 2012

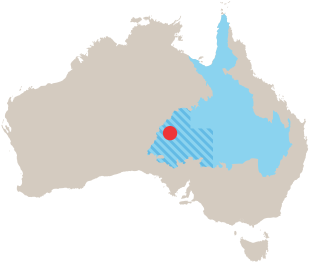


Figure 3.7: Distribution of *Melaleuca glomerata* and *Phragmites australis*, from spectral analysis of HyMap airborne hyperspectral imagery

Vegetation

🟨 *Melaleuca glomerata*

🟩 *Phragmites australis*

Legend

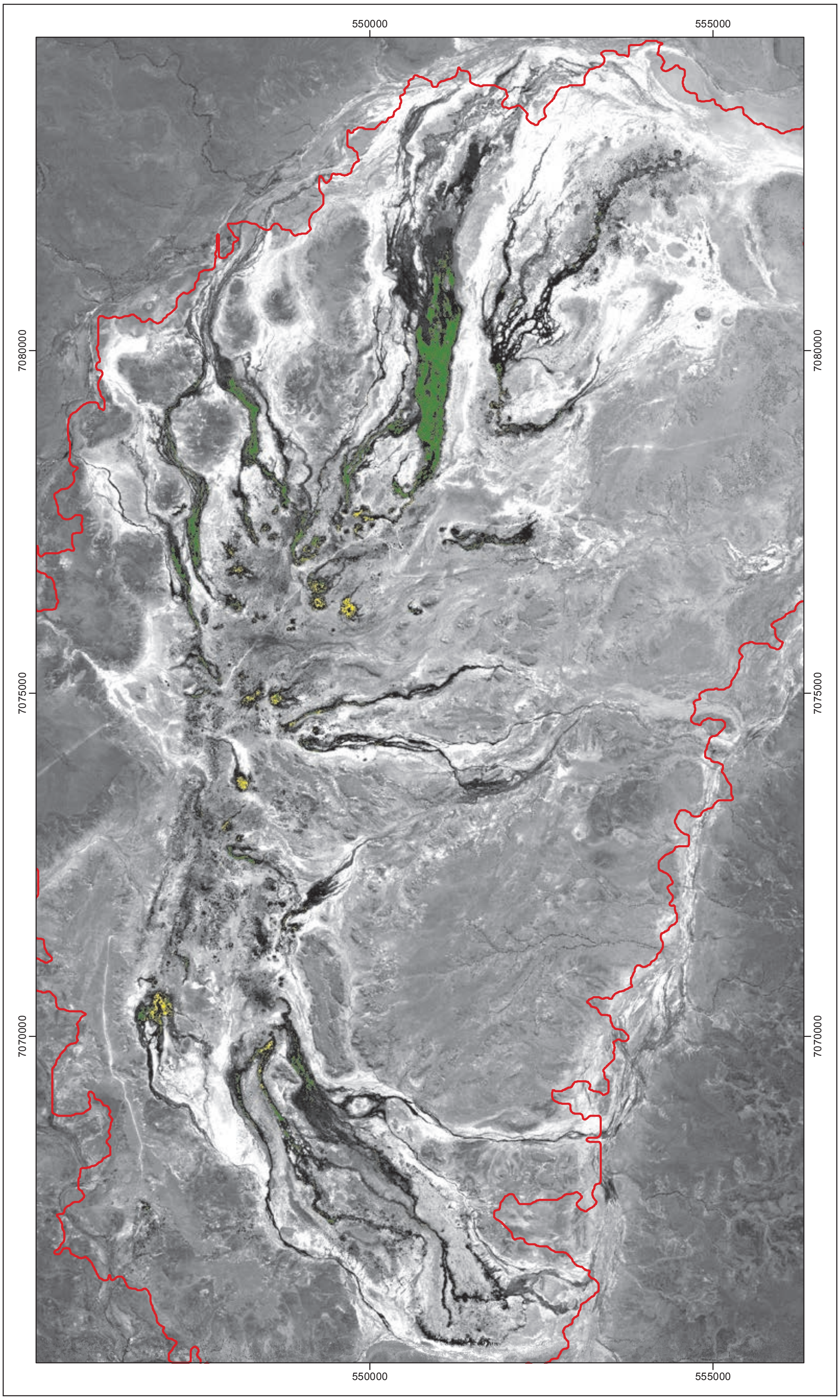
🟥 Spring Discharge Boundary

0 1 2 3

Kilometres

N

Background image: HyMap, 665.7 nm, March 2009.
Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: January 2012



