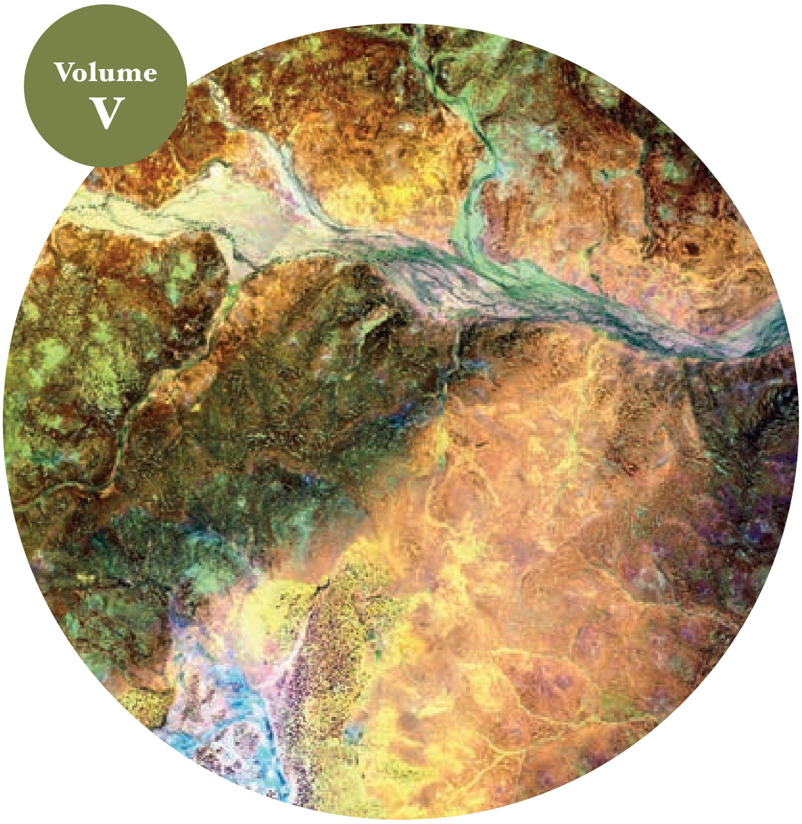
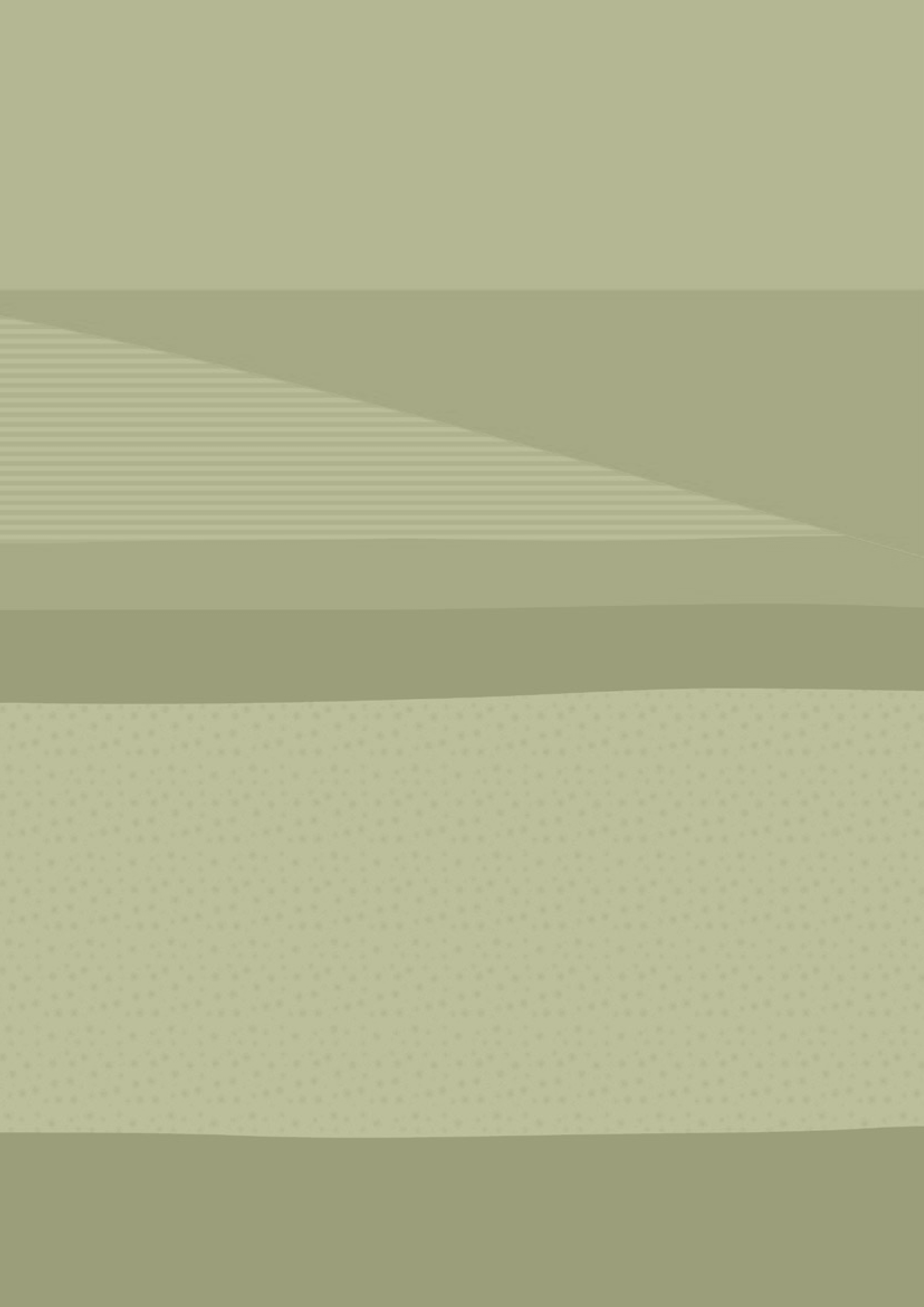
Australian Government
National Water Commission

Groundwater-dependent Ecosystems of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

Volume
V





Volume
V

Groundwater-dependent Ecosystems
of the Western Great Artesian Basin

Allocating Water and Maintaining
Springs in the Great Artesian Basin

Australian Government
National Water Commission

Government of South Australia
Northern Territory Government

Flinders University
The University of Adelaide
National Research Flagships
CSIRO

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About the editor

Travis B Gotch

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 has been undertaken on behalf of the Commission by:

- Travis Gotch (Scientific Editor), South Australian Arid Lands Natural Resources Management Board, Department of Environment, Water and Natural Resources, Government of South Australia.

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- Friends of the Simpson Desert
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- ARC Discovery Grant 2007–10 (Murphy, Austin and Adams) for the project ‘Evolution of the unique fauna of the Great Artesian Basin mound springs: the impact of aridification and climate change’
- ARC Linkage Grant 2006–09 (Austin, Murphy, Cooper and Adams) for the project ‘Comparative phylogeography of mound springs-invertebrates: identifying genetically divergent populations for conservation and management’.

Background

Photo: Travis Gotch

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:

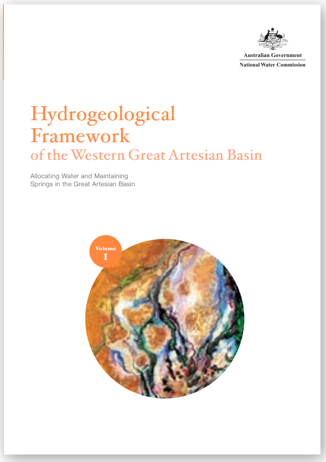
- South Australian Arid Lands Natural Resources Management Board
- Flinders University of South Australia
- The University of Adelaide
- South Australian Department for Environment, Water and Natural Resources
- Northern Territory Department of Natural Resources, Environment, the Arts and Sport
- Commonwealth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

Volume
I



Australian Government
National Water Commission

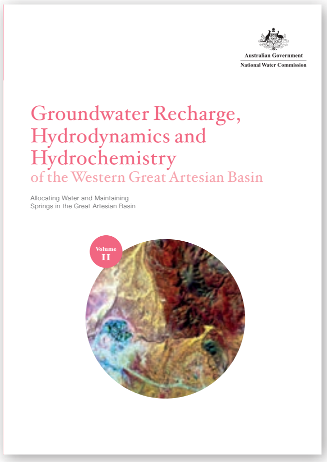
Hydrogeological Framework
of the Western Great Artesian Basin

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
II



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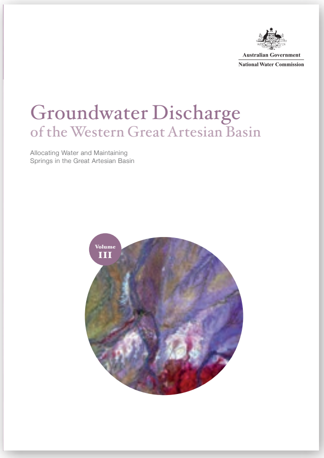
Groundwater Recharge, Hydrodynamics and Hydrochemistry
of the Western Great Artesian Basin

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 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

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Springs in the Great Artesian Basin

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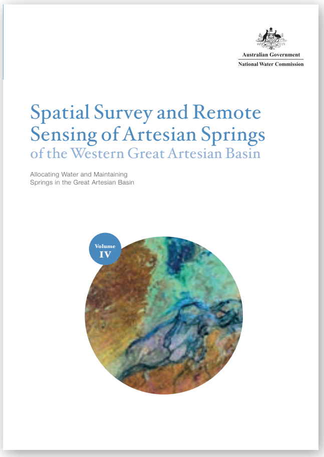
III

Volume
III

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.


Australian Government
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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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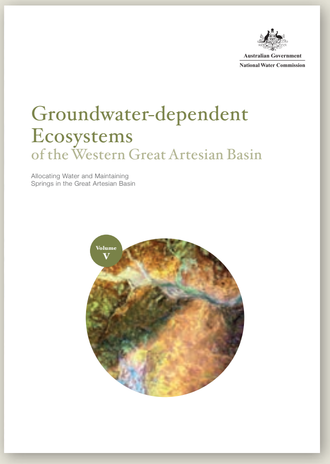
IV

Volume
IV

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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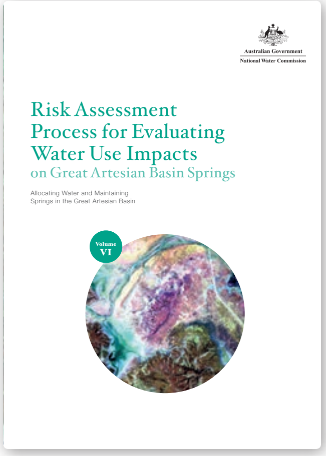

Australian Government
National Water Commission

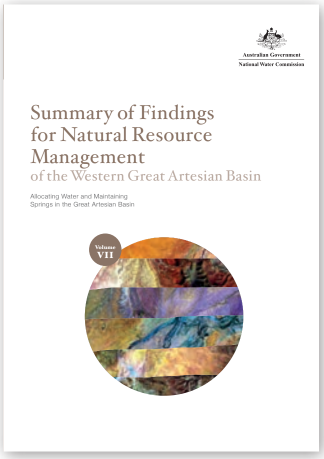
Risk Assessment
Process for Evaluating
Water Use Impacts
on Great Artesian Basin Springs

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
VII


Australian Government
National Water Commission

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.

Executive summary

This volume presents the results of several research projects related to groundwater-dependent ecosystems (GDEs). It also includes a general overview of GAB spring literature, with particular focus on flora and fauna and provides general reference for those unfamiliar with the biological uniqueness of GAB springs. The general history of studies into spring biology on the western margin of the GAB is also documented.

Analysis of various palaeo-ecological reports establishes a baseline condition for GAB springs prior to European settlement. This analysis helps to:

- reconstruct the salinity, pH and nutrient levels of aquatic spring environments over the past 1000+ years
- analyse historical vegetation composition
- examine changes in spring flow and water quality over the last 20 000 to 30 000 years.

Flora and fauna reports are presented. The fauna report is a summary of three scientific papers and focuses solely on aquatic invertebrate fauna. The flora section is divided into two parts: the first utilises vegetation and environmental data from springs in the Lake Eyre and Lake Frome supergroups to identify environmental determinants of vegetation patterns; while the second explores the genetic structure of GAB spring and coastal wetland populations of the sedges *Gahnia trifida* and *Baumea juncea*, comparing the results with previous work on *Eriocaulon carsonii*. A separate, dedicated study of *Phragmites australis* is also presented.

This volume also presents a review of the effects and impacts of grazing in riparian and spring environments, and a community survey into the values of GAB springs that consulted a wide range of stakeholders. A summary of the key findings has been included in this volume.

Finally, a series of on-ground works to enable the return of environmental flows to the Dalhousie Springs complex is reported. This work consisted of the removal of invasive Date Palms from the springs and monitoring the recovery of the springs after their removal.

1

Introduction

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

1. Introduction

This report presents the results of the groundwater-dependent ecosystem (GDEs) research component of the Allocating Water and Maintaining Springs in the Great Artesian Basin (AWMSGAB) Project. The research presented in this report comprises several major components:

- a general review of the biological and ecological literature surrounding the Great Artesian Basin (GAB) springs
- an examination of the palaeo-ecology of the spring environment of the western margin of the GAB
- a detailed examination of the genetic diversity and relationships of sub-populations of aquatic fauna within the springs of the Lake Eyre Supergroup
- an examination of the parameters driving floristic diversity in springs and an investigation onto the genetic diversity and relationships of several flora relict species
- a comprehensive and detailed review of *Phragmites australis* and its function in GAB springs
- a report detailing the methodology and results of on-ground works to enable the return of environmental flows in GAB springs
- a review of the impacts of grazing on GAB spring environments
- a stakeholder survey of community values and views around GAB springs along the western margin of the GAB.

The outcomes and findings of the grazing and stakeholder survey reports are summarised in this volume but the full reports have not been included due to space and time considerations. They can be obtained by application from the South Australian Arid Lands Natural Resources Management Board (SAALNRMB).

While each of the components listed above were completed independently, there were several shared objectives. Table 1.1 provides objectives and related report components.

Photograph on facing page:
Travis Gotch

Table 1.1: Study objectives and their relationships to the report sections

Study objectives	Study components					
	Biological review	Palaeo-ecology	Fauna	Flora	*Phragmites*	Return of environmental flow
Identify suitable spatial scales for management of GAB spring flora and fauna	•		•	•		
Examine the palaeo-climate and history of the springs		•	•	•		
Investigate the impacts, real or perceived, of *Phragmites australis* on GAB springs		•		•	•	
Return environmental water to Dalhousie Springs						•
Increase the knowledge base of GAB spring species			•	•		

1.1 Biology and ecology of South Australian GAB springs

Chapter 2 presents a general overview of GAB spring literature with particular focus on flora and fauna of the GAB springs. It serves as a general reference for those unfamiliar with the biological uniqueness of GAB springs and documents the general history of studies into spring biology on the western margin of the GAB.

1.2 Palaeo-ecological analysis of artesian springs

Chapter 3 presents a palaeo-ecological analysis of GAB springs reports and attempts to establish a baseline condition for GAB springs prior to European settlement. It outlines the results of studies to reconstruct the salinity, pH and nutrient levels of aquatic spring environments over the past 1000+ years; to analyse historical vegetation composition; and to examine changes in spring flow and water quality over the last 20 000 to 30 000 years. This was achieved using integrated analyses of the chemical and biological remains in several targeted artesian spring groups. Diatom assemblages were used to infer past salinity, pH and nutrients using calibration and regression techniques (Fritz *et al*. 1991; Gell 1997), while plant macrofossils were used to reconstruct the aquatic plant structure (Reid *et al*. 2007).

1.3 Fauna of the GAB springs

Chapter 4 presents as summary of three scientific papers and focuses solely on aquatic invertebrate fauna. The aims are two-fold. First, to use genetic techniques to identify genetically distinct lineages and probable new species between the springs in two well-recognised groups of GAB springs endemics: *Phreatomerus latipes* (isopod) and the three *Trochidrobia* (hydrobiid snails) species known from Southern Lake Eyre Supergroup. Second, to synthesise this information to develop a summary of findings to identify areas of endemism.

Research on amphipods and *Fonscochlea* snails already exists in the literature, although some additional preliminary work on amphipods and ostracods was also undertaken in a final review of the GAB springs bioregion.

The research shows that each of the taxa demonstrates distinct lineages between spring groups and complexes, suggesting dispersal between springs is low to absent, the level of biodiversity in GAB springs is vastly underestimated and, finally, that these genetic differences correspond with geographic barriers and regions in most taxa. This similarity may be used to identify priority areas for conservation management in the Lake Eyre Supergroup (see Volume VI: Risk Assessment Process for Evaluating Water Use Impacts on Great Artesian Basin Springs (Green *et al.* 2013)) for a process of evaluating water-use impacts on GAB springs.

1.4 Flora of the GAB springs

Chapter 5 presents a flora report consisting of two parts. The first utilises vegetation and environmental data from over 1000 springs in the Lake Eyre and Lake Frome supergroups to identify environmental determinants of vegetation patterns at GAB springs. The second explores the genetic structure of GAB spring and coastal wetland populations of the sedges *Gahnia trifida* and *Baumea juncea*, comparing the results with previous work on *Eriocaulon carsonii*. The second component helps to determine the appropriate spatial unit for managing impacts to GAB spring flora.

Understanding the nature and ecology of the GAB spring vegetation and the degrees of isolation between spring groups and complexes is critical to the management of endangered ecosystems.

1.5 *Phragmites australis:* Knowledge to support its management on GAB springs

Phragmites australis is a widespread plant in springs of the western margin of the GAB. Some current management models assume it is an introduced species, but it has been present on springs in this region for at least 37000 years and probably much longer (as discussed in Chapter 3). The specific adaptations of *P. australis* are such that it is a vigorous competitor for space and nutrients on GAB springs. *P. australis* has been found to impact on endemic and relict flora species and is perceived as a threat to native plant and animal communities on GAB springs in northern South Australia. These plant and animal species are listed as Endangered under the Australian Government's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Chapter 6 presents a literature review and ecological synthesis, intended to be a knowledge platform to guide and inform future decisions on managing the threat imposed by *P. australis*. It addresses three questions:

- Are GAB springs that are currently grazed by cattle and apparently free of *Phragmites* at risk of being colonised by *Phragmites* if cattle are removed? If *Phragmites* can be controlled to the point of being eliminated, then is it likely to re-establish?
- Is it possible that *Phragmites* has reached its maximum or near-maximum extent on some GAB springs?
- Why is *Phragmites* invading GAB springs?

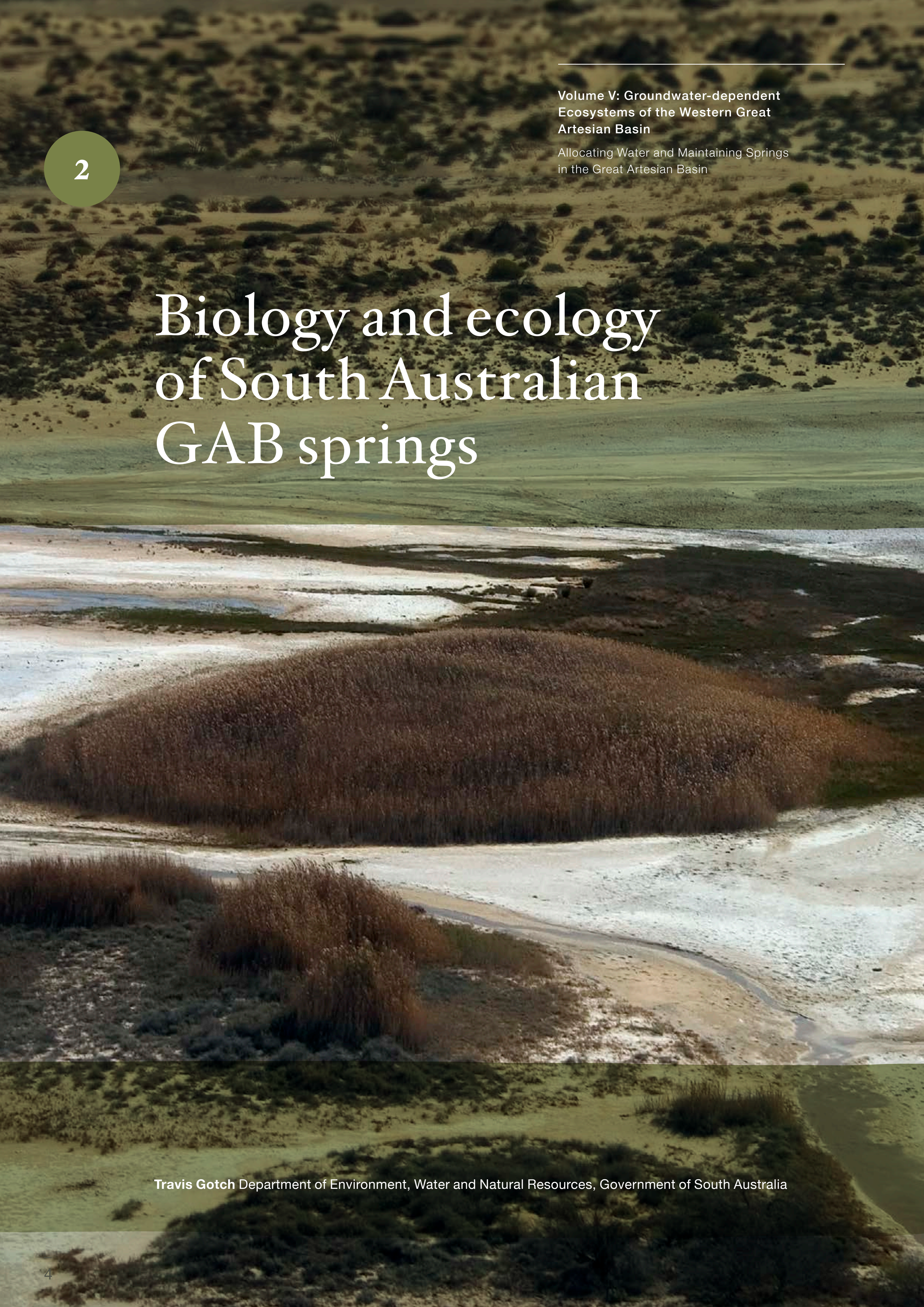
1.6 Grazing management

Chapter 7 presents a summary of the key findings from two related studies that are available from the SAALNRMB:

- a review of grazing on springs
- a stakeholder survey of community values and views around GAB springs along the western margin of the GAB.

1.7 Date Palms and the return of environmental flows

Finally, Chapter 8 presents the results of a series of on-ground works to enable the return of environmental flows to the Dalhousie Spring Complex. This work consisted of the removal of invasive Date Palms and monitoring the recovery of the springs after their removal.



2

Biology and ecology of South Australian GAB springs

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

2. Biology and ecology of South Australian GAB springs

2.1 Introduction

The arid zone of South Australia is one of the driest locations on the continent, yet it contains a number of significant wetlands that are normally isolated from one another but are periodically connected by flood events. These wetlands are habitats that have been isolated by the desertification of the surrounding environment over the past 25 million years (Krieg 2000). The wetland habitats in the arid zone include the river systems of the Lake Eyre catchment, the Cooper Creek and Coongie Lakes system, the Diamantina River and Goyder's Lagoon System, the Finke and Macumba River systems and the Neales River system. Many of these systems are biologically very important, but it is the springs of the Great Artesian Basin (GAB) that really stand out as ecological and evolutionary 'hot spots' (see Chapter 4 for more information) (Gotch *et al*. 2008; Murphy *et al*. 2009; Fensham *et al*. 2010; Murphy *et al*. 2010; Hale & Brooks 2011). The GAB springs have been important features of the landscape for hundreds of thousands of years and it is the stability and consistency of water discharge from the GAB that drive their ecological significance. Periods of continuous discharge in spring groups have been documented as lasting up to 740 000 years (Prescott & Habermehl 2008). Dating work from the Allocating Water and Maintaining Springs in the Great Artesian Basin project (AWMSGAB Project) identified spring deposits of 750 000 years (see Volume III: Groundwater Discharge of the Western Great Artesian Basin (Love *et al.* 2013b)), however this age is at the effective upper limit of the techniques used. Other techniques are currently being explored to date material that is thought to be older than 1 ma (Priestley pers. comm.).

During the past million years, the climate in the region has seen episodic wet conditions interspersed with periods of dryness, ultimately resulting in the desert conditions seen today. Wetland species that were probably once widespread either contracted into steadily diminishing habitat areas or went extinct until it was only in the springs that truly aquatic flora and fauna could survive. The springs now form a discontinuous arc of wetlands along the western margin of the GAB (Figure 2.1). The geological and hydrogeological nature of the springs has been discussed in detail in Volume I: Hydrogeological Framework of the Western Great Artesian Basin (Keppel *et al.* 2013) while the spatial structure and distribution of the springs is described in Volume IV: Spatial Survey and Remote Sensing of Artesian Springs (Lewis *et al.* 2013). The springs are arrayed in a distinct spatial hierarchy with clear nomenclature. This is fully explained in Chapter 2, Volume IV (Lewis *et al.* 2013), however for clarity, the key points are summarised here:

- Spring supergroups are regional clusters of spring complexes.
- Spring complexes are a cluster of spring groups that share similar geomorphological settings and broad similarities in water chemistry.
- Spring groups are tight clusters of spring vents and wetlands that source their water from the same fault or structure and share similar water chemistry.

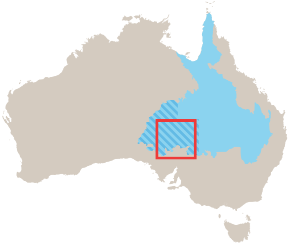
Photograph on facing page: Travis Gotch

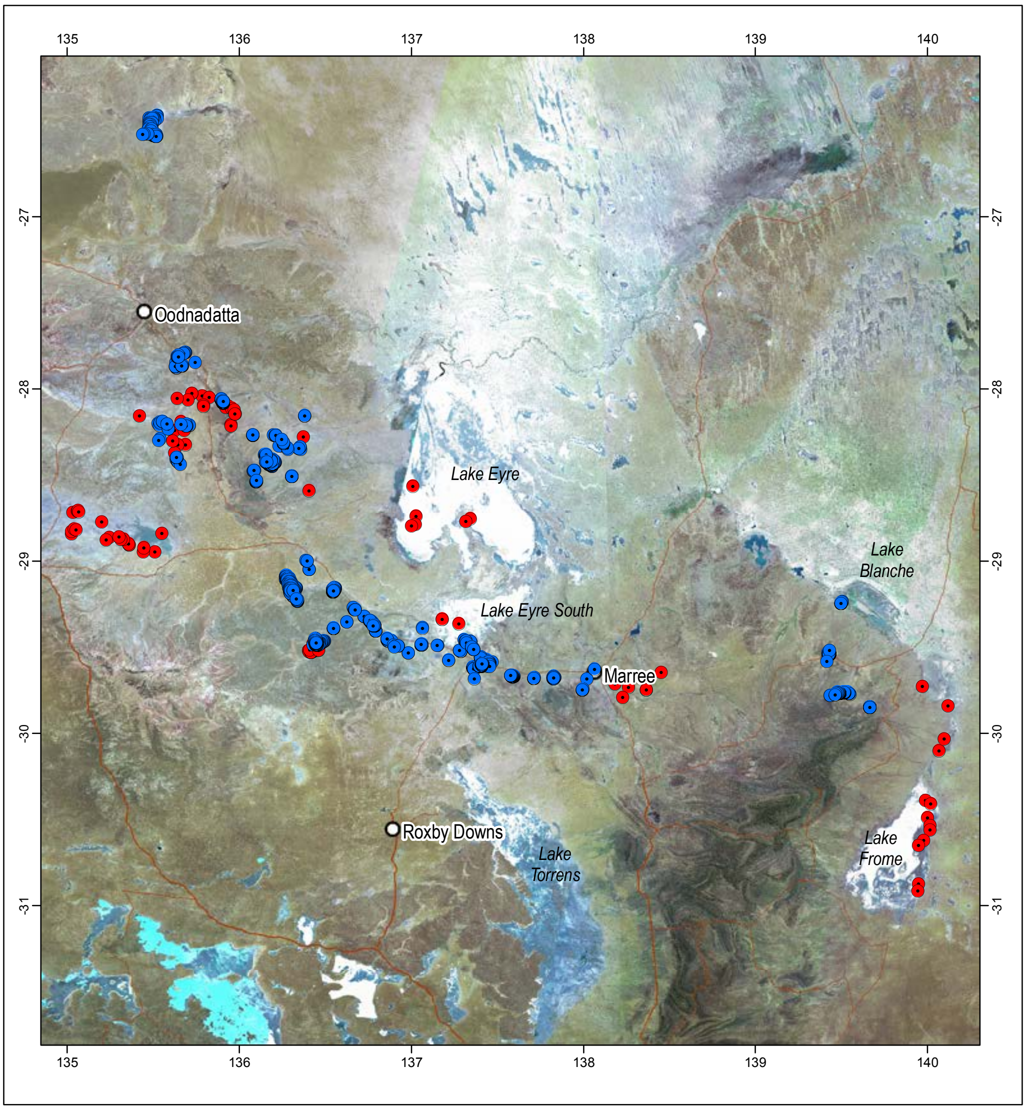
Figure 2.1: Distribution of GAB springs in South Australia

Legend

- ● GAB Springs (Surveyed)
- ● GAB Spring (Not Surveyed)
- ○ Town
- — Primary Road
- — Secondary Road
- ⬚ Borders

Produced by SAALNRMB
Map Projection: Lambert Conformal Conic
Map Datum: Geocentric Datum of Australia 1994
Date: February 2012





The terminology used to describe GAB springs was established by Ponder (1986) and further refined to include hydrogeological parameters by Fatchen and Fatchen (1993). Another terminology based on Ponder (1986) is current elsewhere in Australia (Fensham & Fairfax 2003); the two main differences being the use of hydrogeological parameters to assist in the classification of groups in South Australia and the use of a distance limiter in Queensland. Other than this, the two systems are essentially the same and can be relatively easily interchanged.