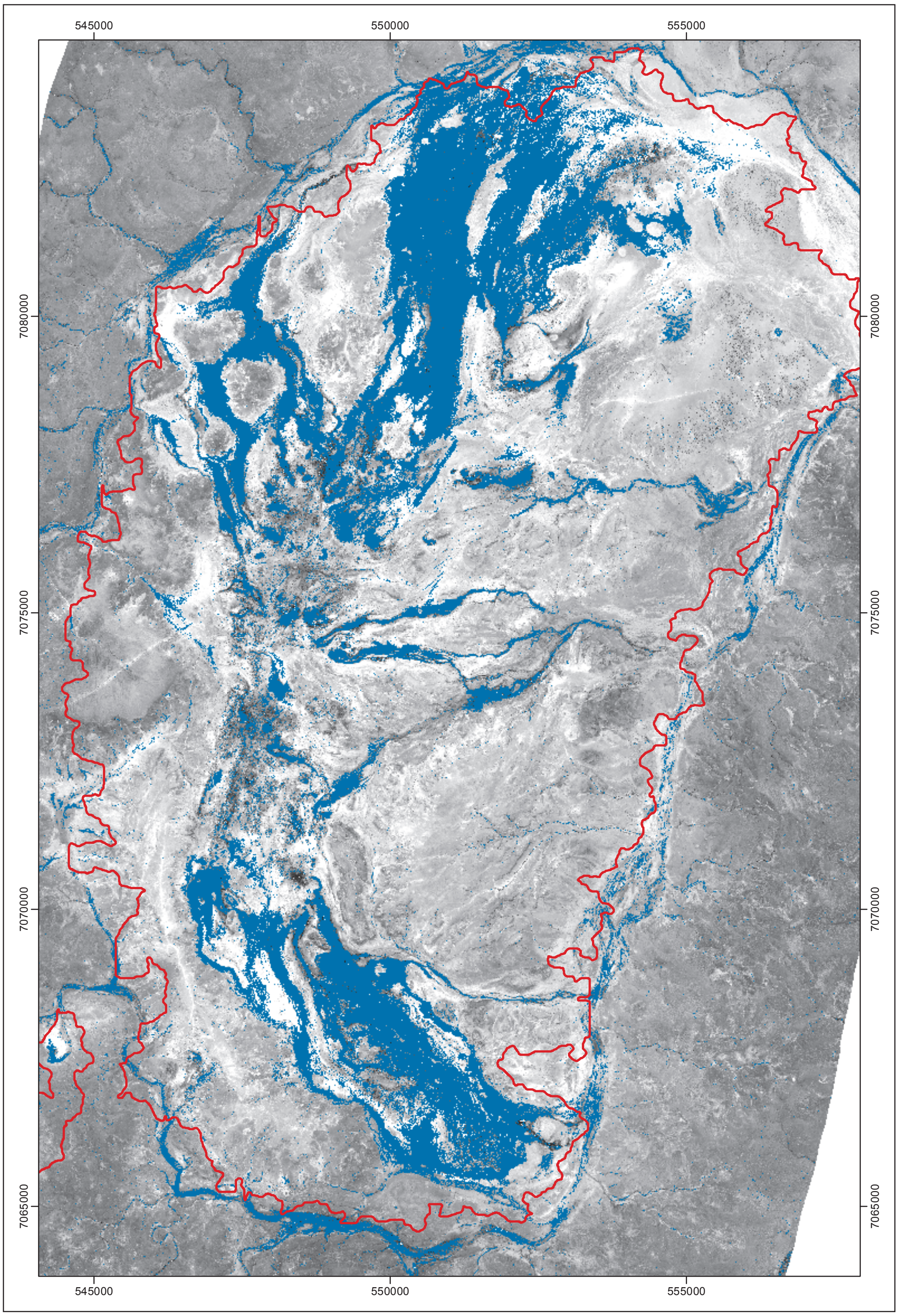


Figure 3.8: Distribution of surface moisture, from NDSMI analysis of HyMap airborne hyperspectral imagery

Background image: HyMap, 665.7 nm, March 2009.
Produced by The University of Adelaide - School of Earth & Environmental Sciences
Map Projection: UTM Transverse Mercator
Map Datum: Geocentric Datum of Australia 1994
Date: January 2012