In the arid environment of northern South Australia, the springs form habitats that are analogous to islands for species that are dependent on water for their existence (Harris 1981). Isolation and genetic drift over thousands of years have evolved a unique biota that contains many short-range endemics and relicts (see Chapter 4 for more detail) (Gotch *et al*. 2008; Murphy *et al*. 2010; Clarke *et al*. 2011).

The presence of permanent fresh water in arid environments gives the springs an ecological importance greater than would be expected from their small area (Harris 1992). In addition to the numerous endemic and relict species mentioned above, the springs themselves are windows into the evolutionary history of the Australian arid zone.

2.1.1 Cultural importance and history

The GAB springs of the Lake Eyre region have particular cultural importance to the local Aboriginal people and to the western settlers who arrived more recently (Harris 1992). Numerous authors have reported on evidence of the springs being used as habitation areas (Harris 1981; Hercus & Sutton 1985; Hughes & Lampert 1985; Kinhill Stearns 1985; Florek 1987; Hercus 1990; Harris 1992; Hughes & Hiscock 2005). Based on artefact deposits found at the sites, habitation of the spring dates back to the early Holocene period (Florek 1987). The springs are culturally important to a number of Aboriginal peoples; in the western recharge zone these include Arabunna, Lower Southern Arrente, Wokangurru, Kuyani, Deri, Pirlatapa, Malijangapa and Yandruwantha. Numerous stories and song-lines are associated with different springs and the importance of these sites to the traditional inhabitants of the land cannot be under-estimated (Hercus 1980; Hercus & Potezmy 1995; Ah Chee 2002). Warburton and Babbage were the first Europeans to see the GAB springs in the Lake Eyre South region when they discovered the Coward Springs Complex (Warburton 1858). In 1870, it was decided that the route for the Overland Telegraph would follow the chain of springs on the south-western margin of the Great Artesian Basin. Pastoralists soon followed the explorers, in turn followed by the Old Ghan Railway (Harris 1985; Gee 2000).

2.1.2 Physical characteristics

Great Artesian Basin springs typically consist of a number of vents discharging water to the surface surrounded by a wetland. They range in size from small individual soaks to large, established spring complexes with total wetland areas of almost 1300 ha (see Volume IV (Lewis *et al.* 2013) for more information). Depending on the local geomorphology and water chemistry, vents may form pools—some of which are very large. (The main pool at Dalhousie was bathymetrically surveyed by the author in 2003. It comprises several vents, two within the pool itself and several more flowing in from an adjacent mound; collectively these vents discharge over 10 ML/day to the surface. The pool is 160 m long, 66 m wide and 11 m deep.) The wetland that is created from the discharge is known as the tail, and again these can vary in size from very small to very large (examples can be found in Volume IV (Lewis *et al.* 2013)). Many springs have a distinctive mound associated with them and the processes involved in their creation are fully detailed in Volume I (Keppel *et al.* 2013). It is the wetland environment that is supported by the GAB discharge that contains the biological, evolutionary, social and cultural values associated with the springs.

2.1.3 Habitats and biota

Floristically, GAB springs in the western GAB tend to have stands of *Phragmites* sp. around the vent and *Cyperus laevigatus* dominating the tail (Symon 1985). GAB springs are biodiversity 'hot spots' and are home to a number of endemic and relict organisms (Ponder 1986). The isolation of these wetlands has resulted in the evolution of specific biota associated with the springs (Fatchen & Fatchen 1993). Symon (1985) described the flora of the GAB springs and identified the presence of several endemic and relict plant species. These include the GAB spring endemic Salt Pipewort (*Eriocaulon carsonii*) and two relict species, *Gahnia trifida* and *Baumea juncea*. Several detailed studies have occurred examining the biology and population genetics of *E. carsonii* (Davies *et al*. 2007b; Davies *et al*. 2010), while *G. trifida* and *B. juncea* are investigated in Chapter 5. The two latter species represent disjunct populations whose normal distribution is in south-east Australia (Symon 1985). Bore drain vegetation is distinctly different from that of GAB springs (Fatchen & Fatchen 1993). Diversity tends to be lower, with *Typha* sp. present in place of *Phragmites* sp. Bore-drain Sedge (*Cyperus laevigatus*) is also common and the endemic and relict species are absent.

Many of the GAB springs contain microstromatolites of which very little is known. It has been speculated in previous studies that these organisms are important factors in the creation of the mounds typical of springs along the western margin of the GAB and this has recently been supported by research undertaken as part of this project (Keppel *et al*. 2011; Keppel *et al*. 2013).

The GAB Springs of the western recharge are blessed with a diversity of short-range endemic fauna (Gotch 2005; Fensham *et al*. 2010). It is predominately this fauna, along with the distinctive geomorphology of the springs, that gives the springs their conservation status (Hale 2010). Due to the unusual nature of the spring biota, the aquatic endemic fauna of the GAB springs has been well documented in the past. Significant invertebrate species include the Hydrobiid snails, *Fonscochlea* spp. and *Trochidrobia* spp. (Ponder 1985; Ponder 1989; Ponder *et al*. 1989; Ponder *et al*. 1995; Ponder 2004; Worthington Wilmer *et al*. 2008), the Ostracods including *Ngarawa dirga* (De Deckker 1979), amphipods of the genus *Austrochiltonia* (Zeidler 1989; King 2009; Murphy *et al*. 2009) and the isopods of the genus *Phreatomerus* sp. (Murphy *et al*. 2010). GAB springs are also home to endemic fish species (Glover 1990) and, along with bore drains, are important habitats for migratory and wetland birds (Badman 1987). With the exception of bores that have been drilled into spring groups, no GAB spring aquatic endemic flora or fauna have been found on bore drain wetlands in South Australia (Gotch, unpublished data).

In addition to aquatic fauna, there are a number of water-dependent terrestrial fauna associated with GAB springs. Until relatively recently, these have tended to be overlooked by most researchers. Early explorers and naturalists collected specimens from the area but often did not record precise locality information or preserve their collections correctly, resulting in damaged specimens (Pulline 1914). Later surveys were conducted more rigorously but tended to be general biodiversity surveys over limited collection periods (Greenslade 1985).

Photo: Travis Gotch

More recent assessment of the terrestrial invertebrate fauna highlighted the importance of carabid beetles (Coleoptera: Carabidae) as major predators in GAB springs (Gotch 2000). The spider fauna of GAB springs has been examined, particularly the wolf spiders (Araneae: Lycosidae), with some species present on springs showing close relationships to salt lake specialist lycosids (Framenau *et al*. 2006; Gotch *et al*. 2008). The majority, however, are more closely related to lycosids found in riparian and wetland systems in south-eastern Australia (Framenau *et al*. 2006; Gotch *et al*. 2008). The lycosids and carabids are the main invertebrate predators on the springs and have an important role in maintaining the health of the ecosystem.

It is not just the spring wetlands that contain endemic or relict fauna. The wetted zone surrounding springs is a key habitat and is a niche occupied by a previously undescribed Onicidian (see Chapter 4) and lycosid spider related to salt lake wolf spiders (Framenau *et al*. 2006). Other than these two opportune collections, very little is known about the biota and ecological function of this habitat site.

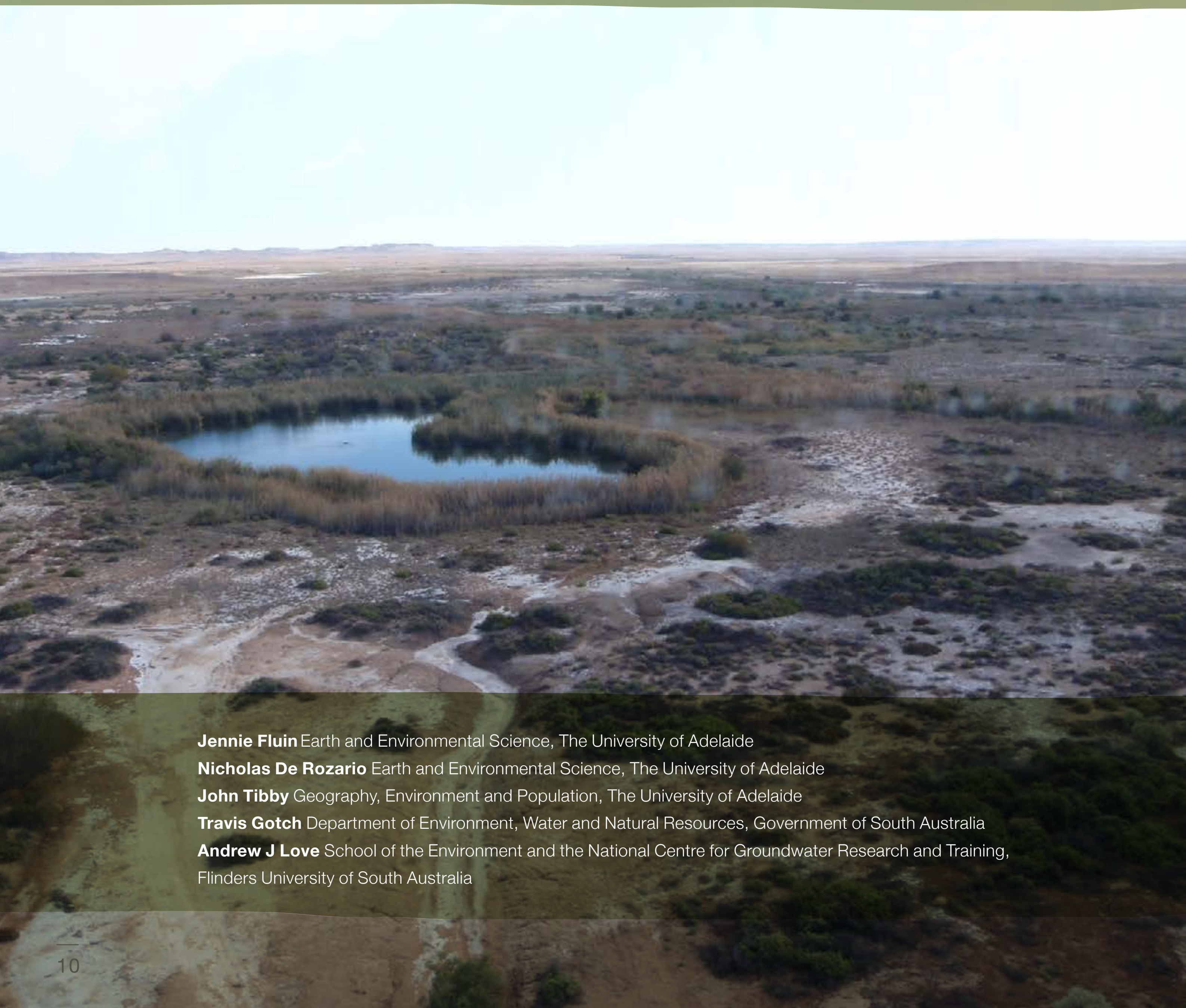
2.1.4 Biological and scientific significance

It is difficult to argue against the GAB springs' position as one of the biologically special places in the world. In addition to the geological and hydrogeological features of the springs, the isolation and long-term stability of the environment have contributed to the creation of nature's evolutionary jewels. Many species remain to be discovered and documented. In addition to high biodiversity, the area is also a natural laboratory for theoretical ecological concepts to be tested and validated against real world data.

The GAB springs offer a unique window into the evolutionary history of the interior of Australia, however this is entirely dependent on the continual flow of water. With this in mind, the sustainable management of the GAB resource is essential not only for economic reasons but also to preserve the natural history of the GAB springs.

3

Palaeo-ecological analysis of artesian springs in the GAB of South Australia



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3. Palaeo-ecological analysis of artesian springs in the GAB of South Australia

3.1 Introduction

The baseline condition of groundwater-dependent springs in the Great Artesian Basin (GAB) prior to non-Indigenous settlement can be derived from ecological archives preserved in the aquatic sediments. The integration of multiple fossil indicators allows for the reconstruction of biological conditions over many thousands of years. These reconstructions enhance the vision of natural resource managers and the community, enabling them to develop appropriate ecological targets and resource use guidelines. Of particular interest to this study is the reconstruction of the presence of *Phragmites australis,* as there is an assumption in many current management models that this species is a European artefact that requires active control. Also of interest is a reconstruction of fire regimes surrounding spring groups, as this will give an insight into both Indigenous connections with springs and also a recorded history of the relationship between *Phragmites australis* presence and regular burning.

3.1.1 Aims of research

The key aims of this research were:

1. to determine the changes in aquatic vegetation composition and abundance since the last glacial maximum, and relate to historical land use practices
2. to assess the degree of limnological change since non-Indigenous settlement in the region and relate to land use practice
3. to determine the historical patterns of both in-site fire and local fire through the analysis of charcoal remains over time.

To achieve these aims, integrated analyses of the chemical and biological remains contained in the sediments of key artesian springs provided a reconstruction of ecological change and variability over approximately the last 30 000 years. Multiproxy analyses primarily utilised fossil diatom assemblages to infer past salinity, pH and nutrients using calibration and regression techniques (Fritz *et al*. 1991; Gell 1997) and plant macrofossils (Reid *et al*. 2007) which allowed for a reconstruction of aquatic plant structure. These detailed analyses of the Holocene sediments revealed the degree to which the condition of the springs has departed from natural background, providing a record of human impact. When integrated with the outcomes of the hydrogeological components of the project (in particular palaeo-recharge patterns), this enabled analysis of the long-term trophic and limnological functioning of these diverse, complex systems. Together, this data provided spatially and temporally holistic evidence of the ecological character of these nationally iconic assets to steer, and justify, management options to rehabilitate and sustain them into the future.

3.1.2 The use of palaeo-ecology for artesian springs

Broadly defined, palaeo-ecology is a science that uses information gained from biological, chemical, and physical material stored in sediment deposits to reconstruct past environments (Jiří 2010; Stoetzel *et al*. 2011). Palaeo-ecological research is commonly undertaken on sediments collected from lakes (Dodson *et al*. 1994; Mooney & Dodson 2001; Mooney *et al*. 2010), however it is possible to apply these techniques to alternate settings such as creeks, rivers and caves (Forbes & Bestland 2007; Darrénougué *et al*. 2009). Little palaeo-ecological research has been conducted

Photograph on facing page: Travis Gotch

on artesian springs in the Lake Eyre South region and the suitability to apply commonly used palaeo-ecological techniques to sediments of these springs remains largely untested.

3.2 Palaeo-environment of the Lake Eyre South region

One of the key considerations when reconstructing past environments, occupation and fire history of artesian springs in the Lake Eyre South region has been the availability of water. Research by Nanson *et al*. (1991) reveals that from 100 000 to approximately 45 000 years ago, climatic and hydrological regimes were similar to, but probably cooler than, those of today with a trend towards more arid conditions and increased aeolian activity. Magee and Miller (1998) identified Lake Eyre as a predominantly wet lake system for most of the time up until approximately 60 000 years ago, when it switched to a groundwater-dominated system as it progressively dried out. They also cited enhanced winter westerly air circulation 30 000 years ago as being responsible for enhanced winter rainfall in the Lake Eyre South region (Magee & Miller 1998). By 35 000 years ago, Lake Eyre had become dry and remained so until approximately 10 000 years ago (Magee & Miller 1998). Miller (1997) identifies below-average air temperature occurring in the region between 45 000 and 16 000 years ago, with temperatures at least 9°C lower than present.

A trend towards aridity is believed to have accelerated and peaked during the Last Glacial Maximum (LGM), an exceptionally cold and dry period occurring between approximately 24 000 and 18 000 years ago (Magee & Miller 1998). After the LGM, the climate began to ameliorate until approximately 10 000 years ago, when conditions were essentially the same as today (Magee & Miller 1998). Ross *et al*. (1992) provide evidence which suggests conditions in the region during the first half of the Holocene (approximately 5000 years ago) were slightly wetter and warmer than during the late-Holocene. There is also evidence that suggests Lake Eyre remained semi-permanent up until approximately 5000 years ago, with a switch to the current ephemerally flooded playa regime occurring within the last 5000 years (Ross *et al*. 1992).

Research by Johnson *et al*. (2000) identified a 20% reduction in C-4 plant biomass, namely grasses, as a result of landscape degradation post-European settlement, due to the grazing of livestock, drought conditions, and a change in fire management practices. The Johnson findings reflected observations by other researchers who noted the correlation between grazing on the artesian springs and a reduction in plant biomass on the springs (Badman 1991; Fatchen 2001a) .

3.3 Methodology

3.3.1 Overview and site selection

An analysis of aquatic change in a water body over time requires:

- the collection of sediment cores that are continuous and rich in micro- and macrofossils and chemical indicators
- the establishment of timelines down the cores
- sampling and analysis of sediments and identification and enumeration of fossil biological and chemical indicators
- the characterisation of the water quality autecology of a wide range of indicator species and biomarkers
- ultimately, the empirical (and/or qualitative) integration of the establishment, sampling and characterisation in order to derive water quality and spring complex histories for comparison with historical records of events and management regimes.

The initial step in this process involved site selection and 22 individual springs were sampled in April, June and July 2010 to assess their relative suitability for palaeo-ecological research. This involved using a hand-held sediment probe to extract a short sediment core (less than 50 cm) from the centre of each spring. Site suitability was assessed on the presence of limnological sediments (mud/silt/clay rather than sand/calcium-rich sediment), visible presence of aquatic macrofossils and also a low possibility of sediment mixing (influencing factors including the rate of flow from spring vent and presence of cattle and other large herbivores). From this analysis, six sites were chosen for extensive coring and basic sediment description. Two spring groups were then chosen as being the most suitable for detailed palaeo-ecological analysis: Warburton Spring and Beresford Spring. All analyses were conducted on Warburton Spring, while Beresford Spring analysis was limited to dating and diatom preparation.

3.3.2 Sediment coring

Sediment cores were taken from artesian spring vents using a modified Russian or D-section corer (Jowsey 1966). A D-section corer was chosen over other types of corers as it is side-operated and thus avoids compaction of the sediment. Each drive of the corer resulted in a 500 mm long by 54 mm wide D-section drive. Additional length was added to the corer using 1 m steel rods and locking sleeves. Although the D-section corer takes a 50 cm sample of sediment, the nose of the corer disturbs a further 15 cm below this depth. To avoid this disturbance, alternating holes were used when coring, avoiding this disturbed sediment and enabling in-situ drives to be taken along the entire length of the core.

A coring technique was used whereby 100 mm of overlap was taken on each consecutive drive, as shown in Table 3.1. This resulted in each new drive containing 100 mm of the same depth from the previous drive. As each consecutive drive was taken from alternating holes, the 100 mm overlap allowed for the comparison of sediment between drives to ensure consistency between the two coring holes.

Table 3.1: Coring holes and drive overlap

Drive number	Hole	Depth (cm)
1	A	0–50
2	B	40–90
3	A	80–130
4	B	120–170
5	A	160–210
6	B	200–250
7	A	240–290
8	B	280–330
9	A	320–370
10	B	360–410

Sediment cores were placed into a labelled PVC split core tube. Information written on the tray included core name, depth range, top end, bottom end, hole (A or B) and drive number. The core was then photographed next to a tape measure showing the appropriate depth from which the core had been taken. The core and PVC split tube were then wrapped in two layers of plastic film wrap before being placed into a galvanised split core tray for transport to Adelaide for analysis. Upon return to The University of Adelaide, the cores were stored in a cool room at 4°C.

3.3.3 Sediment description

Cores were photographed and stratigraphies described using a modified version of the Troels-Smith method (Kershaw 1997). The bulk density, and the moisture, organic, carbonate contents were analysed following the method by Heiri *et al*. (2001). Samples for this analysis were taken at 5 cm intervals, with a 1 cm^3 sediment sample taken using a cut-off syringe and placed into a porcelain crucible of known weight. The samples were then weighed to determine the weight of the moist sediment and later placed in an oven at 100°C for 12 hours to determine moisture content. Samples were then placed in a muffle furnace at 550°C for 5 hours to determine the organic content, and in a muffle furnace at 950°C for 2 hours to determine the carbonate content. Samples weights were recorded to three decimal places after each stage and weighed immediately after they had cooled to avoid the possibility of moisture being absorbed into the porous crucibles (see Heiri *et al*. 2001).

3.3.4 Charcoal analysis

Charcoal analysis was only completed for the Warburton sediment core (WARB1). A modified version of the Rhodes' (1995) method for the preparation and quantification of microscopic charcoal from sediment was utilised as it is a straightforward yet effective method of charcoal preparation and quantification.

Through the use of very mild reagents and the lack of mechanical agitation, the charcoal particles in this analysis are unlikely to be fragmented or destroyed during the preparation procedure, as detailed by Stevenson and Haberle (2005). Thus, the charcoal assemblage quantified is likely to represent that deposited in the sediment and not one modified by the sample preparation procedure. Grams of charcoal per gram of sediment were calculated for each sample, using results from the moisture, organic and carbonate analysis.

Photo: Travis Gotch

3.3.5 Magnetic susceptibility

The magnetic susceptibility was completed on two cores taken from Warburton Spring (WARB1 and WARB2) and was measured using a Bartington Instruments MS2 Magnetic Susceptibility Meter and high-resolution MS2E Sensor. Measurements were taken at a resolution of 1 cm along the entire length of the core with the MS2E sensor lightly resting on the surface of the plastic film during each measurement. Calibration of the MS2E Sensor was checked at regular intervals by scanning the sensor against a calibration sample of known magnetic susceptibility.

3.3.6 AMS ^{14}C dating

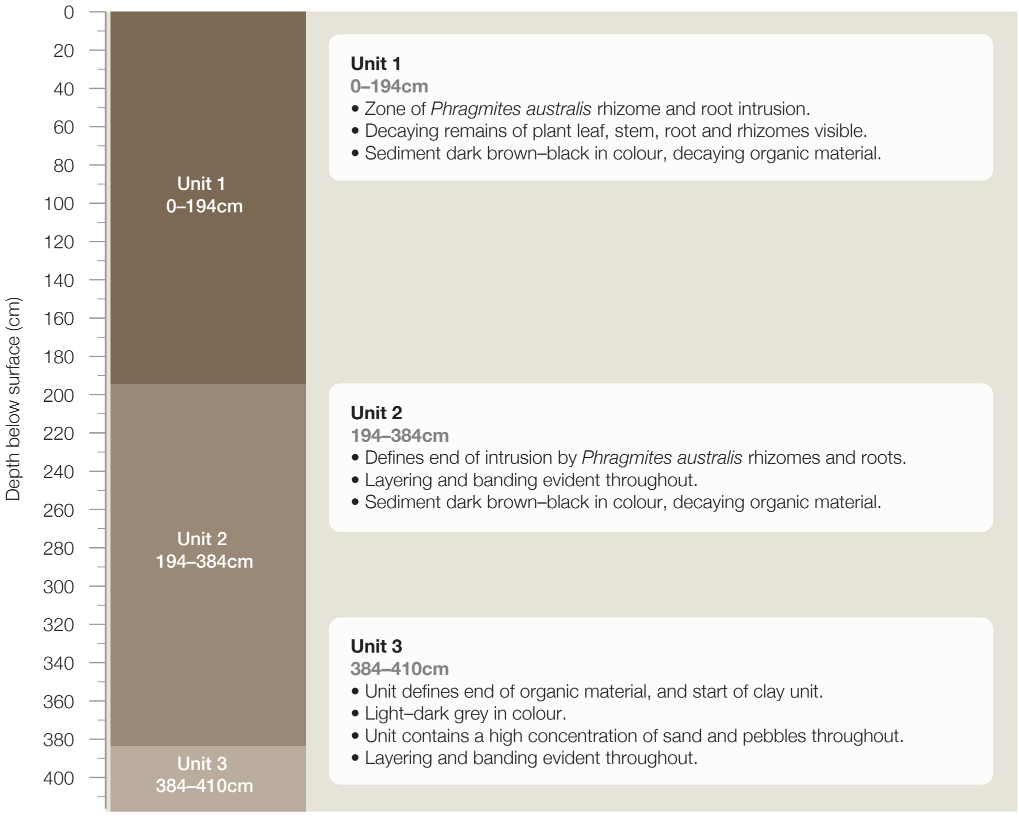
Four Accelerator Mass Spectrometry Carbon^{14} (AMS ^{14}C) dates were obtained for this study; three from Warburton and one from Beresford. The AMS ^{14}C technique was chosen in preference to conventional radiocarbon dating techniques because it is based on particle counting as opposed to decay counting of the isotope, thus a much smaller sample size can be used. Three samples of approximately 10 g were taken from the Warburton Spring (WARB1) core, and a single sample taken from Beresford Spring (BERES1) core. Each sample was collected across 2 cm of depth; the sampling process involving the careful removal of sediment from the core using a clean spatula. The samples were placed into sterilised 50 mL centrifuge tubes and placed into a 40°C oven to dry. The dry weight for each sample was then calculated and recorded. Sediment samples, along with required documentation, were sent to the Waikato Radiocarbon Dating Laboratory, New Zealand, for analysis.

3.3.7 Diatom and phytolith analysis

Diatoms were selected as the major indicator organism in this study as they are the best indicator of palaeo-limnological change over century to millennial timescales (Deeley & Paling 1999). They are particularly suited to precise

Figure 3.1: Diagrammatic representation of the three major units in the Warburton Spring (WARB1) core

Note the second core Warburton Springs Minor (WARB2) had a very similar composition to that of WARB1. This similarity is reflected in the results of the magnetic susceptibility.



Unit 1
0–194cm
- Zone of *Phragmites australis* rhizome and root intrusion.
- Decaying remains of plant leaf, stem, root and rhizomes visible.
- Sediment dark brown–black in colour, decaying organic material.

Unit 2
194–384cm
- Defines end of intrusion by *Phragmites australis* rhizomes and roots.
- Layering and banding evident throughout.
- Sediment dark brown–black in colour, decaying organic material.

Unit 3
384–410cm
- Unit defines end of organic material, and start of clay unit.
- Light–dark grey in colour.
- Unit contains a high concentration of sand and pebbles throughout.
- Layering and banding evident throughout.

inference of past water quality because of their ecological sensitivity and the large number of species commonly found in sediment samples (Reid *et al*. 1995). Importantly, using statistical relationships between diatoms and water chemistry, robust quantitative estimates of past water quality can be produced. In Australian aquatic systems, powerful diatom-based predictive models, as assessed by diatom inferred versus measured water chemistry, have been developed for:

- salinity and conductivity, $r^2 = 0.77$; (Gell 1997) and $r^2 = 0.71$ (Tibby & Reid 2004)
- total phosphorus, $r^2 = 0.74$; (Tibby 2003)
- pH, $r^2 = 0.77$; (Tibby *et al*. 2003).

In an effort to identify phytoliths as well as diatoms in the sediment of the WARB1 core, a modified version of the Battarbee (1986) and Renberg (1990) diatom preparation techniques was used.

3.3.8 Plant macrofossil and cuticle analysis

The loss of submerged plants from wetlands is one of the most important human impacts on aquatic ecosystems in the world. Plant loss frequently results in reduced biodiversity and the maintenance of phytoplankton dominance that, even with significant management intervention, is difficult to eliminate. Despite the importance of this phenomenon, there is considerable debate about the key processes driving ‘switches’ between plant and phytoplankton dominance. Remains of aquatic plants (primarily grass cuticles) were extracted from the sediments to reconstruct aquatic plant structure in these groundwater-dependent systems. Similar work undertaken by Fluin (unpublished data, 2007), (Reid *et al*. 2007), and Dick from the Coorong (2011) has shown clear shifts or phases in aquatic plant presence/absence over time.

Fossil grass cuticles have the potential to yield valuable palaeo-ecological information on grasslands (Piperno 2006). Cuticle analysis was attempted in order to answer the question of presence or absence of *Phragmites australis* over time. Cuticle analysis was undertaken using 1–2 cm^3 samples of sediment. Each sample was immersed in a test tube containing equal parts of 4% hydrogen peroxide solution and 25% ethanol. This was then left to sit for 24 hours. The supernatant was siphoned off before a solution of 40% hydrogen peroxide added and the test tube placed in a water bath on gentle heat. After approximately two hours, the contents of each test tube were washed through an 180 µm sieve. The > 180 µm fraction was then placed into a petri dish.

Each petri dish was then placed under a stereoscope to identify cuticle material which may have been suitable for mounting onto microscope slides. Generally, focus was given to the recovery of larger fragments of cuticle. Suitable pieces of cuticle material were carefully brushed using a pair of tweezers and fine paint brush to remove fibres from the abaxial surface of the cuticle. The cuticle was then washed in distilled water, stained using crystal violet and

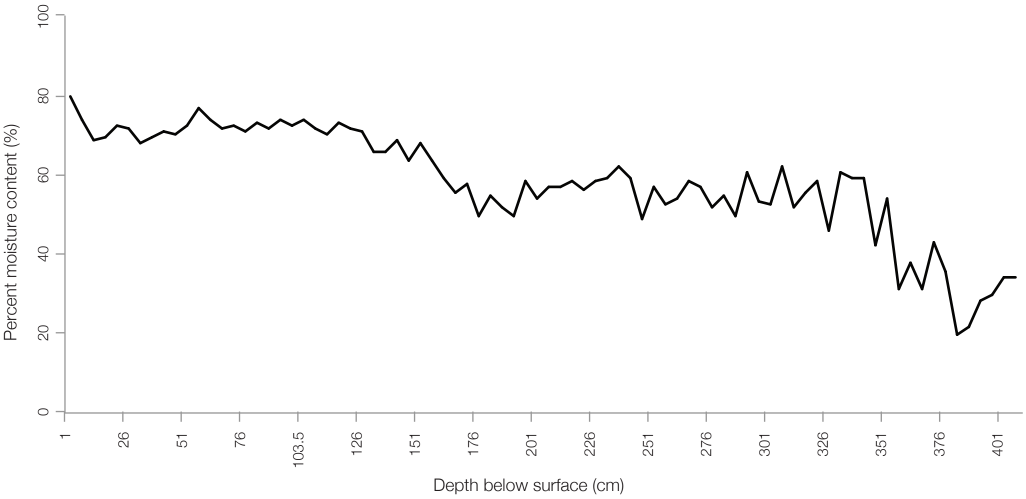


Figure 3.2: Change in the moisture content (%) with depth for core WARB1

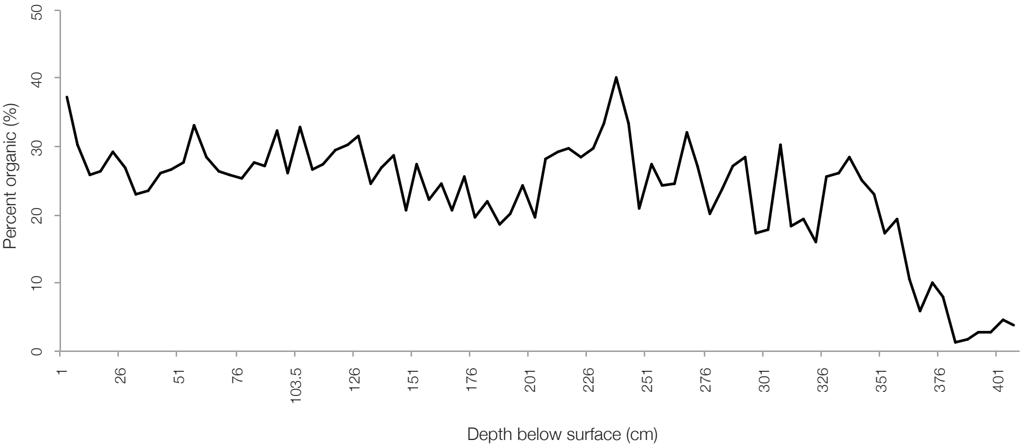


Figure 3.3: Percentage of organic material with depth for WARB1

Figure 3.4: Percentage of inorganic carbonate with depth for core WARB1

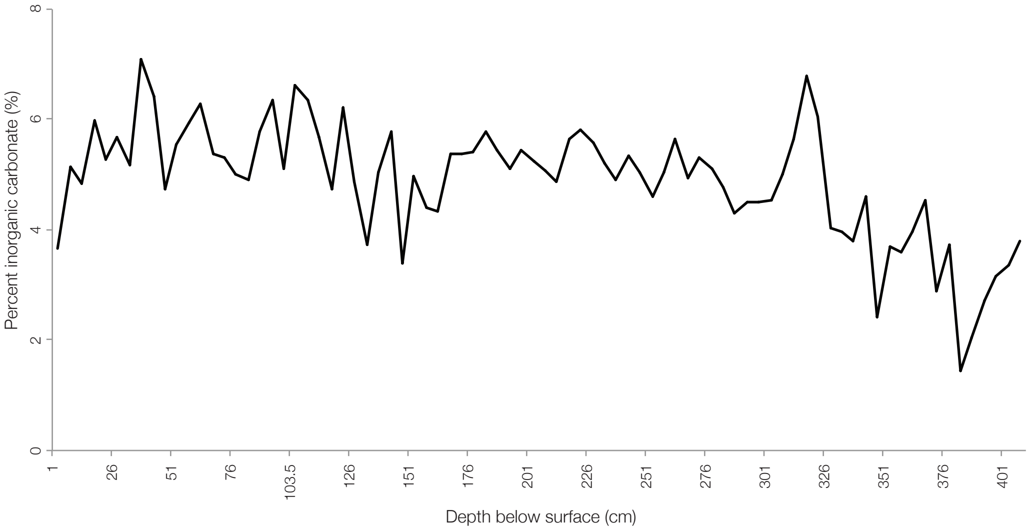
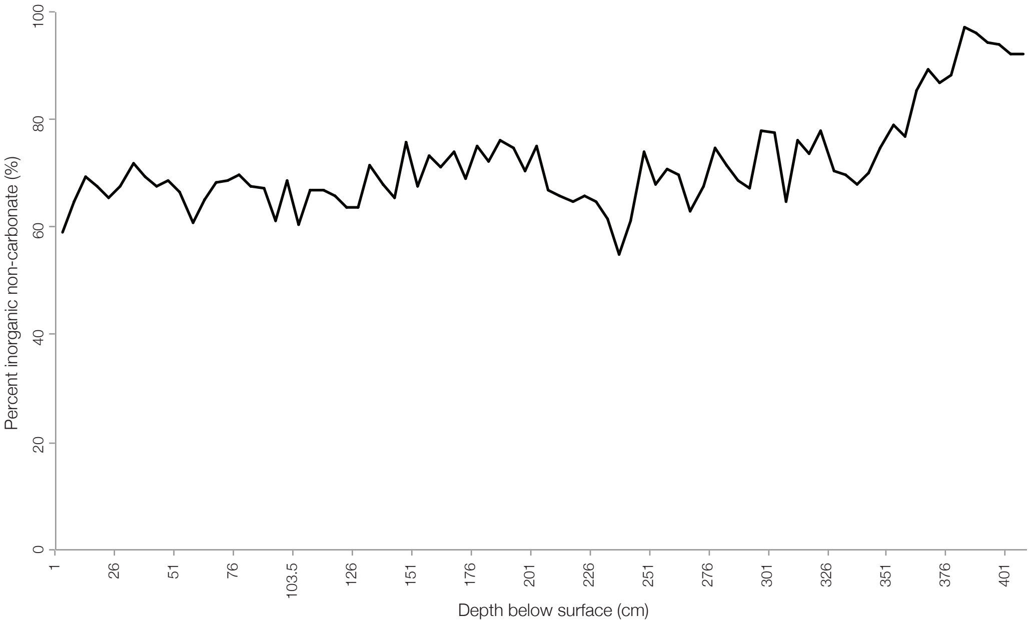


Figure 3.5: Percentage of non-carbonate inorganic material with depth for core WARB1



mounted onto a labelled microscope slide using melted phenol-glycerine jelly. The microscope slides were allowed to dry and the jelly harden before being analysed under a light Nikon Eclipse 80i optical microscope. Fossil cuticles were identified in the slides by comparison with a modern reference collection taken from present-day artesian springs vegetation. In addition, plant anatomy text was used for reference (Metcalfe & Tomlinson 1960).

3.4 Results

3.4.1 Sediment coring

Appendix 1 lists the springs cored (other than Warburton) during the reconnaissance phase of this study and basic information about their content and the suitability of the site to be the focus of future palaeo-ecological research. These cores are all in cool storage at The University of Adelaide.

3.4.2 Sediment characteristics

WARB1 is represented by three distinct units, as is shown in Figure 3.1. Unit one (0–94 cm) is defined by the intrusion of live rhizomes and roots from the modern *Phragmites australis* growing on the surface of the spring. This intrusion is an important factor to consider when analysing the possibility of sediment mixing in the spring. Regions of possible contamination were excluded as localities for 14°C sampling.

Unit two (94–384 cm) is defined by the end of visible intrusion by live *Phragmites australis* rhizomes and roots. It is a predominantly homogenous unit, dark brown to black in colour, although dark brown layering and banding is evident throughout.

Unit three (384–410 cm) is characterised by low proportions of organic material, and the dominance of light to dark grey clay. This unit contains a visible sand fraction and small pebbles are evident throughout. These pebbles were not originally visible during sediment description and only became evident during preparation of the sediment for macrofossil, phytolith, diatom, cuticle and charcoal analysis.

The top 150 cm of the core is relatively moist at 60–80% moisture content (Figure 3.2). From 150 cm to the bottom of the core (410 cm), the moisture content progressively drops to a final bottom moisture content of approximately 20%.

The top 376 cm of WARB1 is highly organic (Figure 3.3), with a mean organic content of 25.3%, before the core transitions into a clay unit from 384 cm to the bottom of the core (410 cm). This clay unit correlates with unit 3, as previously discussed, and has a mean organic content of 2.9%.

Analysis of the inorganic carbonate of the WARB1 core (Figure 3.4) shows a similar pattern to that of both the moisture and organic content analysis of this core. From 0–326 cm (units one and two), the core has an inorganic carbonate content of approximately 5–6%. Further down the core at 326 cm, the inorganic carbonate content drops to approximately 4%; this variation in comparison to the top of the core can be correlated with the occurrence of the clay unit (unit 3).

The vast majority of inorganic content in the WARB1 core is non-carbonate inorganic material (Figure 3.5). The WARB1 core shows a trend of gradual increase in inorganic other from 0–201 cm (approximately 60–78%) before experiencing a sudden decrease at 226 cm (56%) before resuming a gradual increase from 226–410 cm (approximately 75–85%).

3.4.3 Magnetic susceptibility

The results of the magnetic susceptibility are shown in Figure 3.6. Each drive is individually coloured for contrast. As previously discussed in the coring methodology (Section 3.3.2), the overlap between each drive is designed to test the continuity between each drive and the next.

3.4.4 Dating results

As mentioned previously, four AMS ^{14}C dates were obtained for this study; three from Warburton and one from Beresford. The results for the three AMS ^{14}C dates obtained for Warburton Spring are detailed in Figure 3.7.

The single ^{14}C date from the Beresford Spring (BERES1) core was 7884 ± 35 before present (BP) (Figure 3.8). This date is approximately 38 000 years younger than corresponding date obtained from a similar depth in the WARB1 core. This suggests that Beresford Spring may have a much faster sedimentation rate than Warburton Spring.

3.4.5 Charcoal results

Analysis of > 125 μm charcoal particles from the WARB1 core reveals a consistent history of burning on the springs throughout the record (Figure 3.9). When this data is viewed in consultation with the results of the ^{14}C dating from this core, it becomes apparent that burning on the springs occurs well before the settlement of Aboriginal peoples in Australia (see Section 6.1). In comparison to the first part of the WARB1 core (0–151 cm), the second half (151–410 cm) has a much higher charcoal particle count. A particularly concentrated cluster of charcoal particles occurs from 251–351 cm; in terms of chronology this correlates to approximately 37 ka.

3.4.6 Diatom and phytolith analysis

Analysis of phytoliths and diatoms in the WARB1 core reveals a predominate absence of both diatoms and phytoliths. The only occurrence of diatoms was the *Nitzschia* sp. in the top 10 cm. Phytoliths were not observed throughout the WARB1 core.

3.4.7 Plant macrofossil and cuticle analysis

The results of the cuticle analysis of the Warburton Spring indicate the presence of *Phragmites australis* remains from 0–255 cm. Used in conjunction with the results of the ^{14}C dating, it can be stated that *Phragmites* has been present of the artesian spring at Warburton for approximately the last 40 000 years.

3.5 Discussion

3.5.1 Chronology of Warburton Spring and Beresford Spring

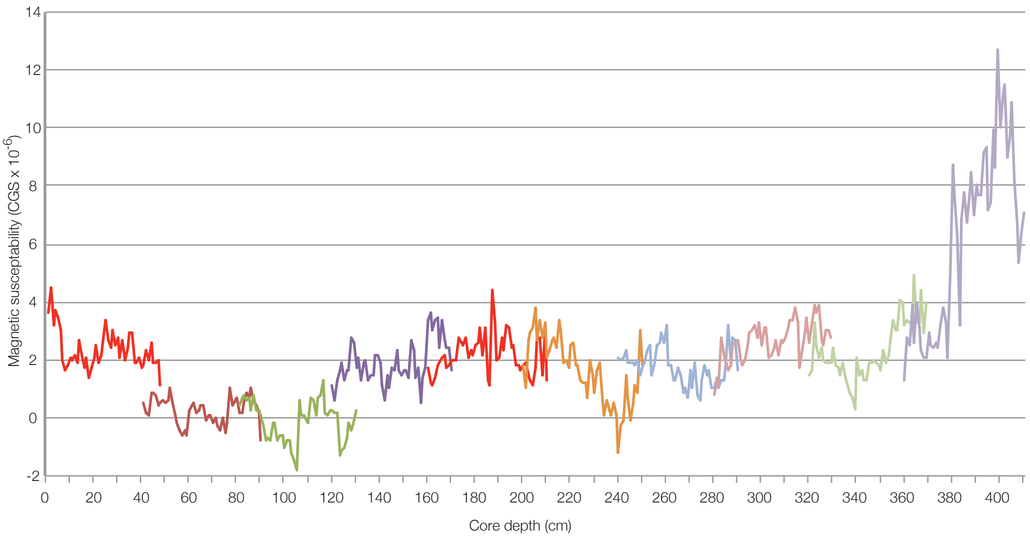
Warburton Spring Major and Minor have not been previously dated using luminescence or ^{14}C techniques, thus there no comparisons to be made with the results obtained from the ^{14}C dating of Warburton Spring in this study. Prescott *et al*. (2008) obtained an age for Beresford Spring, 13.9 ± 1 ka before present, by using luminescence dating of quartz sand grains incorporated in the carbonate artesian deposits. As sediment from Beresford Spring itself, rather than carbonate artesian deposit, was dated in this study, the results of Prescott *et al*. (2008) cannot be directly compared with the ^{14}C date (7884 ± 35 BP) obtained in this study. Despite this, there is a rough consistency with the Prescott *et al*. (2008) date for Beresford Spring, and the date obtained during this study.

The bottom two ^{14}C dates for Warburton Spring (WARB1) are located at or beyond the boundary of the radiocarbon barrier. As detailed by Björck and Wohlfarth (2004), the maximum age for radiocarbon dating is eight half lives or approximately 40 000 to 45 000 years. After

Figure 3.6: Results of magnetic susceptibility analysis (CGS x 10^{-6} over depth)

Warburton Core Magnetic Susceptibility as at 11/05/2010

Various colours indicate the assorted drives.



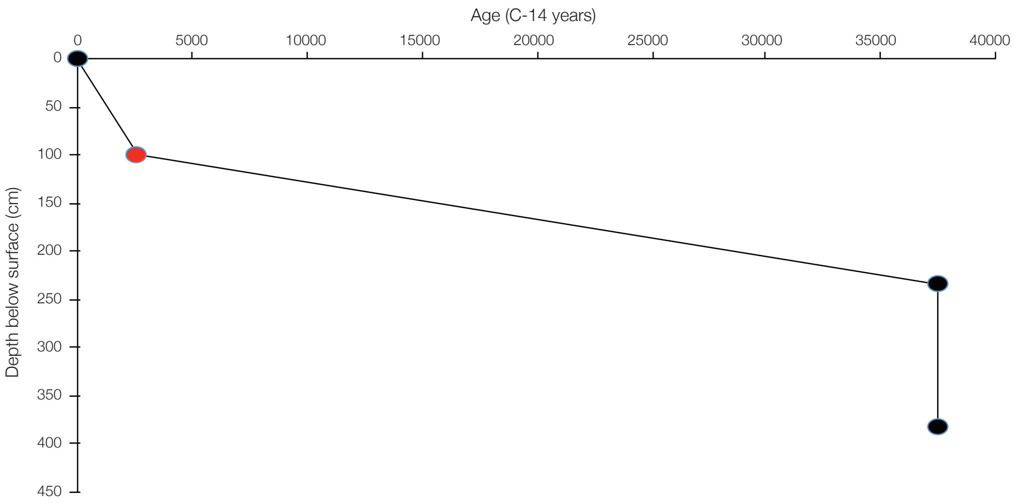


Figure 3.7: Age of the three Warburton Spring sediment core derived from ^{14}C dating

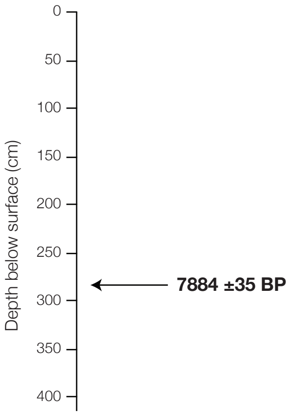


Figure 3.8: Age of Beresford Spring sediment core derived from ^{14}C dating

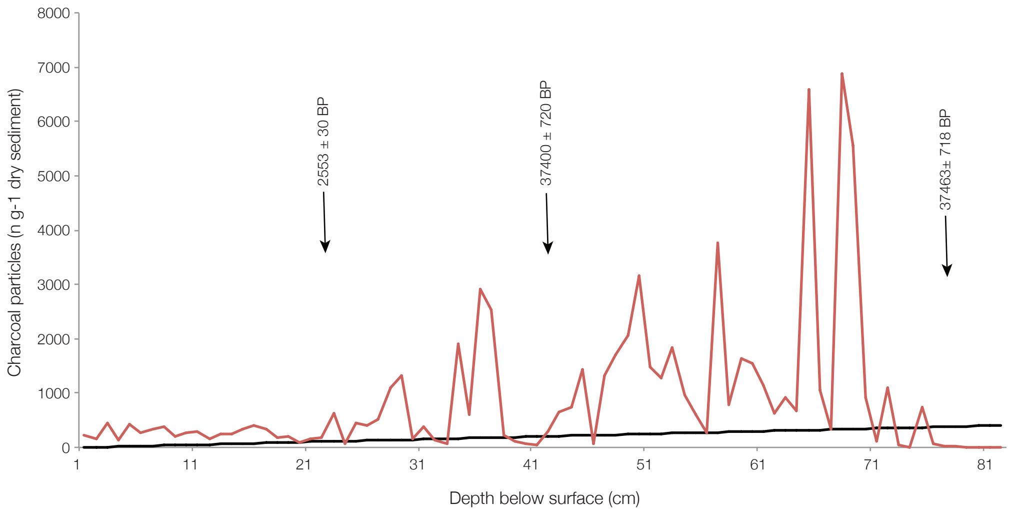


Figure 3.9: Number of charcoal particles per gram of dried sediment in WARB1 core

this point, measurements become infinite and highly susceptible to contamination from modern carbonaceous material (Björck & Wohlfarth 2004). For this reason, thermoluminescence (TL) or optically stimulated luminescence (OSL) would be needed to refine the chronology of WARB1 or similarly aged systems (Prescott & Habermehl 2008).

Using the method of multiple working hypotheses (Elliott & Brook 2007; Markley 2010), there are three possible scenarios which explain the three AMS ^{14}C dates taken for the Warburton Spring (WARB1) core:

- hypothesis 1: dates are correct with three different rates of sedimentation
- hypothesis 2: dates are correct with a hiatus in sedimentation at some stage between 2553 ± 30 BP and approximately 37 000 BP
- hypothesis 3: the first date is erroneous due to bio-perturbation of the surface sediments from 100+ years of cattle grazing and pugging.

These hypotheses are represented and fully explained in Figures 3.10 to 3.12.

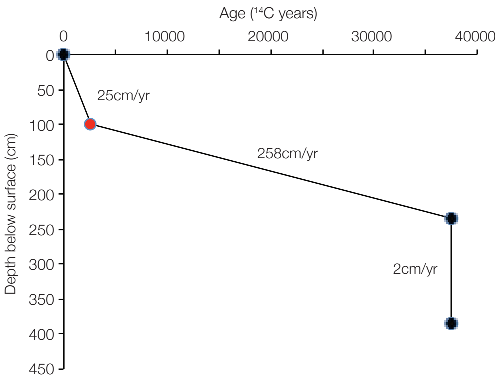
The third hypothesis is the most likely scenario to explain the three radiocarbon dates obtained at Warburton Spring. This hypothesis uses the assumption that there has been a hiatus in sedimentation at some stage between 2553 ± 30 BP and approximately 37 000 BP, followed by a recommencement of sedimentation. This hiatus is likely the result of a change to spring flow fluctuation, and may even be attributed to a change to the location of the spring vent at Warburton Minor. This is supported by Badman (1991) who details the tendency for spring vents and tails to shift location as a result of changes in flow from the aquifer. Changes to the spring vent and tail locations following European settlement may also be attributed to pugging by livestock, installation of piping into artesian bores and vehicle tracks (Mudd 2000).

3.5.2 Reconstruction of the presence of *Phragmites*

The results of the cuticle analysis indicate that *Phragmites australis* was identifiable from all samples from 0–255 cm. Although organic material can be observed below this depth, the cuticle was not readily identifiable using the chromium trioxide technique.

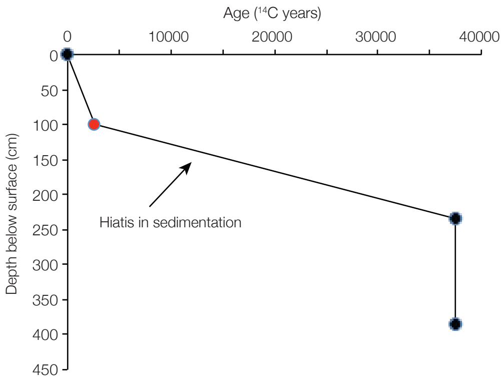
Results from the previous section shows that *Phragmites* existed at Warburton Spring prior to European settlement. The second ^{14}C date from this spring (37400 ± 720 BP), indicates that it is quite likely that *Phragmites* dominated Warburton Spring for the last 37 000 years. The earliest European observation of *Phragmites* on the spring was made by workers on the Overland Telegraph Line in 1870, who describe some of the springs as 'soda flats and reeds 17 feet high and as thick as your finger' (Symon 1985). The dominant vent vegetation at Warburton Spring is *Phragmites* growing to a height of 5.2 m, the taller stems held aloft by the shorter stems around it. Stock have been excluded from this spring group since 2000 (Gotch, unpublished data). This has led to a proliferation of *Phragmites* in the springs.

Prior to this study, one of the only means of determining vegetation history in this region was through the use of indirect proxies. Research by Miller *et al*. (1999) and Johnson *et al*. (1999) assesses the carbon isotopic concentration ($\delta^{13}C$) of *Dromaius novaehollandiae* (Emu eggshells) from Lake Eyre to develop a proxy for palaeo-vegetation over the past 65 000 years. As the eggshell calcite reflects the isotopic composition of the bird's herbivorous diet, changes in the $\delta^{13}C$ can be used to interpret changes to their diet, which is ultimately driven by changes in the isotopic composition of the flora (Miller *et al*. 1997; Johnson *et al*. 1999). The cuticle analysis at Warburton Spring shows that *Phragmites* occurs in the Lake Eyre South region from 40 000 years ago. This concurs with the research of Martin (1990) and Singh (1991).



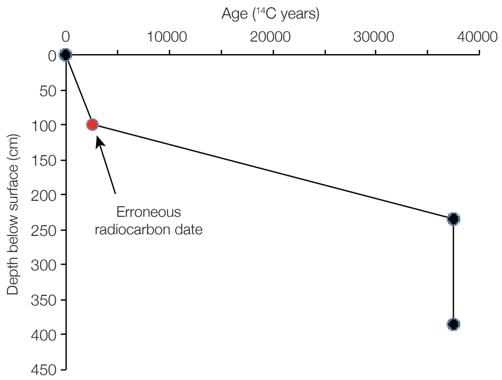
If the three radiocarbon dates are taken as accurate, there was a period of initial rapid sedimentation followed by a slower, relatively constant period of sedimentation. The period above the top radiocarbon date represents a sedimentation rate of 25 cm/yr over the past 2553 ± 30 BP. The period between the first and second radiocarbon dates represents a sedimentation rate of 258 cm/yr over a period of approximately 35 000 years. The period between the second and bottom radiocarbon dates represents a sedimentation rate of 2 cm/yr over the period of 63 years; as these two bottom dates lie at the radiocarbon barrier, they should be viewed cautiously.

Figure 3.10: Spring age, hypothesis 1



If the three radiocarbon dates are taken as accurate, there was a hiatus in sedimentation at some stage between 2553 ± 30 BP and approximately 37 000 BP, followed by a recommencement of sedimentation.

Figure 3.11: Spring age, hypothesis 2



The sediment in the Warburton core is old, a result of a slow sedimentation rate. The top radiocarbon date (2553 ± 30 BP) is erroneous and does not reflect the true age of the sediment depth it represents. The error associated with this radiocarbon date may be attributed to pugging by livestock, causing contamination of the old sediment with modern carbon.

Figure 3.12: Spring age, hypothesis 3

3.5.3 History of burning at Warburton Spring

The analysis of charcoal particles (> 125 µm) preserved in the sediment at Warburton Spring (WARB1 core) reveals a long history of burning in close proximity to this spring. The charcoal fraction analysed (> 125 µm) suggests that this charcoal is local and not aeolian in origin (Whitlock & Larsen 2001). Correlation of this record with Indigenous occupation of the area is difficult, as although there is a long history of archaeological investigation of the Lake Eyre South region (Slaytor 2005), it is difficult to put an exact age on when occupation occurred. Currently, most of the archaeological artefacts found in the Lake Eyre South region date from the last 5000 years (Slaytor 2005). As to exactly when this occupation began, debate still reigns in Australia as to when Indigenous peoples first settled the Australian continent. Research by Miller *et al*. (1999) documents the presence of *Genyornis newtoni* (a large flightless bird) on the Australian continent for more than 100 000 years ago until a sudden disappearance 50 000 years ago. The fact this extinction of *Genyornis* occurs during a period of moderate climate change suggests that human impact and not climate was responsible (Miller *et al*. 1999). Along with the *Genyornis* extinction, there is further archaeological evidence to support the presence of people in south-eastern Australia 50 000 years ago (Bowler 1998; Bowler & Price 1998; Gillespie 1998; Thorne *et al*. 1999; Bowler & Magee 2000; Gillespie & Roberts 2000; Grün *et al*. 2000). However, Hughes and Hiscock (2005) found no artefact evidence of human occupation in this region earlier than the late-Holocene (5000 years BP). Taking into consideration the ^{14}C dates obtained for Warburton Spring, it is quite possible that some of the charcoal in the Warburton Spring core (WARB1) predates all human occupation of the Lake Eyre South region.

Although four ^{14}C dates were acquired as part of this study, the most relevant is the top date (100–103 cm) from the Spring Minor core (WARB1). At 2553 ± 30 BP, this date reveals that burning on the artesian springs is something that predates European occupation of the Australian continent. As the bottom two dates (235–238 cm and 384–386 cm) from this same core lie at the edge of the radiocarbon dating barrier, whilst providing an indication as to the possible age of the core at these depths, these dates (37 400 ± 720 BP and 37463 ± 718 BP respectively) do not provide any conclusive data (Last *et al*. 2001; Björck & Wohlfarth 2004). As previously discussed, several attempts were made to carry out luminescence dating throughout this study, however this could not return results within a suitable timeframe for the study.

Analysis of the fire history at Warburton Spring contributes new knowledge to the existing collection of charcoal study sites in Australia. As detailed in Mooney *et al*. (2010) and observed in data from the Australasian Quaternary Association, there is a lack of charcoal study sites in Australia's arid zone.

3.6 Principal outcomes

The suitability of artesian springs as sites for palaeo-ecological research has been assessed through sediment coring at ten artesian spring sites. In addition, results from the magnetic susceptibility and sediment analysis of a core taken from Warburton Spring indicate that artesian spring sedimentation is characterised by a chronological depositional sequence. The application of palaeo-ecological techniques to GAB springs provides an insight into the ecological history of these iconic sites. This information can be used as a valuable tool when constructing future land management practices in the region.

Due to the absence of diatoms and phytoliths at all sample sites, the study was unable to reconstruct salinity or pH fluxes over time. It is unknown why diatoms have not preserved in the sediment. Modern samples taken from surficial sediment of the springs showed a diverse abundant flora of diatoms, yet they did not preserve in the archived sediments.

The history of *Phragmites australis* has been documented over a period of approximately 37 000 years at Warburton Spring through the application of cuticle analysis. This information provides a useful insight into the past state of Warburton Spring and can be used as a guide when considering future land management practices for this spring.

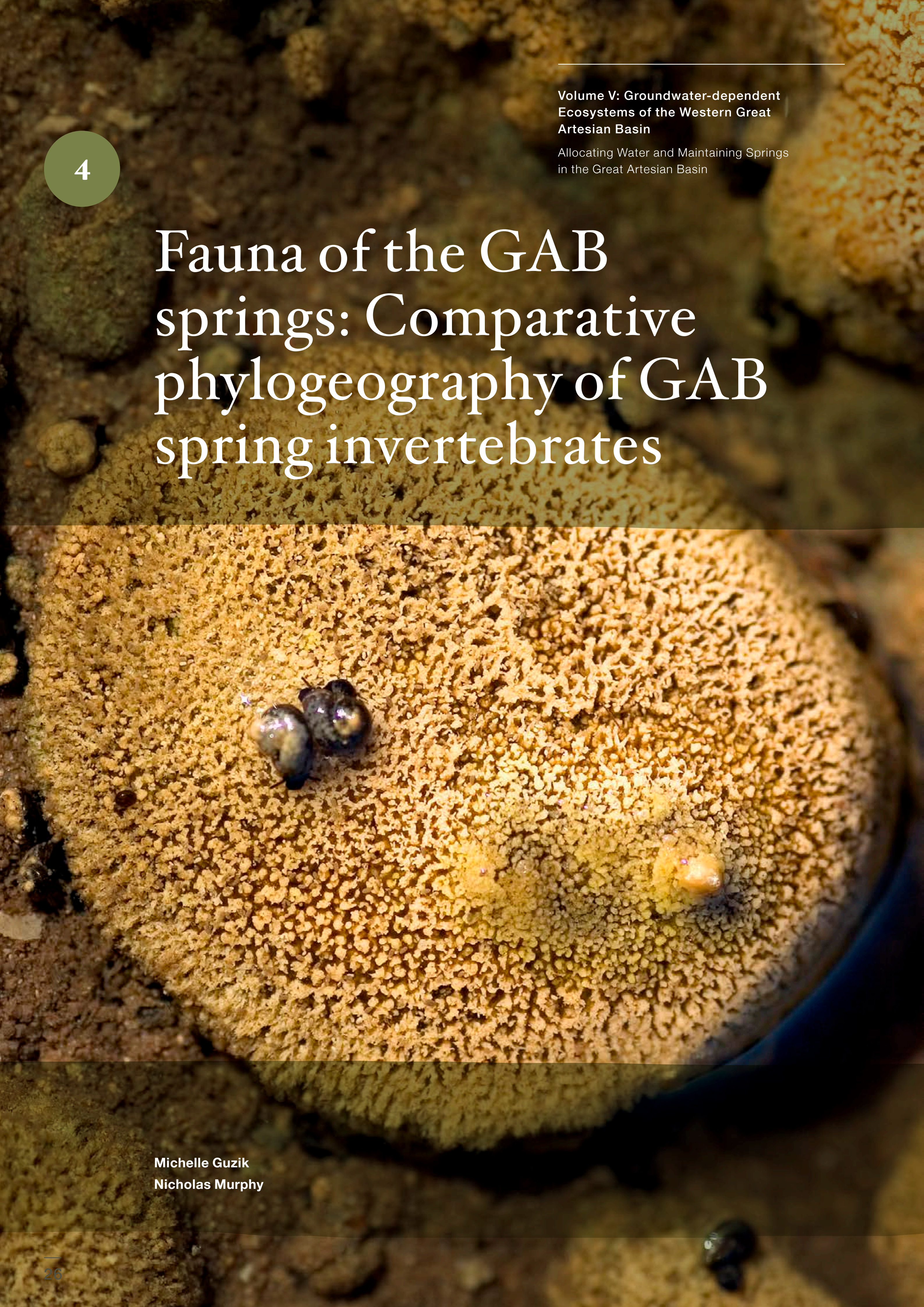
The fire history at Warburton Spring has been determined, indicating the presence of regular burning throughout the history of this spring. This information can be used as a useful tool when considering the effectiveness of prescribed burning as a control strategy for the control of *Phragmites australis*.

3.7 Recommendation for future research

This research highlights opportunities for research on GAB springs to provide critical information about past environments in the arid zone of Australia. The use of ^{14}C dating indicated that some of these sites are among the oldest recorded palaeo records in Australia. Future research is recommended at Dalhousie Springs (and similar sites) where water depth is sufficient to provide optimal conditions for diatom preservation.

Much of the plant macrofossil work involved in this study had never been applied to a setting as unique as artesian springs. As such, there was a high degree of trial and error in terms of the techniques selected. Cuticle analysis proved the most successful of methods and, in the future, it would be beneficial to refine cuticle analysis techniques. Furthermore, more research is required to determine whether identifiable *Phragmites australis* cuticle can be extracted from below 255 cm in the WARB1 core.

Results of ^{14}C dating of the Warburton Spring core show that the radiocarbon barrier can be an issue when obtaining the chronology of GAB springs. In the future, it would be useful to implement alternative dating techniques which have a larger effective time span. Such techniques may include TL or OSL dating. Availability of suitably equipped laboratories and funding are likely to be key challenges faced when attempting these techniques.



4

Fauna of the GAB springs: Comparative phylogeography of GAB spring invertebrates

Michelle Guzik
Nicholas Murphy

4. Fauna of the GAB springs: Comparative phylogeography of GAB spring invertebrates

4.1 Background

The Great Artesian Basin (GAB) springs are an area of rich endemism in Australia, especially given the fragmented size and location of these arid zone habitats. The GAB springs habitat as a whole is federally recognised as a biologically, culturally and hydrogeologically unique region. The endemic flora and fauna that inhabit the springs are considered relicts from a time when arid Australia was 'warm and wet' and are also likely indicators of spring health. The focus of this report is the aquatic invertebrate fauna of the Lake Eyre Supergroup.

This chapter is a summary of a broader research project. This work has been published in a series of three journal papers which contain full details on the methodology and results summarised in this chapter:

- Murphy, NP, Breed, MF, Guzik, MT, Cooper, SJB & Austin, AD 2012, 'Trapped in desert springs: Phylogeography of Australian desert spring snails', *Journal of Biogeography*, vol. 39, pp. 1573-1582.
- Guzik MT, Adams MA, Murphy NP, Cooper SJB, Austin AD 2012, 'Desert Springs: Deep Phylogeographic Structure in an Ancient Endemic Crustacean (Phreatomerus latipes)', *PLoS ONE* vol. 7: e37642. doi:10.1371/journal.pone.0037642
- Murphy, NP, Adams, MA & Austin, AD 2009, 'Independent colonisation and extensive cryptic speciation of freshwater amphipods in the isolated groundwater springs of Australia's Great Artesian Basin', *Molecular Ecology*, vol. 18, pp. 109–122.

Photograph on facing page: Travis Gotch

4.1.1 Endemic invertebrate fauna of the GAB springs

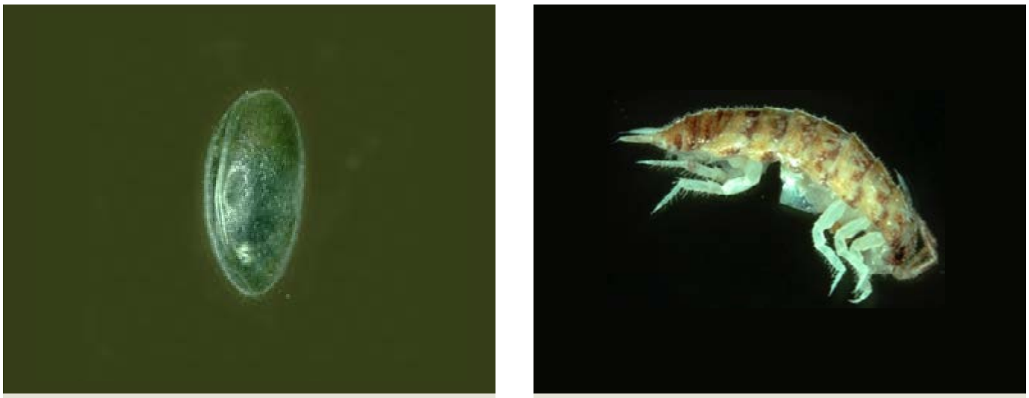
The springs of the western margin of the GAB contain their own suite of endemic fauna, including both aquatic taxa and those associated with the wet margins of the springs (Figure 4.1). These fauna are distinct because they have been restricted to aquatic islands in the desert for a long time, resulting in large numbers of endemic species being present.

The status quo on the GAB springs endemic invertebrates prior to 2008 was that, aside from the hydrobiid snails (Ponder *et al*. 1989; Ponder *et al*. 1995), all other taxonomic groups, e.g. crustaceans (Chilton 1922; Hurley 1959; De Deckker 1979), maintained a single widespread species throughout Southern Lake Eyre (Table 4.1). However, based on substantial evidence, this hypothesis is generally considered an underestimate of the true biodiversity in the region.

Figure 4.1: Endemic aquatic GAB springs fauna from Southern Lake Eyre

A. *Phreatomerus latipes* (Isopoda)

B. *Austrochiltonia* sp. (Amphipoda)



C. *Ngarawa* sp. (Ostracoda) and terrestrial

D. *Haloniscus* (Isopoda: Oniscidea)

Photos: Nick Murphy

Table 4.1: Southern Lake Eyre GAB spring endemic fauna recorded prior to 2008

Endemic taxon group	Described genera	Number of species	Authority	Distribution
Amphipod	*Austrochiltonia*	1	Hurley (1959)	W
Isopod	*Phreatomerus*	1	Chilton (1922)	W
Ostracod	*Ngarawa*	1	De Deckker (1979)	W
Hydrobiid snails	*Fonscochlea*	6	Ponder *et al*. (1995)	R
Hydrobiid snails	*Trochidrobia*	4	Ponder *et al*. (1995)	R

Distribution abbreviations: W = widespread, R = regionally endemic
(adapted from Tap & Niejalke 1998)

4.1.2 Origins of endemic invertebrates in the GAB springs

New studies of GAB springs endemics confirm that there is substantial genetic differentiation within GAB spring endemics, indicative of a previously unrecognised level of evolutionary and cryptic species diversity (Gotch *et al*. 2008; Worthington Wilmer *et al*. 2008; Murphy *et al*. 2010). The origins of this observed genetic variation are considered two-fold based on the results of a study by Murphy *et al*. (2009), in which the phylogenetic relationships between chiltoniid amphipods from South Australian GAB springs and Western Australian calcrete aquifers were tested. They showed that taxa from these two geographically and geologically distinct regions formed paraphyletic relationships, suggesting an ancient link between them. These taxon origins therefore date back to Australia's arid zone prehistory during the Miocene when central Australia comprised a 'warm and wet' forest habitat. A subsequent climatic period of aridification, e.g. early-Pliocene and mid-Pleistocene (Fujioka *et al*., 2005; Fujioka *et al*., 2009; Fujioka & Chappell 2010) is thought to have caused the contraction of inland swamps and lakes, stranding populations to permanent water sources. The groundwater-fed ecosystems surrounded by the arid landscape therefore represent permanent aquatic islands in the desert. In-situ diversification in these contracted habitats through isolation and adaptation has subsequently led to the evolution of new species and high genetic diversity.

If these climatic events influenced all GAB springs fauna simultaneously, there is some possibility that a spatio-temporal pattern exists between taxa and the GAB springs in terms of biogeographically distinct units of taxon groups. It is this latter diversity that is the focus of the current investigation. Similarly, newly evolved taxa may represent very new species that are morphologically indistinguishable because minimal time has passed and has not permitted complete divergence.

4.1.3 Cryptic species

Cryptic species are morphologically similar individuals of a species distinguishable only by other means such as ecology or genetic differentiation (Bickford *et al*. 2006). Their identification often reveals new short-range endemics (Hillis 1987; Harvey 2002; Bickford *et al*. 2006) and can have a decided impact on conservation management strategies, particularly if the outcome is an increase in biodiversity (Harvey 2002; Paquin & Hedin 2004). Genetic data has revolutionised species discovery by identifying genetically distinct lineages that are likely to reflect species level differences. Amongst the GAB springs invertebrate species, diversity is beginning to increase, with extremely high numbers of short-range endemics being discovered in recent studies, including spring snails (Ponder *et al*. 1995), amphipods (Murphy *et al*. 2009) and spiders (Gotch *et al*. 2008). Subsequent taxonomic examination has confirmed that morphological differentiation matches the observed genetic variation between cryptic species (Framenau 2006; Framenau *et al*. 2006; King 2009). The origins of cryptic species are numerous, but fragmentation of habitat and vicariance are often considered drivers of cryptic speciation. Because of the restricted distributions of cryptic species the likelihood of short-range endemics is high.

4.1.4 Comparative phylogeography

Comparative phylogeographic studies between taxa permit investigation of spatio-temporal evolution of multiple species in a region. By quantitatively or qualitatively assessing the congruence between the genetic lineages and geographic distribution patterns of multiple species, it is possible to identify similarities and construct biogeographic models amongst taxa (Garrick *et al*. 2008). Shared phylogeographic patterns amongst taxa have been identified in numerous ecological systems (Schneider & Excoffier 1999; Abellan *et al*. 2007; Garrick *et al*. 2008). These same geographically linked effects of evolution are observed in the GAB springs, with distinct phylogenetic groups corresponding with specific springs and spring groups (Perez *et al*. 2005; Gotch *et al*. 2008; Murphy *et al*. 2009; Murphy *et al*. 2010). Beyond simply detecting shared patterns of evolution, comparative phylogeographic studies identify areas of importance, in particular those with high genetic diversity, for future management and conservation.

4.1.5 Aims of the study

The aim of the study was two-fold. First, molecular techniques were used to examine the phylogeographic structure of two well known endemic invertebrate species that reflect the diverse communities amongst the GAB springs:

- *Phreatomerus*, the monotypic genus that is considered a single species distributed widely throughout the Southern Lake Eyre springs
- *Trochidrobia*, a genus of snails that is represented by four species, three of which have only partially overlapping distributions amongst the Southern Lake Eyre springs and one species that is found only at one spring complex.

In conducting this part of the study there was every chance that new and cryptic species would be identified if the desert landscape had prevented gene flow between fragmented areas of GAB springs. In instances where distinct lineages were observed, a conservative view was taken and new genetic lineages were assigned as evolutionarily significant units (ESUs) that are geographically discrete. Future work will define and describe new species.

The second aim was to compare the patterns of genetic diversity of these co-distributed, biologically diverse groups. Representatives of other GAB springs endemics that have been previously studied were also added to the investigations. This total approach enabled identification of regions of particular significance for conserving maximum genetic diversity across the entire GAB springs, aiding the development of plans for their management and conservation.

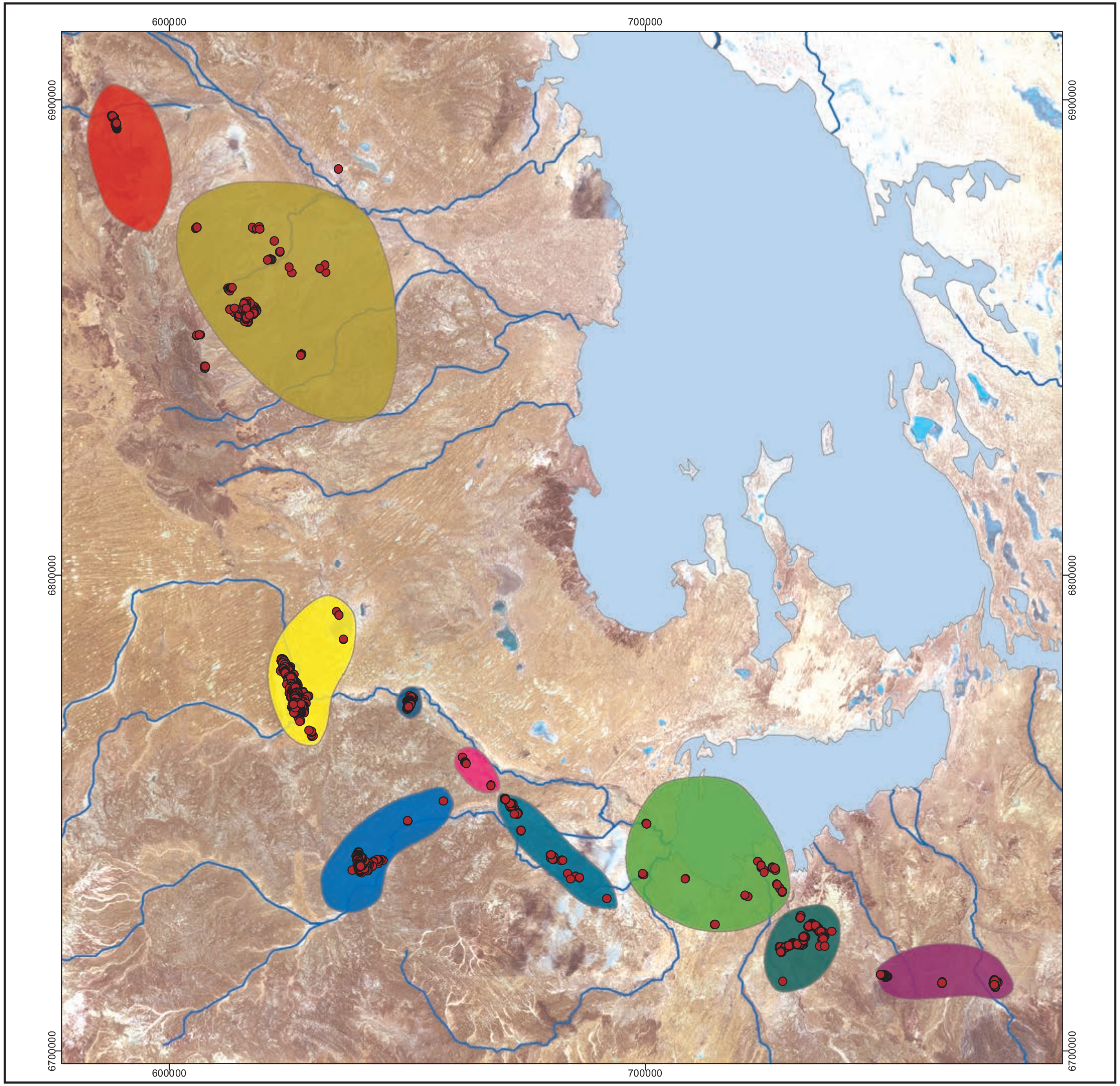


Figure 4.2: Map of GAB spring complexes (named) throughout Southern Lake Eyre

Colours delineate each complex.

Spring Complexes

- 🟥 Beresford Hill
- 🟦 Billa Kalina
- 🟦 Coward Springs
- 🟨 Francis Swamp
- 🟩 Hermit Hill
- 🟩 Lake Eyre South
- 🟥 Freeling
- 🟫 Neales River
- 🟦 Strangways
- 🟪 Wangianna

Legend

- ● Springs
- — Watercourse
- 🟦 Lake Eyre

Background image: Landsat 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: January 2012

Figure 4.3: *Phreatomerus* in GAB spring tail

Photo: Travis Gotch

4.1.6 Nomenclature

The focus of this research was the endemic aquatic invertebrate fauna of the GAB springs. Four key taxonomic groups (amphipods, isopods, ostracods and snails) encompass almost all aquatic invertebrate endemics from the GAB springs. The current report uses the term taxon groups and their recognised family or genus level names to simply describe the key endemics examined, in particular, chiltoniid (amphipods), *Phreatomerus* (aquatic isopods), *Ngarawa* (ostracods), and *Fonscochlea* and *Trochidrobia* (snails). This nomenclature simplifies the taxon groups to names that have been used historically and to which can be applied new genetic lineages found during the current research.

ESUs are a well known tool in conservation genetics for identifying genetically distinct lineages. Typically, these lineages are likely to describe putative and/or cryptic species. ESUs were targeted in this study because they were considered evidence of species-level genetic diversity and an indicator of biodiversity relative to the geographic characteristics of the springs. The implications of ESU-discovery on conservation management of GAB springs as they are treated here are two-fold. First, knowledge of ESUs increases the known levels of possible species biodiversity. Secondly, similar patterns in the geographic distribution of ESUs between geographic locations can help to identify bioregions that can be used in impact assessment and as management units. The primary reason for using ESUs is because it is possible to preserve genetic diversity.

In studying the GAB springs, a number of geographic levels must be considered. The springs have historically been grouped or structured hierarchically based on geographical proximity and some similarity in geology. The major historical groupings are: supergroup, complex, group and individual springs (Chapter 2, Volume IV: Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin (Lewis *et al.* 2013)). These hierarchical groupings are useful in that they set up hypotheses for spatial structure which can subsequently be implemented as geographical management units. The current study was focused on the Lake Eyre Supergroup of GAB springs, examining the spring complex level especially (Figure 4.2) but also spring groups (Section 4.3). Spring endemics were collected from 145 of a total of 1674 springs (approximately 10% sampled) and 10 spring complexes (Figure 4.2). Not all springs yielded all major endemic taxon groups and not all springs were sampled. The aim was to take a first step in identifying the levels of genetic diversity throughout the supergroup and to identify broad genetically divergent ESUs. For such a study, a broad representation of the springs was required and sample sizes were not necessarily required

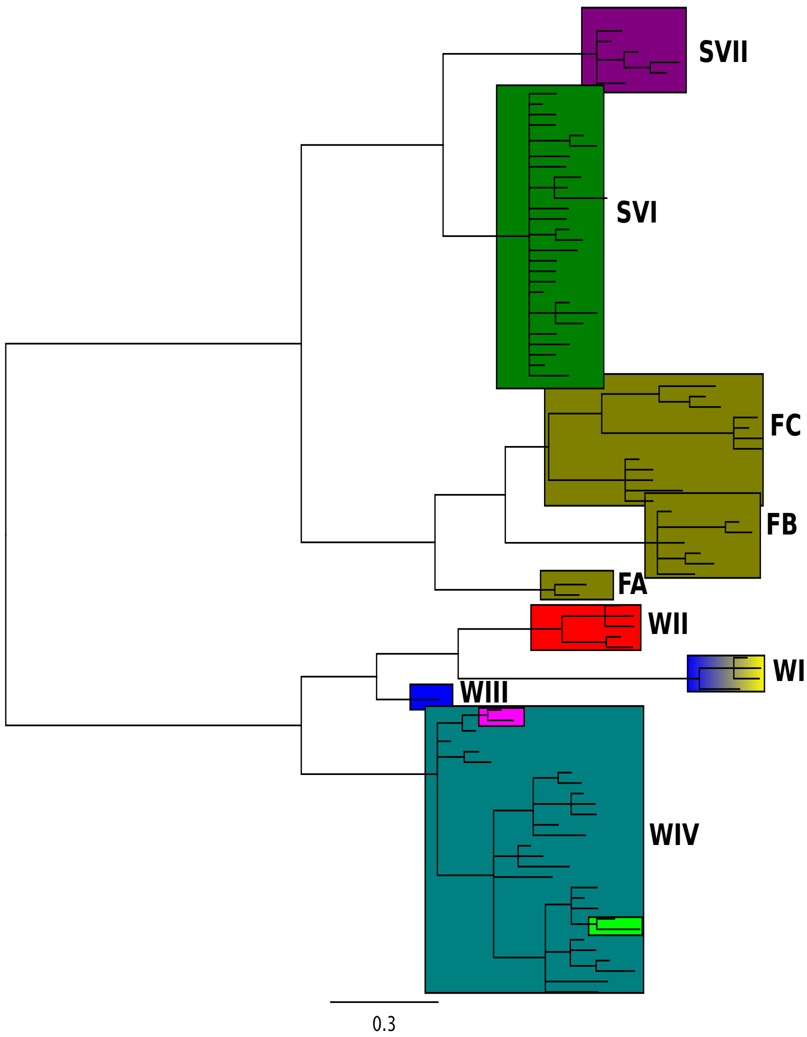


Figure 4.4: Phylogenetic tree of mtDNA CO1 gene sequences of the GAB spring endemic *Phreatomerus latipes*

Note that outgroups have been removed from the figure for illustrative purposes (Guzik et al. 2012).

Spring Complexes
- ■ Beresford Hill
- ■ Billa Kalina
- ■ Coward Springs
- ■ Francis Swamp
- ■ Hermit Hill
- ■ Lake Eyre South
- ■ Freeling
- ■ Neales River
- ■ Strangways
- ■ Wangianna

Colours represent geographic distribution and are based on the colours of spring complexes identified in Figure 4.2. Clade names represent the three major clades (N = northern; S = southern; W = widespread) and ESUs (I = Strangways/Francis; II = Freeling; III = Strangways-only; IV = Coward, Beresford, Southern Lake Eyre, Billa Kalina; V = Neales River; VI = Hermit Hill; VII = Wangianna).

Photo: Travis Gotch

Figure 4.5: *Trochidrobia* snails on a stromatolite at Blanche Cup (CBC001)

The stromatolite is approximately 20 mm in diameter.

to be high but should have been representative of the distribution throughout springs. Therefore, 5–20 individual samples were typically collected per spring and a subset of samples was sequenced (approximately five individuals per spring). At least one spring per group was sequenced. In situations where genetic diversity was high, an assessment was made on whether additional individuals were required. Each spring complex was generally represented by individual samples from all of the spring groups. It was attempted to have sequence data from five springs per group per complex but sometimes this was not possible due to the total number of springs in the complex; sometimes taxa were not present in all springs in all complexes (e.g. Beresford complex contains only two springs). The broad collection strategy, coupled with the nature of phylogenetic data (which is known to represent an historical time scale that eliminates present day stochasticity), accounts for not sampling at every spring.

4.1.7 Notes on methodology

The work presented here is based on analysis of multiple genes and markers as well as Allozyme Electrophoresis. Full details of the genes used and the methods are described in Murphy *et al.* (2009), Murphy *et al.* (2012) and Guzik *et al.* (2012).

4.2 Identifying genetic lineages in GAB spring endemics

4.2.1 *Phreatomerus latipes* isopods

The endemic phreatoicid isopod, *Phreatomerus latipes* (Figure 4.3), is one of the most distinctive crustacean species within the GAB springs and is considered widespread throughout the Lake Eyre Supergroup. Life history traits as a predictor of population genetic structure in such an obligate aquatic invertebrate suggest that *P. latipes* would demonstrate relatively strong population genetic structure (Wilson *et al*. 2009). It bears live young that are pouch-brooded with minimal dispersal ability (Wilson 2008) and in such a fragmented habitat is unlikely to move large distances in the absence of aquatic connections. This is especially the case because it is restricted to freshwater for respiration. A recent comparative phylogeography study of spring endemics from Lake Eyre Supergroup (Hermit Hill and Davenport) confirmed that *P. latipes* does not disperse great distances without aquatic connections (Murphy *et al*. 2010). They showed that the population genetic structure of *P. latipes* is strongly influenced by the arid landscape. In particular, for large geographic distances where spring stream connections are minimal, population genetic structure was strong. Overall, the observations indicate that *P. latipes* could be a likely model for testing cryptic species.

P. latipes was collected from as many of the GAB springs complexes located within the Lake Eyre Supergroup as possible. Individuals were sequenced for the mitochondrial (mt) DNA gene, Cytochrome Oxidase subunit 1 (CO1).

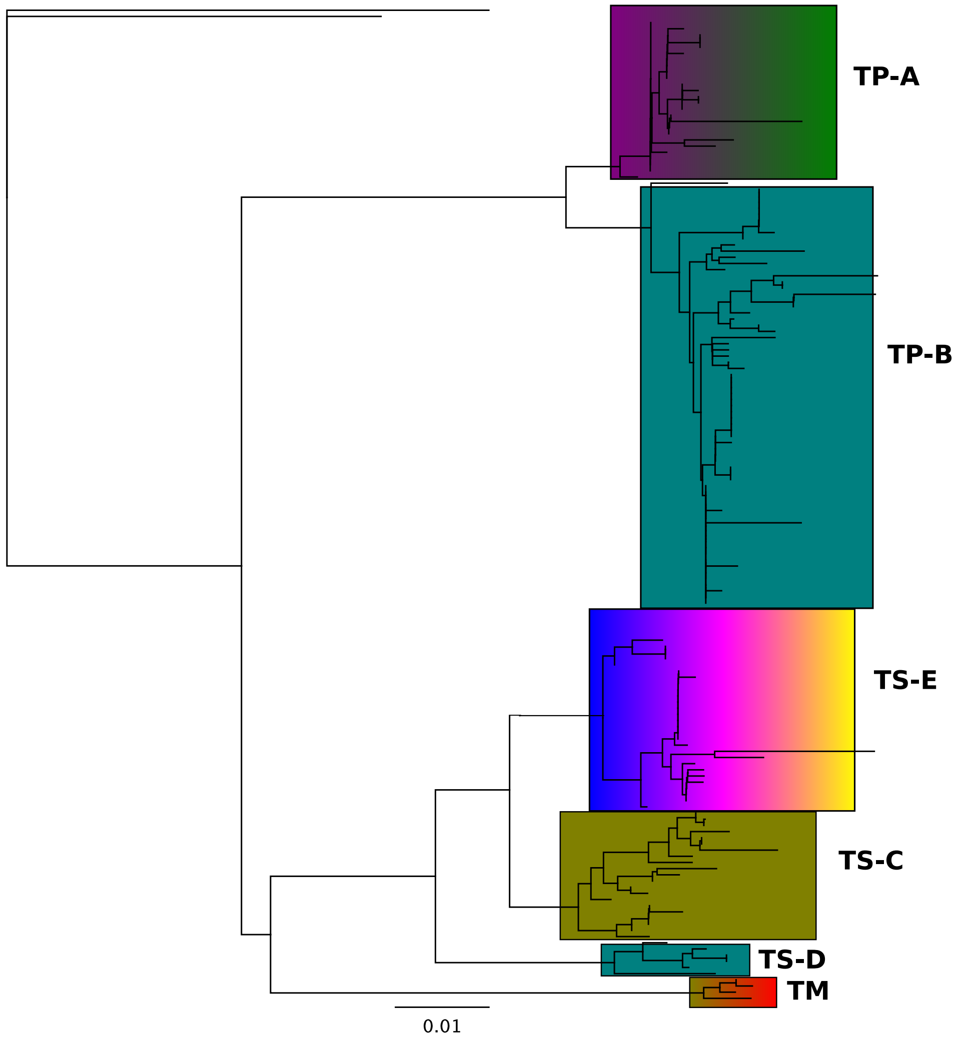


Figure 4.6: Phylogenetic tree of combined CO1, 28S and ITS gene sequences of the GAB spring endemic *Trochidrobia* species

Note that outgroups have been removed from the figure for illustrative purposes (Murphy *et al.* 2012).

Spring Complexes

- 🟥 Beresford Hill
- 🟦 Billa Kalina
- 🟦 Coward Springs
- 🟨 Francis Swamp
- 🟩 Hermit Hill
- 🟩 Lake Eyre South
- 🟥 Freeling
- 🟨 Neales River
- 🟦 Strangways
- 🟪 Wangianna

Colours represent geographic distribution and are based on the colours of spring complexes identified in Figure 4.2. Clade names represent the three *Trochidrobia* species (TM = *T. minuta*; TS = *T. smithi*; TP = *T. punicea*) and ESUs A–E.

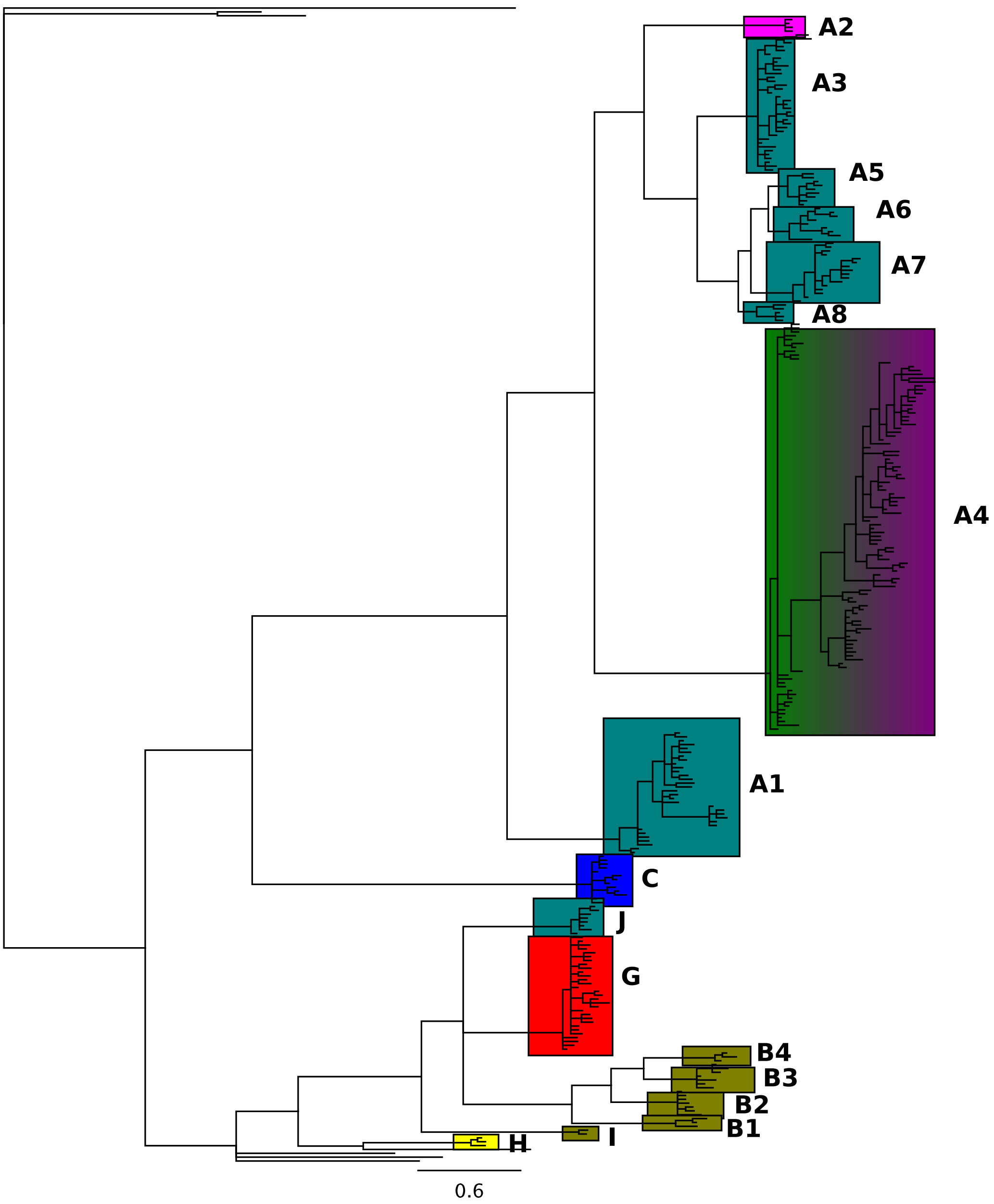
The phylogenetic analysis of CO1 sequences among *P. latipes* of the GAB springs revealed three major clades (N, S, W in Figure 4.4) and nine ESUs I–VII (three sub-clades within clade V, A–C (Neales River), shown in Figure 4.4). A number of these sub-clades correspond with the traditional geographical grouping at the spring complex level: I = Strangways/Francis; II = Freeling; III = Strangways-only; IV = Coward, Beresford, Lake Eyre South, Billa Kalina; V = Neales River; VI = Hermit Hill; VII = Wangianna. Geographically proximate

Figure 4.7: Phylogenetic tree of GAB springs chiltoniids for CO1 gene sequences

Note that outgroups have been removed from the figure for illustrative purposes (Murphy *et al* 2009).

Spring Complexes

- 🟪 Beresford Hill
- 🟦 Billa Kalina
- 🟦 Coward Springs
- 🟨 Francis Swamp
- 🟩 Hermit Hill
- 🟩 Lake Eyre South
- 🟥 Freeling
- 🟨 Neales River
- 🟦 Strangways
- 🟪 Wangianna



Colours represent geographic distribution and are based on the colours of spring complexes identified in Figure 4.2. Clade names represent lineages identified in Murphy *et al*. (2009).

springs typically either shared haplotypes (e.g. within V Neales River and VI Hermit Hill spring complexes clade) or were closely related but maintained substantial population genetic structure (e.g. IV (Coward)). Each of the mtDNA clades showed 2–15% divergence, with Hermit Hill and Neales River showing some of the highest genetic divergences when compared with other complexes. Interestingly, Neales River showed higher similarity and shared a more recent common ancestry with Hermit Hill and Wangianna (5–6%) than the geographically closer Freeling (13%). Freeling, in turn, showed least genetic divergence to the southern Strangways and Francis Swamp haplotypes (3–4%).

4.2.2 Discussion: Cryptic species evaluation

Cryptic species commonly comprise new short-range endemics (Harvey 2002). Their discovery can have a decided impact on conservation management strategies as it increases biodiversity (Harvey 2002; Bickford *et al*. 2006). Desert spring studies consistently demonstrate that invertebrate species diversity is greatly underestimated, e.g. spring snails (Ponder *et al*. 1995; Hurt 2004), amphipods (Murphy *et al*. 2009) and spiders (Gotch *et al*. 2008). Here, an iconic desert spring limited invertebrate is observed, historically considered a single panmictic population across all springs (Mitchell 1985) to comprise nine new ESUs of *Phreatomerus* (see Figure 4.4). These ESUs are conclusively reciprocally monophyletic mtDNA lineages with moderate sequence divergence (11–15%) (Lefébure *et al*. 2006b). Broadly, each of the ESUs corresponds to spring complexes (e.g. I Strangways/Francis, II Freeling, III Strangways-only, IV Coward (including Beresford, Lake Eyre South, Billa Kalina), V Neales River (three sub-clades), VI Wangianna and VII Hermit Hill); an historically arbitrary grouping of spatially close springs and their position relative to Lake Eyre, but which provides little information on geological or hydrogeological characteristics of springs. These results indicate an association between phylogeny and spatio-temporal structure of the landscape, lending support to the hypothesis that climatic history and the landscape has had a major impact on the evolutionary history of *Phreatomerus* lineages. Consistent with that, formally identified for wolf spiders (Gotch *et al*. 2008), snails, amphipods (Murphy *et al*. 2009) and general management regions for the GAB springs (SAALNRMB 2008).

Historically, *Phreatomerus latipes* distribution was assumed to extend throughout the Lake Eyre Supergroup and the species was originally described from both Coward Springs and the now heavily modified Hergott Springs (approximately 65 km apart). The results indicate cryptic species level divergences at similar geographic distances as that seen between Hergott and Coward, and it is unclear to which of the new lineages the original *P. latipes* would have belonged, if at all. Therefore, based on the current results, the authors consider *P. latipes* from Hergott Springs to have gone extinct along with its type locality and it is unlikely that this was the same cryptic species as that of Coward. Based on DNA and morphology, the latter type locality is the appropriate for *P. latipes* in the strict sense. ESUs identified here are relevant to any conservation plan due to the lack of present day migration between them (Section 4.3).

4.2.3 *Trochidrobia* snails

Hydrobiid spring snails are found throughout the GAB springs and have been formally described taxonomically by Ponder *et al*. (1989) (see Figure 4.5). The genus *Trochidrobia* is a very small obligate aquatic group endemic to the Lake Eyre GAB springs. Four species are currently known within this genus, *T. punicea, T. smithi, T. minuta* and *T. inflata*. Two of these species (*T. punicea* and *T. smithi*) are widespread across spring complexes, spanning Lake Eyre drainages, *Trochidrobia minuta* is found in springs in the Freeling and Neales River Complexes while *Trochidrobia inflata* is only found at two spring groups in the Freeling Springs Complex (Ponder *et al.* 1989; Gotch 2005). Previous allozyme analyses undertaken by Ponder *et al*. (1995) demonstrated that the two widespread species are genetically divergent across spring complexes, indicating that diversification within species has occurred.

DNA sequences from three genes (mtDNA gene COI, and two ribosomal (r) DNA genes 28S and ITS) were generated from the 156 *Trochodrobia* individuals examined in this study. Analyses of both the combined data set and the extended COI data set showed a consistent pattern of lineage divergence within and amongst the *Trochidrobia* species examined (Figure 4.6). Given the greater level of divergence found in COI, compared with the two rDNA genes, the COI tree resolved relationships within species much more clearly where 2–3 new ESUs are seen in *T. smithi* and *T. punicea*. The strong geographic clustering of genetic lineages suggests that the surrounding landscape has played a large role in the historic distribution and maintenance of genetic diversity in *Trochidrobia*. These results confirm the findings of Ponder *et al*.(1995) and are strikingly similar to phylogenetic studies undertaken on other GAB spring crustacean groups, including Murphy *et al*. (2009), and on desert spring systems in general such as Meffe and Vrijenhoek (1988) and Seidel *et al*. (2010).

4.2.4 Amphipods

The chiltoniids are highly diverse within and between spring groups; with restricted distributions of diverse genetic lineages, even among neighbouring springs. Details of this work are partly published in Murphy *et al*. (2009) and some unpublished data shown here in Figure 4.7. Subsequent research led to the taxonomic description of two new GAB springs endemic genera and species from Lake Eyre Supergroup *Arabunnachiltonia murphyi* (Clade C in Murphy *et al*. (2009)) and *Wangiannachiltonia guzikae* (Clade 4c in Murphy *et al*. (2009)) (King 2009). There are additional cryptic amphipod species awaiting description.

4.3 Comparison of new short-range endemics amongst GAB springs

In the first part of this report (Section 4.2) phylogeographic results of two exemplar taxa were described (*Phreatomerus* and *Trochidrobia*). However, substantial additional results for other GAB springs endemics (chiltoniids and *Ngarawa*) were also collected with funding from the Australian Research Council (Linkage and Discovery grants awarded to N. Murphy and A. Austin of The University of Adelaide at the time of the research). Therefore, the second part of this report collates all available data available, including that of Ponder *et al*. (1995) for *Fonscochlea*, to compare data for ESUs. The aim of collating this information was to inform on the distribution of new ESUs that were observed and to assess the vulnerability of spring complexes, groups and individual springs. Vulnerability is defined here as springs/groups/complexes with high numbers of endemic ESUs that are vulnerable to risk factors such as drawdown. The information has been collated in two tables in order to:

- identify the diversity of ESUs in spring groups and complexes (Appendix 2)
- identify the vulnerability of spring complexes based on the presence or absence of ESUs in each spring group and complex (Appendix 3).

Vulnerability is highlighted in these tables with a colour-coding system where red indicates high ESU diversity and orange indicates moderately high ESU diversity at the two geographic levels (spring complex and group).

4.3.1 Evolutionarily significant units

In systems where extinction through anthropogenic impacts is an imminent issue, understanding the phylogeographic structure

Photo: Travis Gotch

of the system serves to identify levels of genetic diversity for the purpose of future conservation. A case is emerging for a number of distinct phylogeographic management units throughout the Lake Eyre Supergroup that aim to conserve both ESUs and springs that have a shared phylogeographic history (Ponder *et al*. 1995; Gotch *et al*. 2008; Worthington Wilmer *et al*. 2008; Murphy *et al*. 2010). Extinction and reactivation of springs is a naturally occurring phenomenon but extraction from the GAB has reduced the flow of many Lake Eyre Supergroup springs. For conservation purposes, identification of new genetic diversity signifies an increase in biodiversity. Further to this, similarities in the distribution of ESUs across broad geographic regions can prevent micro-management of individual springs (as is current practice) and can permit large-scale preservation of bioregions with some flexibility for stochastic habitat loss.

The criteria for defining an ESU were a reciprocally monophyletic clade of individuals that do not show any evidence of gene exchange with other ESUs. Typically within a taxon group, individuals of an ESU were geographically isolated but occasionally ranges were shared and in the absence of gene flow this suggested sympatry. The current research identifies a total of 42 new ESUs amongst 31 spring groups and across all five aquatic invertebrate taxon groups: chiltoniid (17), *Phreatomerus* (9), *Trochidrobia* (6), *Ngarawa* (9), *Fonscochlea* (15) (see Appendix 2). Between taxon groups, there was a great deal of diversity in the distributions of ESUs, from a restricted distribution of a single-spring group, e.g. *Phreatomerus*, ESU B3 (spring group NMI) and chiltoniid, ESU A7 (spring group CJS, see Appendix 3) to a maximum distribution of two adjoining spring complexes (e.g. *Fonscochlea*, FAq1 at Beresford and Coward). Generally though, each individual ESU corresponds to the spring complex grouping (see Appendices 2 and 3). Based on these results, a clear view is being formed that the springs can be broken up into geographic regions that harbour suites of genetically distinct short-range endemics from a number of taxon groups. These can be used as management units.

It is possible that the number and distribution of ESUs is underestimated given the number of springs actually sampled compared with the number that exist throughout the region. However, the sampling regime was designed to maximise coverage of the springs for the genetic data. Furthermore, genetic data by nature is a temporal representation of genetic change (e.g. mutation) that accumulates over time and, if sampled comprehensively, reflects gene flow for the entire population. For this reason, the authors are confident, and make the assumption that the ESUs observed represent the majority of genetic diversity throughout the Lake Eyre Supergroup. The authors are also confident that the geographic extent of the supergroup and all spring complexes and groups was well covered. Therefore, the term ESU distributional limit is herein used as a way of defining the geographical extent of an ESU. This term can reflect a number of different geographical scales, from individual spring groups, spring complexes, to multiple spring complexes. This term also highlights that the distribution of individuals that comprise an ESU are largely restricted to the locations that in which they were observed. Whilst it is possible that unsampled ESUs and geographically widespread ESUs might exist, they are likely to be very rare.

4.3.2 Genetic diversity and dispersal between springs

Genetic diversity is the accumulation of mutations over time and can increase between populations when barriers to gene flow and/or dispersal are present. As mentioned earlier, by definition there is no evidence of gene flow between ESUs. Interestingly, within ESUs the genetic diversity and divergences amongst spring groups and complexes was generally very high. Indicative of population genetic structure and minimal to absent gene flow between geographically isolated springs, such results suggest probable allopatry induced by the landscape. The ESUs found in the Coward and Hermit Hill regions were used as an example of the levels of migration and gene flow in *Phreatomerus* and the impact that landscape structure can have on genetic diversity within a spring complex. High gene flow was observed between all spring groups in ESU VI at Hermit Hill complex and low to absent gene flow between spring groups in ESU IV (Coward, Beresford, Lake Eyre South, Billa Kalina). These results suggest that movement among the geographically close and low-lying spring groups at Hermit Hill by *Phreatomerus* must be relatively easy and facilitates gene flow. Conversely, the highly structured landscape between the spring complexes and groups in the Coward region generally has substantial geographic barriers to gene flow in the region, which also promotes genetic differentiation. Interestingly, as a taxon group comparison, the amphipods showed that present-day gene flow between spring groups was low to absent in the Hermit Hill Spring Complex (Murphy *et al*. 2010).

Based on the findings, it seems very likely that most aquatic invertebrate endemics without a dispersive lifestyle (e.g. *Phreatomerus*, chiltoniids and snails) rarely migrate or re-colonise geographically distant springs. It may also be possible that rapid changes in water chemistry could have serious consequences to GAB spring endemic fauna (Gotch pers. obs.). The short range endemism displayed in these groups may be influenced by the variety of physico-chemical conditions encountered across the study, making it possible that conditions differ between regions enough that survival of translocated species could be compromised.

4.4 Discussion

4.4.1 Vulnerability and conservation implications

Collation of the data on ESUs and their presence or absence throughout the Lake Eyre Supergroup (see Appendices 2 and 3) has revealed three key points:

- First, spring groups and complexes are the most robust level of management. Whilst more detailed research is required to adequately assess gene flow and stochasticity between springs within a group, especially in the Neales Spring Complex, there has been general observation that intra-spring group generic variation is too high for a general model of spring management.
- Second, a large number of ESUs are vulnerable, restricted to single spring groups (e.g. 11 chiltoniids, 1 *Phreatomerus*, 1 *Trochidrobia*, 3 *Ngarawa*, shown in Appendix 3).
- Finally, there are many spring groups that are vulnerable due to the high number of short-range endemic ESUs that they harbour (see Appendix 2).

Overall, major biogeographic patterns that are equivalent to the spring complex level generally overlap amongst taxon groups. However, there are also many differences, suggesting that a single rule for biogeographic units cannot be applied to all taxa. The current results provide an easy to read representation of ESU diversity throughout springs and locations of high vulnerability. Such information can be used to make general vulnerability risk assessments of spring groups and/or spring complexes.

4.4.2 Management scales

A number of spatial levels will be important for spring management, especially the spring complex and spring group. Spring complexes encompass major geographic regions that broadly represent the distributional limits of ESUs. However, such a broad grouping does not account for the known levels of ESU diversity among all of the taxon groups. Therefore, spring groups have also been identified as a fine-scale representation of genetic diversity without the stochasticity that individual spring inherently have. The distribution of ESUs across spring complexes and groups has been identified in Appendix 2 and 3. These tables highlight locations of highest vulnerability to disturbance (indicated by orange and red colouring). It has been established that most of the endemic aquatic invertebrate taxon groups comprise short-range endemic ESUs, and that the geographic range they occupy can be as small as a single spring group or as large as a spring complex. Further to this, single spring groups can harbour up to nine ESUs (e.g. HDB and WDS). This report recommends that, in risk assessments, conservation of as much as possible of the biodiversity that is available within the system be preserved—especially genetic diversity.

5

Flora of the GAB springs: Ecology of GAB vegetation

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5. Flora of the GAB springs: Ecology of GAB vegetation

5.1 Background

The Great Artesian Basin (GAB) springs support wetland plants, many of which are not found elsewhere in the arid zone. The wetland area supported by individual springs in South Australia is typically less than 100 m^2, although some springs in the Lake Eyre Supergroup support wetlands that cover several hectares (supported by data from this study). Seven threatened plant species occur on the springs across the GAB, including the nationally endangered Salt Pipewort (*Eriocaulon carsonii* ssp. *carsonii*),which is only found on the GAB springs (Davies *et al*. 2007a). The GAB spring populations of three plants (*Baumea juncea*, *Gahnia trifida* and *Utricularia dichotoma*) are also of biogeographic interest as they represent major disjunctions from their typical habitat in temperate coastal wetlands (Harris 1992). Plant species richness at GAB springs tends to decrease from east to west across the GAB, with greatest species diversity within the eastern recharge zone, and decreasing diversity westward to Lake Eyre as the habitat surrounding the GAB springs becomes increasingly arid (Fensham, unpublished data).

Artificial bore drains and GAB springs support a number of wetland plant species otherwise rare in the arid region, however species that occur at bore drains are largely distinct from the spring flora (Badman 1999) and there are few examples of these habitats being colonised by plants endemic to spring wetlands (Fensham *et al*. 2008). Using Badman (1995 & 1999) and Fatchen and Fatchen (1993) as a guide, several species found predominantly on GAB springs were identified for a focus study group. The other group of wetland species examined contain species that can be found on GAB springs and in other wetland environments in the region.

Vegetation communities at individual springs can be highly dynamic. For example, several focus group species were observed to colonise or become locally extinct at individual springs between 1983 and 1992 (Fatchen & Fatchen 1993). Bore-drain Sedge (*Cyperus laevigatus*) is often the first coloniser of GAB springs (Fensham *et al*. 2004), but there does not appear to be a clear pattern of succession at GAB springs in central Australia (Fatchen & Fatchen 1993). Rather, species will opportunistically colonise available habitat created by the formation of new springs, the shifting position of spring tails or removal of vegetation by grazing.

Photograph on facing page: Travis Gotch

5.1.1 Threats to GAB spring-dependent flora

Vegetation at GAB spring wetlands faces a number of threats, the foremost among these being reduced spring flow due to drawdown of the aquifer (Fensham *et al*. 2008). Drawdown has apparently caused the endangered GAB spring endemic *E. carsonii* to become extinct from its type locality at Wee Watta Springs in New South Wales (Chambers *et al*. 2003).

Domestic, feral and native animals can severely impact GAB spring vegetation by grazing, rooting and trampling. Grazing impacts have been managed at several springs and spring groups by fencing to exclude stock. However, removal of stock has been followed by the proliferation of Common Reed (*Phragmites australis*) at some springs and a decline in other focus group species, including *E. carsonii*, which declined in abundance in the Hermit Hill Spring Group following erection of fences in the 1980s (Fatchen & Fatchen 1993; Davies *et al*. 2010).

Exotic plant species can adversely impact spring vegetation by competing for resources or excluding other species from the wetland habitat. Ponded pasture grass species *Urochloa mutica* and *Hymenachne amplexicaulis* are established at springs in the Barcaldine supergroup in Queensland (Fensham *et al*. 2008). A program to remove Date Palms (*Phoenix dactylifera*) at Dalhousie Springs has resulted in a significant return in water availability to other plants (see Chapter 8).

5.1.2 Aims

Given the nature of the threats to spring vegetation outlined above and the frequently small and isolated nature of plant populations at GAB springs, the aims of the research were to provide a better understanding of:

1. the roles of biotic and hydrological parameters in determining vegetation patterns at GAB springs
2. connectivity of plant populations between springs, spring groups and coastal wetlands
3. appropriate management units and priority sites for conservation.

The first aim is addressed by using vegetation and environmental data from over 1000 springs in the Lake Eyre and Lake Frome supergroups to identify environmental determinants of vegetation patterns at GAB springs. The second and third aims are addressed by exploring the genetic structure of GAB spring and coastal wetland populations of the sedges *Gahnia trifida* and *Baumea juncea*, and comparing the results with previous work on *E. carsonii*. Overall, the aim is to provide a better understanding of the nature and ecology of vegetation at GAB spring wetlands in order to guide appropriate management of these endangered ecosystems.

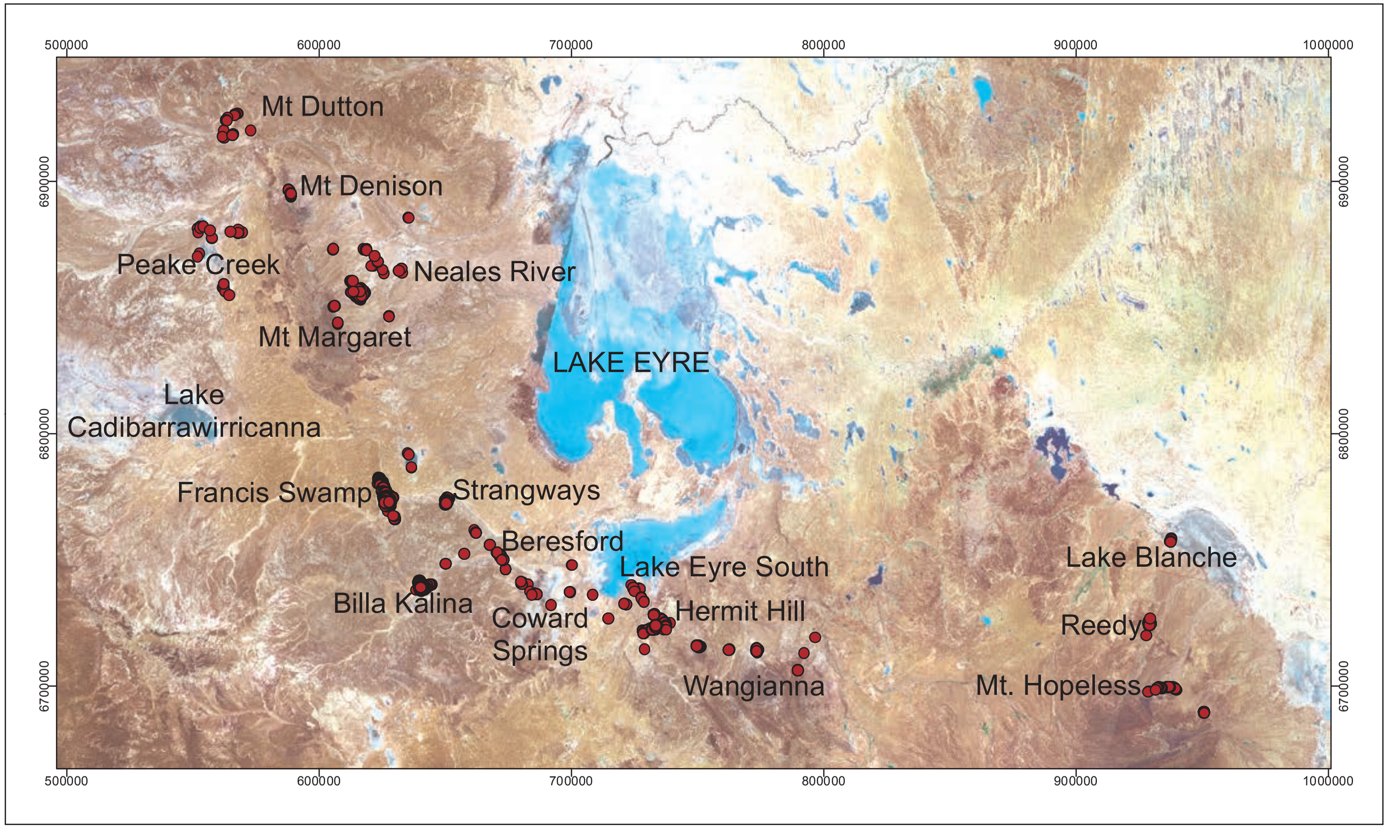


Figure 5.1: Study area and location of spring complexes used in this study

Legend

● Springs

Background image: Landsat 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: January 2012

5.2 Environmental determinants of vegetation at GAB springs

Plant communities at GAB springs in central Australia vary in species richness, composition and relative abundance of each species. Spring water salinity and other environmental parameters also differ between springs. Spring water chemistry is influenced locally by geological factors as well as mixing with shallow saline aquifers and on a broader scale by the different water sources for the GAB. Historically, recharge has occurred anywhere where the aquifer has outcropped to the surface. In recent times (circa the last 35 000 years), recharge into the GAB has been limited mainly along the eastern margins and to a lesser extent in the northern portion of the western margin around the Finke River (for more detail, see Volume I: Hydrogeological Framework of the Western Great Artesian Basin (Keppel *et al.* 2013) and Volume II: Groundwater Recharge, Hydrodynamics and Hydrochemistry of the Western Great Artesian Basin (Love *et al.* 2013a). There are several sub-basins within the western margin of the GAB; this is most readily observed with the springs to the east of Blanche Cup in the Coward Spring Complex (Figure 5.1) tending to have higher levels of bicarbonate, whereas those to the north-west have higher levels of sulfate (Habermehl 1982; Fatchen & Fatchen 1993). Anecdotal evidence suggests different plant communities may also correspond with this division, for example Badman (1999) suggests *Phragmites australis* is dominant to the east, whereas the bulrush *Typha domingensisis* is more frequent to the north-west and at bore drains.

Grazing by domestic, feral and native animals can also influence the composition of plant communities at GAB springs. Prior to the 1980s, the vast majority of South Australian GAB springs were subject to grazing on pastoral leases, though fencing has subsequently been employed to exclude stock from many springs. However, local extinctions as a result of competition with other species, particularly *Phragmites*, have been recorded at South Australian GAB springs, often following the removal of stock (Fatchen & Fatchen 1993; Davies *et al*. 2010).

The lack of knowledge regarding the determinants of vegetation patterns at South Australian GAB springs creates difficulties for those seeking to achieve specific management outcomes, such as prioritising conservation needs, maintaining flows, maximising plant species richness or increasing the abundance of rare species such as *E. carsonii*. In order to assist in the development of effective management strategies for GAB and other spring wetland ecosystems, vegetation and water chemistry data was analysed for 1127 GAB springs in the Lake Eyre and Lake Frome supergroups (Niejalke unpublished data), in combination with data on flow rate and stock impact, to examine how variation in environmental variables affects the diversity and abundance of the focus group flora and other wetland plant species. Statistical modelling (ordination, correlation and ordinal regression analyses) was used to investigate associations of species abundance and richness with water pH, specific conductivity, spring flow rate, stock impact, wetland area and the number of active vents in a spring group.

5.2.1 Methods

Study site and data collection

Vegetation, water chemistry, flow rate and stock impact data were collected for 1127 springs over 16 spring complexes between 1995 and 2005, including Mt Margaret (8 springs surveyed), Beresford Hill (3), Coward (78), Mt Denison (27), Francis Swamp (43), Hermit Hill (294), Billa Kalina (33), Lake Eyre South (14), Neales River (89), Mt Hopeless (468), Peake Creek (12), Lake Blanche (10), Strangways (13), Mt Dutton (12), Wangianna (20) and Lake Cadibarrawirracanna (3) spring complexes, as

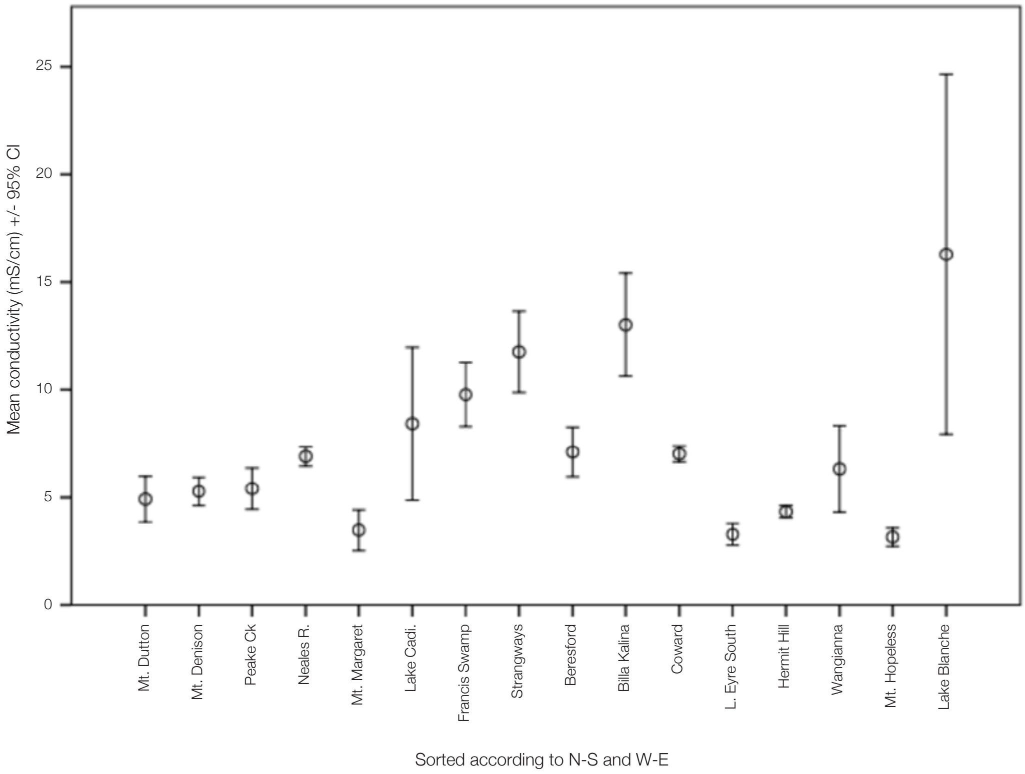


Figure 5.2: Error bar plots of spring water conductivities at 16 South Australian GAB spring complexes

Complexes are listed in order from most north-westerly to most easterly.

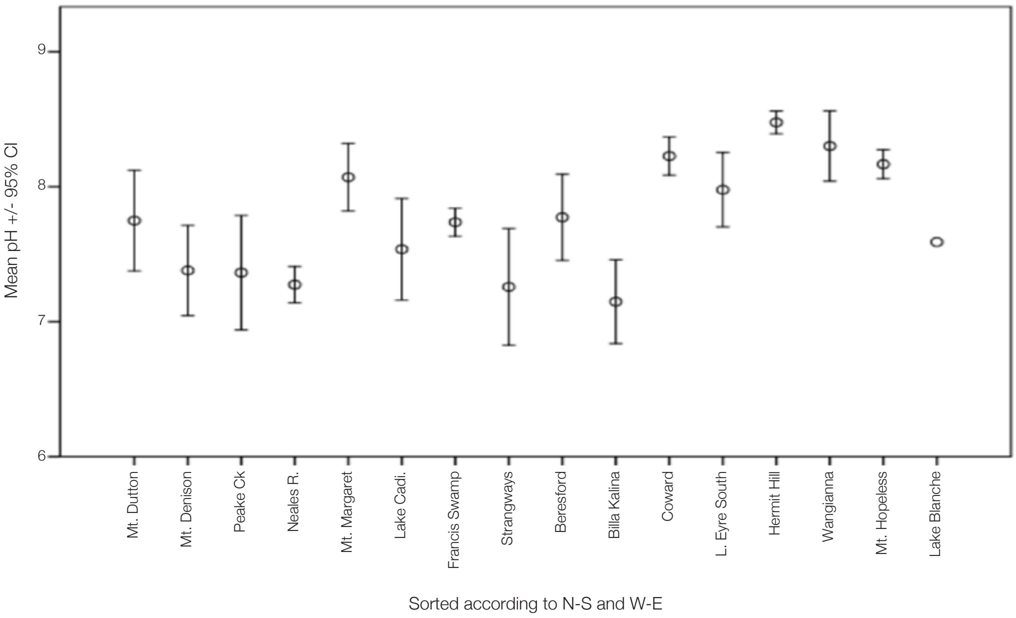
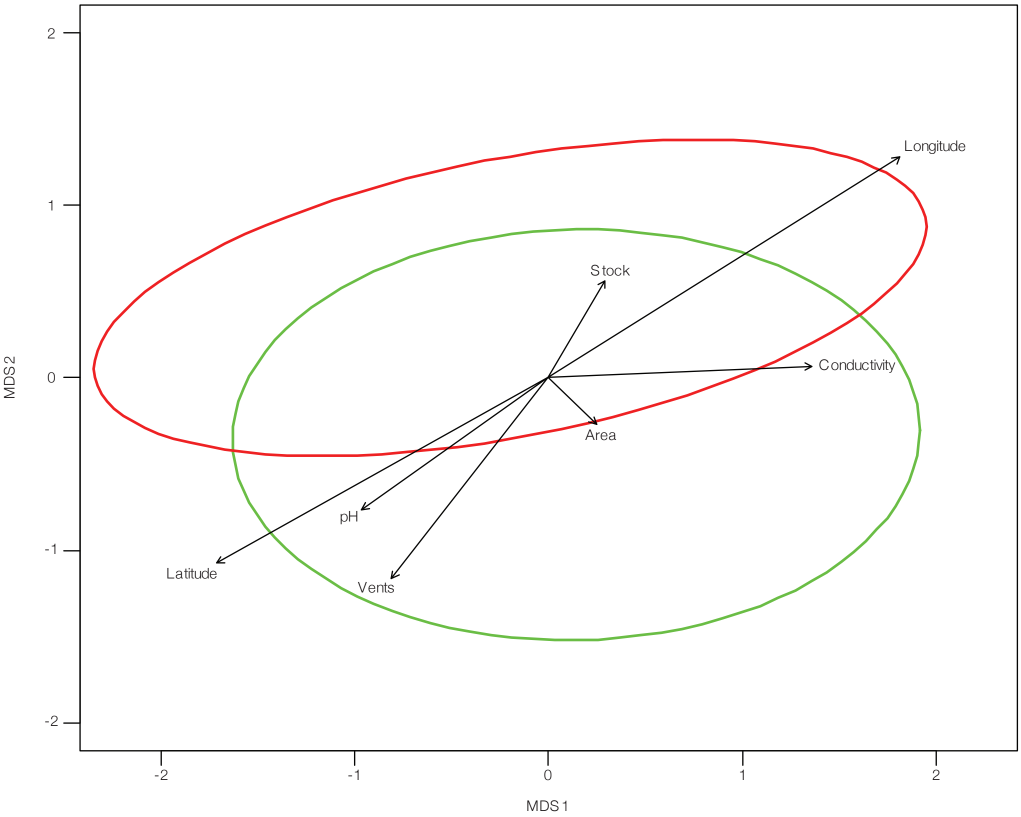


Figure 5.3: Error bar plots of spring water pH at 16 South Australian GAB spring complexes

Complexes are listed in order from most north-westerly to most easterly.

Figure 5.4: NMDS ordination of 458 GAB springs using abundance data for 18 plant species (stress = 0.185).

Green and red ellipses represent 95% confidence ellipsoids around springs at which focus group taxa were present and absent, respectively.



shown in Figure 5.1. Annual precipitation in the region is low (approximately 120 mm per year), thus the vegetation at these springs is almost entirely dependent on groundwater. Flow rate and stock impact were recorded as ranks and scored as follows; flow: 1 = spring inactive (no wetland vegetation present); 2 = damp (wetland vegetation present); 3 = soil saturated; 4 = surface water present; 5 = flowing surface water in spring 'tail': stock impact: 1 = nil; 2 = pugged; 3 = lightly grazed; 4 = lightly grazed and pugged; 5 = grazed and pugged.

Statistical analysis

Ordinations were performed separately using two sets of species abundance data—one including only the focus group flora (*Eriocaulon carsonii*, *Phragmites australis*, *Gahnia trifida*, *Juncus kraussii*, *Samolus repens*, *Sporobolus virginicus*, *Baumea juncea* and *Utricularia dichotoma*), and one with all plant species recorded at the springs. Species were excluded from the ordination analysis if they were recorded on 1% or less of the 1127 springs.

The effects of different environmental variables on the positioning of species in the ordinations were examined, and the latitude and longitude of springs were included in these analyses to investigate the effect of geographical position on floristic composition. Ordinations were performed using the R statistical package (Oksanen *et al*. 2009; R Development Core Team 2009).

Associations between individual environmental variables and the abundance of individual species, the number of focus group species or the number of plant species present at springs or spring groups were explored with Spearman's rank correlations calculated using PASW Statistics 18.0. Further analyses were undertaken using mixed-effects ordinal regression models to explore the relationship between the abundance of plant species and various sets of the measured environmental variables. The latter analyses allow for correlations among environmental variables and they also model the variability among spring groups. Correlations between the abundance of particular species and environmental variables were restricted to data from complexes in which those species were present, assuming that if a species is present in a spring complex, it is capable of colonising any of the springs in that complex if conditions are suitable.

5.2.2 Results

Environmental data and species distributions

Spring wetlands are typically small, with a median size of 79 m^2 for springs in this study. The total number of active vents in a spring group ranged from one (for 18 spring groups) to 234 (Reedy Springs, Mt Hopeless). Specific conductivity of spring water ranged from 0.2 mS/cm to 33 mS/cm (with an outlier of 100.1 mS/cm at a spring in the Mt Hopeless spring complex). Spring complexes between Lake Cadibarrawirracanna and Coward tended to exhibit the highest conductivity, with the exception of Lake Blanche (median conductivity 15.2 mS/cm), as shown in Figure 5.2.

The pH of spring water varied from 3.90 to 10.83, with plants present across the complete range of pH values. Spring complexes to the east of and including Coward Springs had median pH values exceeding 8, with the exception of Lake Eyre South and Lake Blanche, whereas those to the northwest of Coward, except Mt Margaret, had lower pH values (Figure 5.3).

The sedge *Baumea arthrophylla* had the most restricted distribution of the focus group taxa, and was present only at 12 springs in the Mt Denison spring complex. Sea Club-rush (*Bolboschoenus caldwelli*) was the most restricted of the other wetland taxa, present at five springs across four spring complexes. *Phragmites australis* and *Cyperus laevigatus* were the most widespread focus group and other wetland species, respectively. *Cyperus laevigatus* was also the most common plant species on springs that had only a single plant species present. The introduced taxa *Cotula coronopifolia* and *Polypogon monspeliensis* were present on between 11 and 21 springs at four to seven complexes.

Multivariate analyses of differences among springs

The ordination dataset for all plant species included 18 species (or species groups) across 458 springs. The ordination indicated that springs supporting the focus group flora did not cluster completely separately from springs without any of the focus group flora (Figure 5.4). Latitude and longitude explained the largest proportions of variation in the ordination, indicating the importance of geographic position in determining vegetation patterns at these springs. *Utricularia dichotoma* and *Eriocaulon carsonii* were associated with low-conductivity springs in the eastern spring groups. The remainder of the focus group flora were associated with springs with low stock impact, whereas the majority of the other wetland taxa were associated with stocked springs (Figure 5.4).

Influence of environmental variables on species abundance

Conductivity

Non-parametric correlation analysis revealed that associations between conductivity and abundance of individual species varied amongst the focus group taxa (Table 5.2). A strong negative association was found between spring water conductivity and abundance of *E. carsonii* and *U. dichotoma* in spring complexes where they were present. Indeed, these species were not present on springs where conductivity exceeded 5 mS/cm (Table 5.1). A similarly negative association with conductivity was observed for *B. juncea*. In the ordinal multiple regressions, the latter three species again showed significant negative associations with conductivity, and for *E. carsonii* and *U. dichotoma*, conductivity was the sole independent variable in the final regression model of their abundance on spring vents (Table 5.3).

Table 5.1: Ranges of conductivity (mS/cm) and pH on springs occupied by focus group and other wetland plant species

Species	Conductivity			pH		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Focus group flora						
Eriocaulon carsonii	1.26	2.08	4.87	6.80	8.20	9.62
Phragmites australis	1.50	4.25	33.00	3.90	8.23	10.83
Baumea arthrophylla	3.63	4.49	8.79	6.94	7.15	8.02
Baumea juncea	2.66	3.73	11.51	6.92	8.67	10.05
Gahnia trifida	2.71	4.04	11.51	6.73	8.54	9.84
Utricularia dichotoma	1.40	1.81	3.24	6.80	8.08	9.20
Juncus krausii	2.86	7.14	24.30	6.21	7.66	9.53
Samolus repens	2.85	8.12	27.40	6.17	7.65	8.64
Sporobolus virginicus	1.26	4.72	28.40	5.75	7.92	10.05
Other wetland flora						
Bolboschoenus caldwellii	4.37	4.77	6.65	7.00	7.63	7.74
Chara spp.	3.88	8.29	22.00	6.67	7.43	8.17
Cyperus gymnocaulis	1.82	6.84	21.66	3.90	7.44	8.90
Cyperus laevigatus	0.19	4.11	100.10	4.40	8.04	10.83
Filamentous algae	0.19	3.28	100.10	6.80	8.20	9.93
Fimbristylis spp.	1.39	3.60	10.88	7.00	8.52	10.83
Polypogon monspeliensis	3.31	6.27	27.40	6.67	7.13	8.29
Samphire spp.	6.25	10.03	33.00	5.75	7.69	8.94
Schoenoplectus spp.	1.94	8.77	19.66	6.73	7.64	8.31
Spergularia spp.	2.53	7.94	15.20	6.40	7.58	9.32
Typha domingensis	0.19	4.62	12.50	4.40	7.63	8.72

Table 5.2: Signs of statistically significant Spearman rank correlations between environmental variables and the abundance of focus group and other wetland plant species at South Australian GAB springs

Focus group flora	Conductivity	pH	Flow	Stock
Eriocaulon carsonii	-	0	+	+
Phragmites australis	0	+	+	-
Baumea juncea	-	+	+	-
Gahnia trifida	+	+	+	-
Utricularia dichotoma	-	0	+	+
Juncus krausii	+	-	+	0
Samolus repens	+	0	+	0
Sporobolus virginicus	+	0	+	-
Other wetland flora				
Chara spp.	0	0	0	0
Cyperus gymnocaulis	+	-	+	+
Cyperus laevigatus	-	-	+	+
Filamentous algae	-	+	+	0
Fimbristylis spp.	0	+	+	-
Samphire spp.	+	-	-	+
Spergularia spp.	+	-	0	+
Typha domingensis	0	-	+	+

Zeroes indicate non-significant correlations. Plant species occurring at fewer than 25 springs were not included.

Table 5.3: Direction of effect of ordinal multiple regression coefficients measuring association between environmental variables with the abundance of focus group and other wetland plant species at South Australian GAB springs

Focus group flora	Conductivity	pH	Flow	Stock
Eriocaulon carsonii	-			
Phragmites australis			+	-
Baumea juncea	-	+		
Baumea arthrophylla				
Gahnia trifida		+		
Utricularia dichotoma	-			
Juncus krausii			-	-
Samolus repens			+	-
Sporobolus virginicus	+			-
Other wetland flora				
Bolboschoenus caldwelli				
Chara spp.				
Cyperus gymnocaulis	-			
Cyperus laevigatus	-	-		
Filamentous algae				
Fimbristylis spp.	-	+	-	
Polypogon monspeliensis				
Samphire spp.	+			+
Schoenoplectus spp.				
Spergularia spp.				+
Typha domingensis		-		+

Blanks under particular environmental values indicate that variable was not included in the final predictive model for that plant taxon.

Table 5.4: Species richness and species present in each spring complex

Spring complex	*Eriocaulon* *	*Phragmites* *	*B. juncea* *	*B. arthrophylla*	*Gahnia* *	*Utricularia* *	*Juncus* *	*Samolus*	*Sporobolus* *	*Bolboschoenus*	*Chara* spp.	*Cotula*	*C. gymnocaulos*	*C. laevigatus*	*Filamentous algae*	*Fimbristylis* spp.	*Polypogon*	*Samphire* spp.	*Schoenoplectus* spp.	*Spergularia* spp.	*Typha*
Mt Dutton		x									x		x	x	x		x				x
Mt Denison		x	x	x	x		x	x	x	x	x		x	x			x			x	x
Peake Creek		x						x	x	x	x	x	x	x	x		x				x
Neales River		x			x		x	x	x	x	x	x	x	x	x		x	x		x	x
Mt Margaret													x	x	x					x	x
Lake Cadi.		x							x					x	x			x	x		x
Francis Swamp		x	x		x		x	x	x			x	x	x	x		x	x	x	x	x
Strangways					x		x	x	x					x				x	x		
Beresford Hill		x						x		x				x	x			x	x		
Billa Kalina		x					x	x	x		x	x	x	x			x	x	x	x	x
Coward		x	x				x	x	x				x	x					x		
Lake Eyre South	x	x							x					x	x						x
Hermit Hill	x	x	x		x		x		x					x	x	X		x		x	x
Wangianna		x							x					x				x			
Mt Hopeless	x	x			x	x	x	x	x				x	x	x	X			x		x
Lake Blanche								x			x				x		x	x		x	

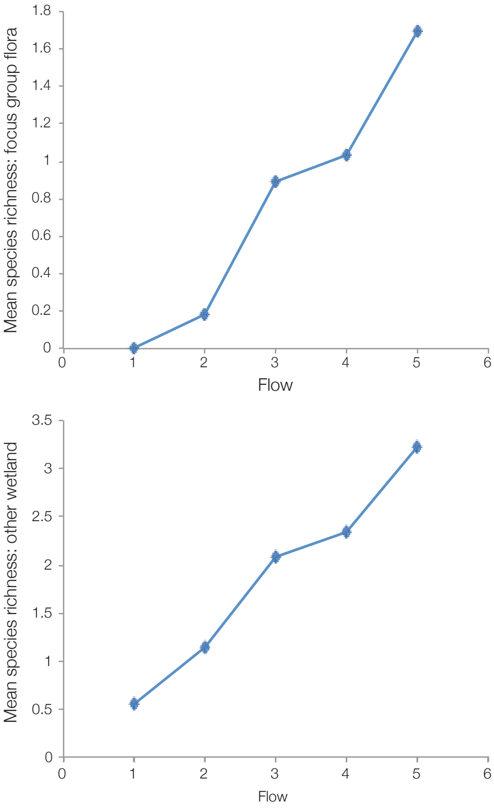
* Focus group species

Table 5.5: Signs of significant correlations of environmental variables with the number of focus group and other wetland plant species recorded at a spring

Environmental variable	Focus group flora		All species	
	Coefficient	P	Coefficient	P
Conductivity			-	
pH	+		+	
Flow	+		+	
Stock	-		-	
Number of active vents (richness by spring group)	+		+	

Four species, *Phragmites australis*, *S. repens*, *J. kraussii* and *S. virginicus,* were present at a much wider range of conductivities than the other focus group species, and for three of these there was a significant positive association between conductivity and abundance (Table 5.2). In the ordinal regression models, the focus group species that occurred across a wide range of spring groups did not have conductivity as a significant predictor, except for *S. virginicus* which was more abundant on springs with higher conductivities (Table 5.3).

Figure 5.5: Influence of flow rate on plant and focus group species richness at all springs



pH

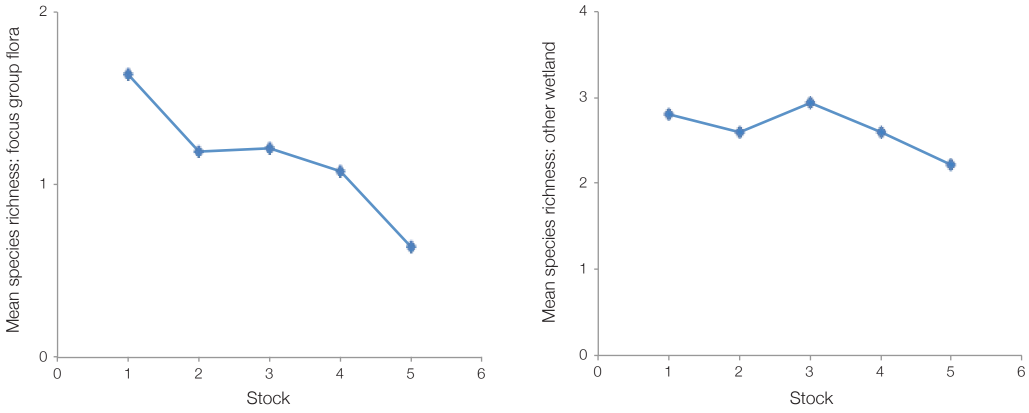
Significant positive non-parametric associations of abundance with pH were apparent for three of the focus group flora (*B. juncea*, *G. trifida* and *P. australis*). These positive associations were also significant in the ordinal regressions for the sedges *B. juncea* and *G. trifida*. Some taxa were only abundant within a small pH range, whereas others showed a much broader tolerance (Table 5.1). *Phragmites australis* and *S. virginicus* tolerated the broadest range of pH, both being present over a pH range of 6 to 10 (not including outliers).

Flow and stock

The focus group taxa shared similar responses to flow rate and stock impact, with abundance of all focus group taxa increasing with increasing flow (Table 5.2, Figure 5.5), and the abundance of the half of focus group species negatively correlated with stock impact, although significant positive associations were present for *E. carsonii* and *U. dichotoma*. In contrast, all significant associations of species abundance with stock impact were positive for the other wetland taxa (except *Fimbristylis* spp.), and only five of the eight other wetland taxa in Table 5.2 showed a significant positive association with flow.

In the ordinal regression models, all of the focus group species for which stock impact was included in the final model exhibited a negative association with stock impact (Table 5.3). In

A. all springs



B. excluding fenced springs

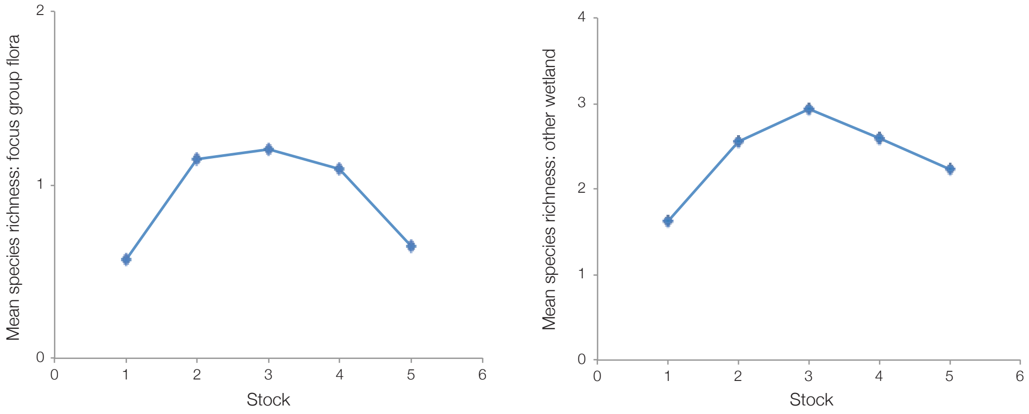


Figure 5.6: Influence of stock impact on other wetland plant and focus group species richness at springs

contrast, all of the other wetland species for which stock impact was included in the final model exhibited a positive association with stock impact. Flow was not usually included as a significant predictor in the ordinal regression models, perhaps because of its correlations with the other predictors such as conductivity.

Species richness

GAB spring wetlands in the Lake Eyre and Lake Frome supergroups are relatively species poor. The maximum number of plant species recorded at a single spring was 10, with up to six focus group taxa present at a spring. Neales River and Francis Swamp had the greatest plant species richness of the 16 spring complexes (15 species, Table 5.4). Mt Hopeless and Mt Denison spring complexes supported seven of the nine focus group species, with six focus group species present within the Hermit Hill and Francis Swamp spring complexes.

Conductivity was negatively correlated with the number of species present at a spring, whereas flow and pH were positively correlated with focus group and plant species richness (Table 5.6).

Focus group and species richness in general were negatively correlated with stock impact. The greatest number of focus group species was recorded in springs with no stock impact when all springs were included, whereas maximum total plant richness occurred in lightly grazed springs. However, associations of species richness with stock impact may be biased by the use of fencing to exclude stock from springs supporting diverse flora. Excluding fenced springs from the analysis revealed that the maximum number of plant taxa and focus group taxa occurred at intermediate stocking levels (Figure 5.6).

The number of focus group species in a spring group, as well as overall plant species richness, was positively correlated with the number of active vents in the group (Table 5.5).

5.2.3 Discussion and management implications

In this study, several physical and chemical factors were identified influencing the abundance and diversity of vegetation at endangered GAB spring wetlands in the study area, which is centred in the arid zone of South Australia to the west and south of Lake Eyre. Although associations vary between species, the focus group flora generally is associated with a different set of environmental conditions to other wetland taxa found on GAB springs.

Stock

It was found that stock impact was a key factor influencing both plant species richness and abundance at South Australian GAB springs. The finding that lightly grazed springs supported the highest plant species richness is similar to the finding that non-native plant species richness peaked with intermediate disturbance at desert springs in the Spring Mountains of Nevada, USA (Fleishman *et al*. 2006), and suggests the potential for the manipulation of grazing as a strategy to maximise plant diversity at GAB springs. However, correlation and ordinal regression analyses suggest stock had varying effects on the abundance of focus group and other wetland taxa, with the majority of focus group species negatively impacted by stock and a number of other wetland taxa present in higher abundance at stocked springs. Positive associations with stocking may result from assisted dispersal or a higher resilience to grazing, trampling or eutrophication in some species. Much attention has been devoted to methods to increase *E. carsonii* populations, such as using periodic grazing or fire to remove competing vegetation (Fatchen & Fatchen 1993; Davies 2005). The use of grazing to achieve this end would require careful management due to the potential negative impact on other components of the focus group flora, including the biogeographic 'relicts' *B. juncea* and *G. trifida*.

The presence of the introduced taxa *Cotula coronopifolia* and *Polypogon monspeliensis* across the stocked Francis Swamp, Billa Kalina, and Neales River spring complexes suggests that the presence of domestic stock may be assisting introduction of exotic plant species at some South Australian GAB springs. To the authors' knowledge, these exotic species are not adversely impacting South Australian GAB springs at present. However, it would be prudent to monitor the distribution and abundance of these species so that appropriate management could be instigated if they were to become invasive.

Spring flow

Correlation analysis showed focus group taxa were much more reliant on high-flow springs compared to the other wetland taxa. The abundance of all the focus group species was positively associated with flow rate, compared to around half of the other wetland taxa. Furthermore, focus group plant richness was much higher at springs with water flowing in the spring tail compared to those simply with surface water present. These results highlight the importance of high-flow springs to maintaining the diversity and abundance of the focus group flora, and demonstrate that decreases in flow at GAB springs are likely to negatively impact focus group taxa.

Phragmites australis could potentially serve as an indicator species for spring flow rates, as the abundance of this species is strongly positively correlated with flow and it is widely distributed across the GAB. A decrease in abundance of this species could provide an early warning of drawdown at a spring. However, *Phragmites*

Photo: Travis Gotch

australis is also susceptible to grazing, thus this species may only be useful as an indicator of spring flow at fenced springs. The use of permanent wetland vegetation area to determine flow rates has been explored fully in Volume IV: Spatial Survey and Remote Sensing of Artesian Springs (Lewis *et al.* 2013).

Conductivity

Several species-specific effects of the environmental variables included in the analysis have been identified. Several focus group species only attained high abundance in a narrow range of conductivity values, including the endangered *E. carsonii* and the biogeographic ‘relicts’ *U. dichotoma*, *G. trifida* and *B. juncea*. *E. carsonii* was only present in high abundance at springs with conductivities less than 3.7 mS/cm. Prior to the removal of stock and fencing of many spring groups, this species regularly occurred on spring vents, but has since been largely excluded from these habitats due to competition with *P. australis*, and is now typically found in spring tails (Fatchen & Fatchen 1993) where conditions are likely to be less suitable. Almost all other focus group species displayed a much broader tolerance of conductivity or even a positive association of abundance and conductivity.

Species richness

Each of the environmental variables investigated significantly impacted the number of focus group species and the total species richness at the springs. An inverse relationship was found between conductivity and the number of plant species, consistent with the effect of salinity on species richness in other wetland systems. Species richness in a given habitat is typically proportional to habitat size, thus it is not surprising that factors likely to increase total wetland area in a spring group, such as flow and the number of active vents (Fatchen & Fatchen 1993; Fatchen 2001b), were positively correlated with species richness. Total wetland area may be particularly important for the focus group flora, as taxa such as *U. dichotoma* were only recorded at spring complexes with the greatest number of active vents. The predominance of *C. laevigatus* at springs with only a single species present suggests it may act as a ‘pioneer’ species at GAB springs, consistent with results of Fensham *et al*. (2004) that suggest colonisation by *C. laevigatus* represents the first stage of succession at GAB springs.

5.2.4 Conclusion

The findings of this report have important ramifications for the management of endangered GAB spring habitats. Significant reductions in flow at the springs are likely to negatively impact abundance of the focus group taxa and species diversity in general. Extraction of water from the GAB that decreases either the number of active vents in a spring group or the number of springs with flowing surface water will be particularly harmful to these ecosystems. The results also highlight the importance of the quantity and quality of water. Both the pH and conductivity of spring water had a significant effect on species abundance and richness at the springs. Changes to the flow regime that also alter water quality could have unforeseen additive or synergistic effects on plant communities. Positive correlations between the number of active vents in a group and both species diversity and abundance of focus group taxa support the practice of treating spring groups as the management unit rather than individual springs. Finally, efforts to increase the abundance of the endangered *E. carsonii* by removing competing vegetation would be best directed toward springs where the discharge water conductivity is less than 5 mS/cm.

5.3 Genetic structure of relict wetland plant species at GAB springs

Central Australia has become increasingly arid since the Miocene approximately five million years (ma) ago. Palaeo-botanical evidence indicates wetlands were still widespread in central Australia at the Pliocene–Pleistocene border, approximately 2.5 ma ago (Martin 2006). GAB springs often represent the only permanent natural water sources in many parts of arid central Australia and they support several wetland plant species not found elsewhere in the region. Two species of particular interest are the sedges *Baumea juncea* and *Gahnia trifida*. GAB spring populations of these species are more than 300 km from their typical habitat in temperate wetlands in south-west and south-east Australia (Harris 1992) and may represent relicts of previously much broader distributions

Figure 5.7: *Gahnia trifida* at Francis Swamp

Photo: Duncan Mackay

when central Australia was much wetter than today (Martin 2006; Webb 2010).

Due to the naturally discontinuous and scattered distribution of the springs and the inhospitable nature of the surrounding environment, GAB spring populations are typically smaller and more isolated than populations in southern temperate wetlands. Small, isolated populations tend to possess less genetic diversity than large, continuous populations, and reduced levels of genetic variation are associated with an increased risk of extinction (Frankham 2005). Consequently, an aim of this study is to determine whether the disjunct *B. juncea* and *G. trifida* populations of GAB springs are less genetically diverse than more widespread populations of coastal wetlands.

Inter-population dispersal is predicted to be lower amongst small, isolated populations, leading to reduced genetic connectivity or gene flow. If gene flow is insufficient to counteract the effects of genetic drift (the random change in frequency of gene variants, also known as alleles, due to chance), populations will become genetically distinct. Establishing levels of gene flow between GAB spring populations is therefore important for understanding the potential of different springs to have independent evolutionary trajectories, and to assess the probability of recolonisation following local extinction due to changes in flow (e.g. drawdown), grazing or competition. Identifying genetically distinct populations can guide conservation and management decisions as to the appropriate scale at which populations should be managed (e.g. individual springs, spring groups or complexes). Hence, the aim is to determine whether gene flow occurs between GAB spring populations of *B. juncea* and *G. trifida*, or whether they are effectively isolated and functionally independent of each other.

Species persisting in patchy island-like habitats such as the GAB springs may experience increased inbreeding, as reduced mate availability increases the chance of mating among related individuals, or increased self-fertilisation (selfing) in self-compatible species. Inbreeding can cause a decline in reproductive fitness, known as inbreeding depression. Therefore, a third aim of this study is to determine whether isolated GAB spring populations exhibit greater levels of inbreeding than coastal populations.

Figure 5.8: *Baumea juncea* (foreground) at Hermit Hill spring complex

5.3.1 The species

Gahnia trifida (common name: Cutting Grass or Coast Saw Sedge) is a rhizomatous perennial that grows in 1–2 m high tussocks (Figure 5.7). It is typically found adjacent to swamps and creeks in temperate regions of southern Australia, as well as occurring on artesian springs in arid central Australia. The species flowers year-round, with inflorescences arranged in a series of spikelets, each spikelet typically containing a single bisexual flower (Jessop 1981).

Baumea juncea (R.Br.) Palla (common name: Bare Twig Rush) is a rhizomatous perennial that grows in small tussocks up to 1 m high in brackish or saline swamps in Australia as well as occurring on artesian springs in arid central Australia (Figure 5.8). Rhizomes can be greater than 1 m in length (pers. obs.). The size of the nut (2–3 mm) presumably prevents significant wind dispersal, and nuts may be dispersed by water or animals such as birds. Both *B. juncea* and *G. trifida* are likely to be wind-pollinated. Both species are able to produce genetically identical plants, or clones, that are independent of the parent plant by sending up new shoots from underground rhizomes.

Figure 5.9: Geographic location of *Gahnia trifida* populations used

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

Figure 5.10: Geographic location of *Baumea juncea* populations used

Legend

- ● Vegetation populations
- ▇ Lake Eyre
- ▇ Waterbodies

0 100 200 300 400

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: March 2012

Table 5.6: Genetic and genotypic diversity (mean ± SE) in coastal and GAB spring *G. trifida* populations.

Region		R	NA	AR	HO	HE	%P
GAB springs	Mean ± SE	0.72 ± 0.04	2.4 ± 0.2	2.3 ± 0.2	0.27 ± 0.06	0.32 ± 0.05	0.77 ± 0.06
Coastal	Mean ± SE	0.97 ± 0.02	3.7 ± 0.3	3.3 ± 0.3	0.41 ± 0.05	0.49 ± 0.04	0.94 ± 0.04

R = genotypic richness; NA = number of alleles per locus; AR = allelic richness; HO = observed heterozygosity; HE = expected heterozygosity; %P = percentage of polymorphic loci.

5.3.2 Methods

Population sampling

Ten *G. trifida* populations were sampled, including four coastal sites and six spring groups near Lake Eyre in central Australia (Figure 5.9). Sites were sampled over similar spatial scales in the spring and coastal regions, with distance between sites ranging from 10 to 200 km at the coastal sites, and 3.5 to 224 km at the springs. Samples for a single population were collected within a 1 km radius, with the exception of Strangways and Francis Swamp where the most distant samples were separated by approximately 1.3 and 10 km, respectively. Where possible, samples were collected 5 m apart to reduce the chance of sampling the same clone. A total of 18 to 60 samples were collected per population.

Seven *B. juncea* populations were sampled, including four coastal populations and three GAB spring populations near Lake Eyre in central Australia (Figure 5.10). Mambray Creek is one of the closest coastal *B. juncea* populations to the GAB springs. Samples for a single population were collected within a 1 km radius, with individual collections separated by a minimum of 5 m to reduce the chance of sampling the same clone. The Mambray Creek and Tunkalilla populations were exhaustively sampled by this method. Populations with a patchy distribution (Aldinga and GAB spring populations) were sampled by collecting up to 20 samples from each of 4 to 6 patches (or springs). A total of 60 to 80 samples were collected per population, except at Mambray Creek (27 samples).

Molecular analysis

Samples were genotyped using 13 microsatellite loci for *G. trifida*, and 12 microsatellites for *B. juncea*. A locus refers to a specific DNA sequence in the genome, and different variants of the DNA sequence at a locus are known as alleles. Microsatellites are short, tandemly repeated sequences of DNA (e.g. ACACACACAC) that vary in the number of repeats present, with distinct alleles containing a different number of repeats. PCR amplification, capillary separation and allele size scoring of microsatellite loci were performed as described in Clarke *et al*. (2011).

Statistical analysis

Standard genetic diversity descriptive statistics (number of alleles, allelic richness (the number of alleles standardised by the sample size), observed and expected heterozygosity, percentage of variable loci) and the inbreeding coefficient (F_{IS}) were estimated for each population. Each of these statistics measures different aspects of genetic diversity within a population. Clonal richness in a population where N samples revealed G multi-locus lineages was calculated as R = (G-1)/(N-1) (Dorken & Eckert 2001). Statistical differences in genetic and clonal diversity between regions (GAB spring and coastal) were determined using t-tests.

Population structure was investigated using the program ‘Structure’ version 2.3.3 (Pritchard *et al*. 2000). Gene flow between populations was explored by estimating the partitioning of genetic variation within and among populations using the Analysis of Molecular Variance (AMOVA, Excoffier *et al*. 1992) framework. Contemporary migration rates were explored among *G. trifida* populations within the coastal and spring regions using two assignment methods, BayesAss+ (Wilson & Rannala 2003) and GENECLASS2 (Piry *et al*. 2004).

5.3.3 Results

Gahnia trifida

Genetic diversity

214 distinct multilocus genotypes were detected from a total of 267 samples across the ten *G. trifida* populations. Duplicate genotypes (genetically identical clones) were found in all populations except Blackford and Messent, with a small but significant reduction in genotypic diversity (R) at spring populations ($t = 4.90$, $P = 0.001$, Table 5.6). Of the 17 sets of identical genotypes in the springs region, each set was restricted to a single spring, except for a pair of genotypes found at two springs at West Finniss. These results indicate clonal reproduction is only used for local propagation in this species, and that pollen or seed is required for dispersal over longer distances.

GAB spring populations of *G. trifida* tended to show less genetic diversity than coastal populations (Table 5.6). The number of alleles per locus, allelic richness and expected heterozygosity was significantly lower in spring populations than in coastal populations. Spring populations also tended to exhibit lower levels of observed heterozygosity and percentages of polymorphic loci compared to coastal populations. It thus appears that the small, isolated *G. trifida* populations at GAB springs are characterised by lower levels of genetic diversity compared to their coastal counterparts, possibly as a result of genetic drift.

Most populations contained one or more alleles not found in other populations (private alleles).

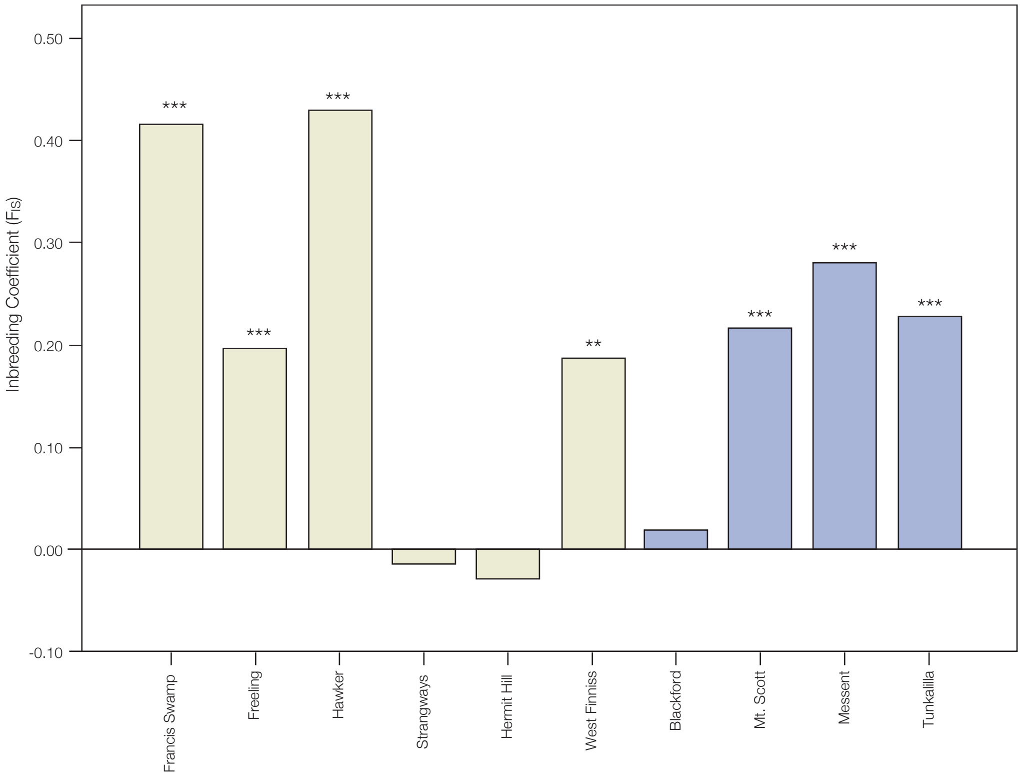


Figure 5.11: Inbreeding coefficient (F_{IS}) values for GAB spring and coastal *G. trifida* populations

** $P < 0.01$
*** $P < 0.001$

Figure 5.12: Migration rates (posterior probabilities) into *Gahnia trifida* populations estimated using BayesAss+

Each column represents a population receiving immigrants, with each colour indicating different potential source populations of migrants.

Consistent with their greater genetic diversity, coastal populations tended to possess more private alleles (three to five per population). Francis Swamp and Freeling Springs contained the greatest number of private alleles amongst the GAB spring populations (three each), with two private alleles at Strangways, one each at Hermit Hill and West Finniss, and no private alleles detected at Hawker. A total of 18 alleles were present in *G. trifida* populations at GAB springs that were not found in coastal populations. Hence, GAB spring populations represent an important genetic resource for the species, and their loss would lead to a 19.1% loss of allelic diversity for the species across the study populations.

Inbreeding

The potential for inbreeding increases in small, isolated populations with low effective population size, such as those at GAB springs. However, it was found that more than half the populations in both GAB spring and coastal regions displayed positive inbreeding coefficients (F_{IS}, Figure 5.11), suggesting that *G. triffida is* likely to be self-compatible, as observed in several other sedges (Snyder & Richards 2005 and references therein). Self-compatible species are typically able to avoid pollen limitation, hence selfing may have assisted *G. trifida*to persist at low effective population sizes at GAB springs by providing reproductive assurance (Aguilar *et al*. 2006). However, high levels of inbreeding are likely to have exacerbated the loss of genetic diversity due to drift.

Gene flow

An AMOVA including all populations showed a high proportion (37%, FST = 0.476, P = 0.001) of genetic variation to be partitioned among populations and between the coastal and spring regions (10%, FRT = 0.102, P = 0.001). However, separate AMOVA analyses for coastal and spring populations revealed contrasting patterns. Spring populations showed much higher levels of genetic differentiation, with 52% of variation among populations in the springs, more than twice that observed in coastal populations (22%).

Analysis of contemporary migration using the programs GENECLASS and BayesAss+ indicated more restricted dispersal distances among spring populations than among coastal populations. Two coastal populations (Blackford and Messent) had mean non-migration rates less than 90% per generation (Figure 5.12), indicating that more than 10% of each population originated from a different source population. Non-migration rates were greater than 95% for all spring populations, with the highest migration rate from West Finniss into Hermit Hill (3.8%, Figure 5.12). Populations are generally considered demographically independent when connected by migration rates less than 10% (Faubet *et al*. 2007), hence all spring populations of *G. trifida* are likely to represent independent units according to this criterion.

Analysis of the genetic structure across the coastal and GAB spring regions using ‘Structure’ indicated the presence of two distinct genetic clusters, one consisting of the Hermit Hill and West Finniss populations, and the other all remaining coastal and GAB spring populations except Strangways. Examining genetic structure within each region showed that the coastal populations of Blackford, Messent and Mt Scott formed a single cluster, with the more distant Tunkalilla population forming a second cluster. These results indicate high levels of historical connectivity between coastal populations separated by 10 to 80 km. Within the GAB spring region, ‘Structure’ analysis revealed six clusters corresponding to the six sampled spring groups, with extensive admixture between the clusters representing Hermit Hill and West Finniss, indicating interbreeding of these genetically distinct populations, but little or no admixture within the other populations.

Table 5.7: Genetic and genotypic diversity (mean ± SE) in GAB spring and coastal *B. juncea* populations.

Region		R	NA	AR	HO	HE	%P
GAB springs	Mean ± SE	0.21 ± 0.05	2.5 ± 0.4	2.3 ± 0.3	0.39 ± 0.05	0.32 ± 0.06	0.72 ± 0.15
Coastal	Mean ± SE	0.22 ± 0.05	2.9 ± 0.6	2.6 ± 0.4	0.40 ± 0.05	0.36 ± 0.06	0.81 ± 0.09

R = genotypic richness; NA = number of alleles per locus; AR = allelic richness; HO = observed heterozygosity; HE = expected heterozygosity; %P = percentage of polymorphic loci

The results demonstrate reduced gene flow among *G. trifida* populations at GAB springs compared to coastal sites. It was found that GAB spring populations to exhibit much higher levels of genetic differentiation, with weak inferred migration rates between Hermit Hill and West Finniss spring groups within the Hermit Hill Spring Complex (less than 1 km apart), and no contemporary migration between populations separated by 25 km (Francis Swamp and Strangways) or more. These results suggest *G. trifida* is unlikely to readily recolonise GAB springs in the case of local extinction within a spring complex.

Baumea juncea

Genetic diversity

The results suggest Australian *B. juncea* populations experience limited recruitment and are largely maintained by clonal reproduction. Using 12 microsatellite loci, only 95 distinct multilocus genotypes were detected from a total of 447 samples, indicating clonal reproduction is much more extensive in *B. juncea* compared to *G. trifida*. Replicate genotypes were often shared between springs within spring groups, but not between spring groups. Clonal growth via rhizomes appears to be highly successful for local spread within a spring group, however pollen or seed is presumably required for dispersal between different spring groups. GAB spring and coastal populations exhibited similarly low levels of clonal richness (GAB spring: $R = 0.21 \pm 0.05$; coastal: $R = 0.22 \pm 0.05$, Table 5.7) indicating substantial contributions of clonal reproduction to population structure in this species.

Unlike *G. trifida*, GAB spring populations of *B. juncea* showed similar levels of genetic and genotypic diversity to coastal populations, with no significant difference detected between regions for any of the parameters examined (all $P > 0.50$, Table 5.7).

Baumea juncea populations at Freeling Springs and Hermit Hill each possessed four private alleles, with an additional two private alleles within the West Finniss population. Populations from the GAB springs contained 10 alleles not found in the coastal populations. Loss of South Australian GAB spring populations would thus reduce the number of allelic variants across the study populations by 13.0%.

Gene flow

The establishment and maintenance of populations by a limited number of founder individuals is expected to result in high levels of genetic differentiation, as was observed in this study. Only a small proportion of genetic variation was a result of differentiation between the coastal and spring regions (2%, $FRT = 0.019$, $P < 0.001$), with a much larger proportion of variation partitioned among populations within regions (34%, $FST = 0.371$, $P < 0.001$). However, GAB spring populations tended to exhibit greater genetic differentiation than coastal populations. When examining genetic differentiation within regions, a greater percentage of variation was partitioned among populations at GAB springs (45%, $FST = 0.451$, $P < 0.001$) compared to coastal populations (28%, $FST = 0.278$, $P < 0.001$), similar to the pattern observed in *G. trifida*. Higher levels of genetic differentiation between GAB spring populations may be due to the absence of intermediate populations to act as stepping-stones for dispersal. However, the Hermit Hill and West Finniss spring populations are only separated by approximately 1 km, yet pairwise FST-values (0.448) indicate these are two of the more genetically distinct populations (range for all pairwise values = 0.150-0.568). In contrast, Hermit Hill and West Finniss populations of *Gahnia trifida* show extensive admixture as well as significant levels of contemporary migration (Figure 5.12). These results suggest the potential for dispersal between populations may be lower in *B. juncea* than in *G. trifida*. It is possible that the absence of seed dispersal vectors, such as seasonal flooding or water birds, has reduced connectivity between GAB spring populations of *B. juncea* compared to coastal populations.

5.3.4 Discussion and management implications

Gahnia trifida

Contrasting patterns of genetic structure observed in spring and coastal *G. trifida* populations are consistent with the expected consequences of population isolation—namely, erosion of genetic diversity and increased inter-population differentiation due to genetic drift, and a decrease in gene flow (Aguilar *et al*. 2008). The results demonstrate that GAB spring populations of *G. trifida* are less interconnected by gene flow than populations in coastal regions and are effectively isolated from one another. The data suggests spring populations currently exhibit low levels of genetic diversity relative to coastal populations. *Gahnia trifida* populations at GAB springs are likely to persist if conditions remain stable, but may be vulnerable to environmental change.

Baumea juncea

Baumea juncea at GAB springs showed greater levels of inter-population differentiation compared to coastal sites, consistent with predictions of decreased gene flow and increased genetic drift in fragmented habitats. Reduced connectivity between *B. juncea* populations at GAB springs, compared to conspecific coastal populations and GAB spring populations of *G. trifida*, indicate this species has limited potential to recolonise spring groups in the event of local extinction. Contrary to expectations, however, GAB spring populations of *B. juncea* show no decrease in genetic diversity compared to less isolated coastal populations. It appears that the extensive use of clonal reproduction to establish and maintain *B. juncea* populations is not associated with a significant loss of genetic diversity in small isolated habitats, and may have assisted the species to persist at GAB springs.

GAB spring populations as a genetic resource

GAB springs support genetic variants of both species not found elsewhere, and loss of these populations would result in a significant loss of genetic diversity. Of particular note are the *G. trifida* populations at the Hermit Hill and West Finniss spring groups that are genetically distinct from all other spring and coastal populations examined. These populations represent an important genetic resource for this species. In addition, Hermit Hill Spring Complex supports one of the most diverse spring floras in the Lake Eyre Supergroup, with six of the eight focus group species present, including the endangered *E. carsonii* and both ‘relict’ species, *G. trifida* and *B. juncea*. The Hermit Hill Spring Complex should be made a conservation priority for its value in terms of both biological and genetic diversity.

Information on the genetic structure of plants at GAB springs is now available for three species, *E. carsonii* (Davies 2005), *G. trifida* and *B. juncea*. Despite different morphological, life history and reproductive characteristics, all three species show significant genetic differentiation and restricted connectivity between spring groups. *E. carsonii* shows higher levels of

differentiation between spring supergroups, and three morphologically and genetically distinct subspecies have been recognised across the GAB (Davies *et al*. 2007a). Genetic differentiation of plant populations between spring groups and supergroups may eventually result in the evolution of new species. Speciation at GAB springs has been observed in other taxa, including amphipod crustaceans (Murphy *et al*. 2009) and hydrobiid snails (Perez *et al*. 2005). GAB springs should be conserved not only for their biological and genetic diversity, but also for the evolutionary processes occurring in these naturally fragmented ecosystems.

Artificial dispersal

Species that exist as small, isolated populations are at risk of reduced reproductive fitness due to inbreeding depression, which can exacerbate the risk of extinction (Frankham 2005). The potential for inbreeding depression can be ameliorated by translocating genetically distinct individuals into a population to augment the genetic diversity already present. Although the study did not explicitly examine whether GAB spring populations of *B. juncea* or *G. trifida* are experiencing inbreeding depression, there is no evidence that GAB spring populations of *G. trifida*, *B. juncea* or *E. carsonii* will benefit from translocation of material between spring groups or complexes. Populations of all species have persisted in small, isolated populations at GAB springs, presumably for thousands of years. Furthermore, *B. juncea* populations at GAB springs do not exhibit reduced genetic diversity compared to coastal populations, and inbreeding coefficients are comparable in GAB spring and coastal *G. trifida* populations. Similarly, Davies (2005) found no reduction in reproductive output in small, isolated populations of *E. carsonii*. At this time, there is no justification for transplanting material between springs to prevent inbreeding depression. Indeed, artificial dispersal could lead

Photo: Travis Gotch

to a reduction in fitness in populations receiving transplants if populations have become highly adapted to local conditions.

The genetic structure of GAB spring populations of *B. juncea*, *G. trifida* and *E. carsonii* suggest each of these species is capable of dispersing between springs within a spring group, but dispersal between spring groups is much more restricted. Transplantation could be considered in the case of local extinction at a spring group. This could restore ecological value within the spring group; however, novel genetic variants cannot be replaced in such a manner. As populations of these species at different spring groups are genetically distinct, extinction of a population across a spring group will result in a loss of genetic diversity for the species.

Volume V: Groundwater-dependent Ecosystems of the Western Great Artesian Basin

Allocating Water and Maintaining Springs in the Great Artesian Basin

6

Phragmites australis: Knowledge to support its management on GAB springs

Jane Roberts

6. *Phragmites australis*: Knowledge to support its management on GAB springs

6.1 Background

6.1.1 Introduction

Hundreds of artesian spring complexes are spread around the margins of the Great Artesian Basin (GAB) (Fensham *et al*. 2008). Being small wetlands in an immense arid landscape, these are effectively ecological islands, and consequently they are of conservation interest due to their uniqueness in Australia and their endemicity. The native species dependent on the surface water habitat formed by the artesian up-flow were listed as an Endangered Community under the federal *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in April 2001, and a recovery plan has been prepared (Fensham *et al*. 2008).

GAB springs in South Australia are in relatively good condition compared with many further east, but the native communities (plant and animal) are under threat from Common Reed (*Phragmites australis*) which has become dominant on springs such as Hermit Hill following stock exclusion (Fatchen 2001a, Lewis 2001). This wetland plant is now recognised as a conservation threat to the distinctive biodiversity of the GAB springs, through competition and habitat change (Davies *et al*. 2010, Kodric-Browne *et al*. 2007).

Management actions

In the mid 1980s, the South Australian Department of Environment and Heritage initiated a protection program that included fencing 10 spring complexes in the period 1985–1988 (Lewis 2001). Stock exclusion is a management action also recommended in the recovery plan. By 2001, it had become apparent that fencing had indeed been effective, with prolific growth of wetland plants to the extent that at seven springs, the vents or pools had become completely overgrown with tall emergent macrophytes, *Phragmites* or *Typha*, whereas prior to fencing there had been 'some' *Phragmites* or *Typha* (Lewis 2001). Thus the irony is that the management action triggering the current *Phragmites* problem was a deliberate measure to protect GAB springs from stock damage.

The threat posed by *Phragmites* may be reduced by imposing a management regime that will stress the plant, and therefore curtail its lateral expansion. To this end, authorities are considering the use of carefully timed controlled burns. Preliminary results of controlling reeds by firing them in 1999 appear positive, at least in the short term (Davies 2001), with no evidence of immediate damage to wetland communities (Munro *et al*. 2009). Clearly, more work is needed to ensure that repeated burning has no effect on GAB springs as functioning ecosystems, and also to avoid cumulative inadvertent long-term effects on the ecological values that are being protected.

Photograph on facing page: Travis Gotch

An alternative long-term vision is to devise a controlled burning program that can progressively reduce the vigour of *Phragmites* to the point of eliminating it from the GAB. However, this may not be a sensible option if *Phragmites* can readily re-colonise and re-establish. Such control programs will require targeted and timely monitoring of vigour and extent through time, and will be sensitive to negative effects on the ecosystem.

6.1.2 Purpose

The purpose of this review is to tap into the very large scientific literature on *Phragmites* to address, as best possible, three questions posed by authorities charged with managing the GAB springs.

- Question 1: Are GAB springs that are currently grazed by cattle and apparently free of *Phragmites* at risk of being colonised by *Phragmites* if cattle are removed? If *Phragmites* can be controlled to the point of being eliminated, then is it likely to re-establish?
- Question 2: Is it possible that *Phragmites* has reached its maximum or near-maximum extent on some GAB springs?
- Question 3: Why is *Phragmites* invading GAB springs?

Questions about firing *Phragmites* are not included here.

A desktop study such as this, done with only limited field experience of GAB springs and no field inspections, cannot expect to answer these questions definitively. However, it can help shape future work by describing growth processes and so help to inform and prioritise management actions.

The review focused on three ecological topics, derived from the three questions: colonisation processes and their likelihood; growth constraints and invasiveness.

6.1.3 Approaches

Structure

This review is structured around the three topics and three questions given above. The topic of invasiveness benefitted from a recent review and synthesis of theories in invasion ecology (Catford *et al*. 2009).

Process

Standard techniques were used for this desktop study: literature search using electronic search engines, access to electronic journals, and critical reading.

The international scientific literature on *Phragmites* is huge, and only a fraction of this has been accessed and used in this review. The international literature is used because it is so rich in terms of topics. However, it is valid to question how studies done using different genetic stock and in different environments can help to understand *Phragmites* on small permanent aquatic habitats in a hot desert environment in northern South Australia. Transferability of information and ecological knowledge is a challenging area in ecology for which there are no quick answers or guides.

The rationale for using and relying on this international literature is as follows:

- it represents a large body of knowledge with considerably more detail and understanding of processes, physiology and genetics than is available in Australia
- this knowledge has accrued through time, and has effectively been 'tested' by being used and applied in different environments, and is constantly being updated
- the knowledge has been published in international journals and so has been subject to peer review
- greater risks would be incurred by managing the problem of *Phragmites* on GAB springs, without accessing this body of knowledge.

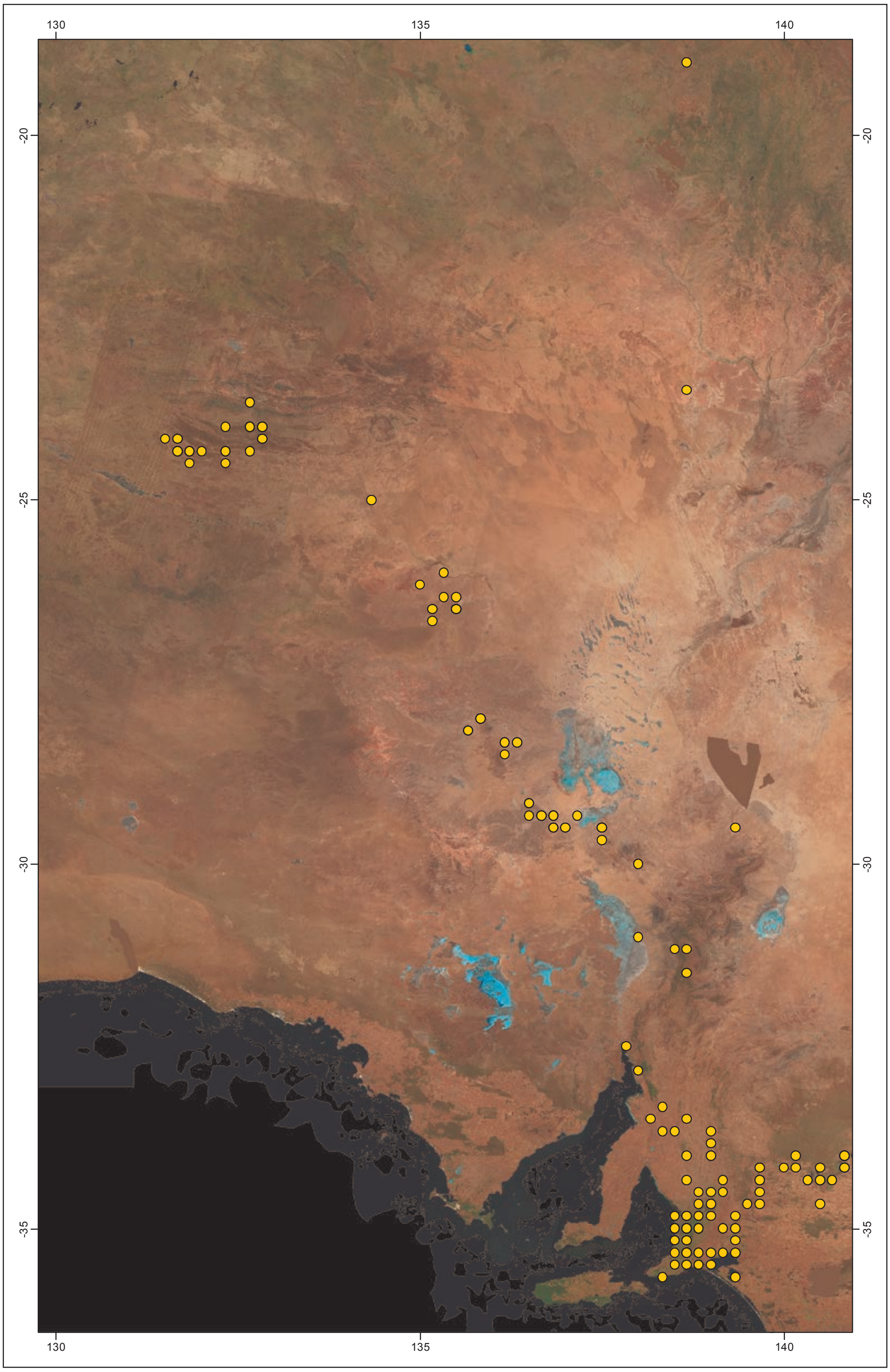


Figure 6.1: Herbarium (AVH) records for *Phragmites australis* in central Australia (see Appendix 4)

Species distibution

● *Phragmites australis*

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

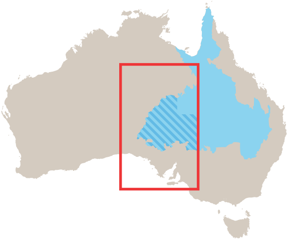


Photo: Dylan Koerner, DEWNR

The international literature on *Phragmites* comes mostly from Europe and more recently from North America. Where possible and relevant, studies are included that come from hot dry environments and from within Australia.

Assumption

An important assumption is made regarding the identity of *Phragmites* occurring on GAB springs. Three species of *Phragmites* occur in Australia and their distributions as based on herbarium records are shown in Figure A4.1 (Appendix 4).

Phragmites australis occurs through most of mainland Australia and Tasmania except the tropical north. The other two species, *Phragmites karka* and *Phragmites vellatoria*, occur mostly in the north, with occasional records further south, including from the area where GAB springs occur in northern South Australia, to the south and west of Lake Eyre. The three species are very similar in appearance.

Although recognised as two species in Australia's Virtual Herbarium (AVH), *P. karka* is not recognised in some international literature (e.g. Lambertini *et al*. 2006) whereas *P. vellatoria* is. According to the AVH, both *P. australis* and *P. karka* occur on GAB springs in South Australia. *P. australis* has been collected much more frequently and is therefore assumed to be more common. The distribution of *Phragmites australis* as given by herbarium specimens through the study area is shown in Figure 6.1.

6.2 Context: *Phragmites*, GAB Springs, Invasion Theories

6.2.1 *Phragmites* in perspective

Phragmites is an emergent macrophyte, usually 1–3 m tall in Australia but occasionally reaching 4–5 m: heights as much as 6 m have been reported overseas (Clevering & Lissner 1999). It is a rhizomatous perennial grass, with cane-like shoots, also known as culms. It has 'a broad ecological amplitude and is able to acclimate to a range of conditions' (Brix 1999).

Phragmites has a world-wide distribution, occurring in North America, South America, Europe, Africa, Asia and Australia. It also has a wide latitudinal range, variously reported as 00 to 700, and altitudinal range. Collectively, these indicate considerable climatic range.

Phragmites australis is recognised as having considerable genetic variability (Lambertini *et al*. 2006, Hansen *et al*. 2007). Its basic chromosome number is 12 but nearly all material is euploid, i.e. having more than two complete sets of chromosomes. Ploidy levels range from 4x to 12x, and the different ploidy levels have specific distributions around the world. All material in North America and Europe is tetraploid (4x) except in the Danube Delta where tetraploids and octoploids (8x) co-exist. Plants through Asia are octoploids. Most Australian material is also octoploid though decaploid (10x) material has been collected from the Murrumbidgee River (Clevering & Lissner 1999). *Phragmites* is considered to be a morphologically variable species, and variations in ploidy level account for some morphological variability. For example, European octoploids are generally more robust (larger leaves, taller and thicker shoots) than other ploidy levels tested (Hansen *et al*. 2007). Ecotypes are commonly referred to in the literature but their existence is largely assumed rather than demonstrated by appropriately controlled experiments (Clevering & Lissner 1999). In contrast, origin and provenance are consistently found to be important.

Phragmites has been utilised by different cultures around the world. It continues to be economically important in countries such as Romania and Hungary. Contemporary economic uses include paper, cardboard and insulation (Romania) and roofing material (e.g. Hungary, England).

The die-back of *Phragmites* across Europe, where dieback was defined as ‘visible abnormal, non-reversible, spontaneous retreat, disintegration or disappearance of mature stands’ (Clevering & Lissner 1999), prompted a continent-wide program of research known as EURREED. This resulted in numerous studies on different aspect of *Phragmites*. In North America, the opposite situation prevails: *Phragmites* has become invasive along much of the eastern coast (Chambers *et al*. 1999), and this has stimulated considerable research there.

In Australia, attitudes to *Phragmites* are mixed. The species has been lost from reaches of lowland rivers in the Murray-Darling Basin (e.g. Roberts 2000) which has unrecognised implications for river functioning. In some areas, *Phragmites* is considered a valuable plant for its bank stabilisation properties (e.g. Frankenberg 1997) but in others it is seen as unnecessary (e.g. Roberts *et al*. 2006) covering 5–41% of reaches of the Wimmera River.

6.2.2 *Phragmites* and GAB springs

GAB springs as aquatic habitats

As aquatic habitats, GAB springs are very diverse. The hydrogeological and geological processes involved in their creation are covered in detail in Volume I: Hydrogeological Framework of the Western Great Artesian Basin (Keppel *et al.* 2013) and Volume II: Groundwater Recharge, Hydrodynamics and Hydrochemistry (Love *et al.* 2013a), while the biological features of the springs are reviewed in Chapter 2 of this volume. GAB springs occur on the margins of the Great Artesian Basin, singly or, more commonly, clustered together. The distribution of GAB springs on the western margin of the GAB is shown in Figure 2.1. A distinctive hierarchical terminology has been developed to describe groups of springs. This is explained in Chapter 2 and in greater detail in Volume IV: Spatial Survey and Remote Sensing of Artesian Springs (Lewis *et al.* 2013).

Water quality has a strong influence on aquatic fauna and wetland productivity. Broadly speaking, water quality in the South Australian GAB springs depends on water source. If from uplands on the eastern margin in Queensland then it is likely to be carbonated and relatively rich in sodium; if from uplands west of the Simpson Desert and Lake Eyre then it is likely to be sulfated and rich in calcium, and sometimes corrosive (Boyd 1990).

Water quality data for over 20 springs and bores surveyed by the Nature Conservation Society of South Australia (Table 6.1), was generally neutral to slightly alkaline, brackish, low in soluble phosphorus but high in nitrate-nitrogen (Mitchell 1985).

Temperature of the discharging water is warm, mostly 20–35°C and mostly fairly constant, so likely to promote growth in contrast to the marked diurnal temperature variations nearby.

Phragmites as a threat

As an emergent macrophyte, *Phragmites* has three characteristics that make it an effective competitor and hence a threat to communities and habitats on GAB springs: rhizomatous clonal growth, shoot height and shoot density.

Once established, it grows laterally by rhizome extension into adjacent areas wherever conditions are suitable, and forms dense relatively tall stands. Direct competition is effected through space occupancy and shading. The affected plants are usually shorter or shallow-rooted species and communities of the GAB springs, of which the most notable is Salt Pipewort (*Eriocaulon carsonii*), a small sedge, endemic to GAB springs and listed as Endangered under the EPBC Act (Fatchen 2001a, Davies *et al*. 2009).

The same three characteristics change the aquatic habitats of both vents and tails on the GAB springs, altering their character and reducing their extent.

In vent habitats, *Phragmites* grows deeper into large pools than most other plants. Its dense growth shades the water surface, converting open water into dense shade-casting reed beds. In addition, lack of disturbance such as waves or currents means *Phragmites* builds up rafts of organic matter that can extend across a pool. Both these reduce the extent of open water habitat on which endemic fish are dependent (Kodric-Brown *et al*. 2007). An additional threat to fish in deep pools is oxygen deficiency in the water, resulting from decomposition of the accumulation of fallen leaves and stems of *Phragmites* (Kodric-Brown *et al*. 2007).

In tail habitats, *Phragmites* grows into the soft moist soil of the dynamic outflow, displacing plants and causing dramatic habitat loss by desiccation through transpiration (Kodric-Brown *et al*. 2007).

Herbarium records show that *Phragmites australis* occurs widely through the area where GAB springs occur in northern South Australia (Figure 6.1), implying that this threat is quite widespread.

Phragmites and GAB springs

Clearly, GAB springs offer favourable habitats for *Phragmites* (Figure 6.2). No growth studies have been done but comments on heights and estimates of biomass are given in Symon (1985), Davies (2001), Fatchen (2001) and Anonymous (undated).

Table 6.1: Water quality of GAB springs in 1978

Water quality parameters	Range	Sample size
pH	7.2 to 8.3	8
Pool conductivity (m mhos)	5943 to 14,700	6
Phosphate (PO_4) mg/L	Below detection (0.01)	5
Phosphate (PO_4) mg/L	0.013 to 0.02	2
Nitrate (NO_3) ppm	3 to 14	7

Figure 6.2: Short *Phragmites australis* growing on the slopes of an artesian spring in the Northern Territory (non GAB)

The spring borders the Finke River, Northern Territory which is occasionally eroded by floods (left). Soils are quite saline, as indicated by deposits at the surface, the samphire (right) and presence of charophytes probably *Lamprothamnium* sp. (not confirmed) in the soaks running down the slope (not shown), and poor structure. Different age-classes are evident, some senescent and some relatively new growth. Much taller *Phragmites* was growing very densely across the pool (not shown) but all tall shoots were senescent with a sparse understorey of short green shoots. Flowering panicles are noticeably absent. Photographs by Jane Roberts, September 2009.

It has become a problem on GAB springs subsequent to fencing, however fencing does not always result in a problem: four of the twelve springs protected by the GAB Springs Protection Program do not have *Phragmites* (Anonymous, undated). Moreover, the patchy distribution of *Phragmites* on GAB springs was evident before the protection program began. Botanical notes from a survey of over 20 springs and bores by the Nature Conservation Society of South Australia (NCSSA) in 1978 found *Phragmites* at 13 of the 19 springs or named spring groups visited (Symon 1985). In contrast to its patchy occurrence on GAB springs, *Phragmites* was not recorded at any of the bores and tanks visited by NCSSA (Table 6.2, from Table 1 in Symon 1985).

Table 6.2: Occurrence of *Phragmites* at springs and bores or tanks in 1978

	With *Phragmites*	Without *Phragmites*
Springs	13	6
Bores	0	5

Thus, although *Phragmites* is widespread through northern South Australia (Figure 6.1), it does not occur on all GAB springs and may not occur in all the types of aquatic habitats in the region.

6.2.3 Invasion success

Invasion ecology is rich in hypotheses and theories that seek to explain invasion success, and there are also a few that address invasion failure. Navigating through this sprawling and ever-expanding branch of ecology in order to retrospectively understand the invasion success of a particular species such as *Phragmites* could be unproductive, as the literature on the target species is so large and histories at individual sites non-existent.

Instead, this study explores invasiveness and invasion success by drawing on the simpler integrative holistic PABH framework synthesised by Catford *et al*. (2009). The PABH framework recognises that just four factors underpin the very many hypotheses explaining invasiveness: propagule pressure (P), the abiotic characteristics of the invaded ecosystem (A), biotic characteristics meaning the recipient community and of the invading species (B), and human interference (H). These are described below.

Three of these, propagule pressure, abiotic characteristics and biotic characteristics, are factors driving invasion; the fourth, human interference, is a modifier of the three main drivers, but potentially as influential.

Table 6.3: Invasion Timeline (from Catford *et al.* 2009)

Stage/ process	1. Transport	2. Introduction	3. Colonisation	4. Naturalisation	5. Spread	6. Impact
Definition	Movement of plants or plant propagules to new location	Arrival of plant or plant propagules into new location	Survival of introduced plants	Survival and reproduction enabling pioneer population to be self-sustaining	Dispersal of propagules and spread of populations outside of area where first introduced	Harmful impact of species to ecology and economy
Driving factor	Propagule pressure	Propagule pressure	Propagule pressure, abiotic characteristics, biotic characteristics	*Propagule pressure*, abiotic characteristics, biotic characteristics	Propagule pressure, abiotic characteristics, biotic characteristics	Propagule pressure, Abiotic characteristics, **biotic characteristics**
Spatial scale	Regional and continental	Local	Local	Local	Regional	Local and Regional
Human assisted	Yes, generally	Yes, generally	Yes, but not essential	No	No, but can exacerbate	No

Driving factors shown in bold are believed to be primary influences; driving factors shown in italics are usually considered secondary influences.

As well as synthesising processes and factors resulting in invasion, Catford *et al*. (2009) produced an Invasion Timeline showing six stages of invasion: transport, introduction, colonisation, naturalisation, spread and impact (Table 6.3). The Invasion Timeline integrates the terms used in different invasion theories, placing them on a common ground.

Propagule pressure (P)

Propagule pressure means the number of individual propagules of a species arriving at a region where it is not native over a period of time. Propagule pressure is a driving factor in the first three stages of the Invasion Timeline, i.e. in transport, introduction and colonisation (bold text in Table 6.3). The probability of establishment increases as propagule pressure increases.

Five components of propagule pressure can be recognised (Catford *et al*. 2009):

- propagules per introduction
- frequency of introduction
- human use
- propagule characteristics
- dispersal modes and avenues.

Abiotic characteristics (A)

The driver abiotic characteristics refers to the physical conditions at the site where the propagules arrive. If these are not favourable, then the species will not establish. In summary, GAB springs can be seen as small but abundant and reliable patches of an essential resource (water), dotted through an extensive landscape where that resource is not abundant. Prior to European settlement and the appearance of bores and tanks, GAB springs would have been the only habitat patches suitable for wetland plants such as *Phragmites* over a large area.

Four components of abiotic characteristics can be recognised (Catford *et al*. 2009):

- resource availability
- condition and regimes
- episodic disturbance
- geographic location.

The literature informing these is interpreted as factors that can constrain growth, so the growth responses and tolerances of *Phragmites* are explored in Section 6.4.

Biotic characteristics (B)
The third driver, biotic characteristics, refers to the traits of the invading species and of the recipient community, and their interactions. Recipient community means more than other vascular plant species: it refers to any organism or suite of organisms that affect plants so includes insects, pathogens, and herbivores. Biotic characteristics are a principal driving factor of the later stages of invasion, from colonisation onwards (Table 6.3).

The six components of this driver recognised by Catford *et al*. (2009) are:

- invader traits
- enemies
- competition
- mutualism
- commensalism
- trophic cascades.

These components are linked to impact, as well as success, which is outside the scope of this review. Only one of these components is considered here, invader traits, and it is considered only narrowly from the restricted view of colonisation, in relation to number and viability of propagules in Section 6.3.2.

Human interference (H)
The fourth driver, human interference, is not shown in the Invasion Timeline. This is because it is not a driving factor in its own right but can have a catalytic role and thus make any of the three driving factors, P or A or B, effective or ineffective. Dispersal is an example of this catalytic role. People may carry seeds, deliberately or inadvertently, and because people now travel using mechanised transport, propagules can be distributed well beyond their ‘normal’ dispersal range.

Human interference is here interpreted to mean contemporary and historic or earlier human actions, behaviours, possessions and activities. It therefore embraces more than people. The presence of feral animals, and activities such as pastoralism, mining and tourism are examples of human interference, if these alter the characteristics of P, A or B. The scale of human interference is immense and constantly evolving.

No components of this driver were proposed by Catford *et al*. (2009).

An issue of scale
The invasion timeline makes a clear distinction between non-indigenous invaders and indigenous weeds (not shown here). For non-indigenous invaders, the timeline starts with the first stage, transport, whereas for indigenous weeds it starts at the fifth stage, spread. *Phragmites australis* is an indigenous species so the review should start with spread.

However, there are very large distances implied in dispersing *Phragmites* through central Australia. This review considers it useful, in terms of ecological understanding, to separate regional-scale processes such as dispersal of *Phragmites* to GAB springs from areas beyond the arid zone (i.e. transport) from dispersal amongst GAB springs (i.e. spread). It therefore considers transport and spread separately in Section 6.3.2, which is consistent with the PABH framework which gives the spatial scale for transport as regional and continental, and for spread as simply regional (Table 6.3).

6.3 Colonisation and recovery

6.3.1 Context

An invasive species is one that successfully passes through the first five stages in the Invasion Timeline (Table 6.3). To paraphrase this, in words taken nearly verbatim from Richardson *et al*. (2000), an invasive species must:

- as a result of dispersal, arrive at a site beyond its previous geographical range (transport)
- establish a population of adult plants (introduction and colonisation)
- then reproduce and increase to become a colony that is self-perpetuating (naturalisation)
- then disperse more widely in its new region (spread)
- eventually become incorporated into the local flora.

This sequence can be conceptualised (Figure 6.3) so as to emphasise the different spatial scales involved in transport and spread.

6.3.2 Colonisation

Invasiveness of *Phragmites* in relation to GAB springs is here examined by exploring the following topics under the umbrella of colonisation:

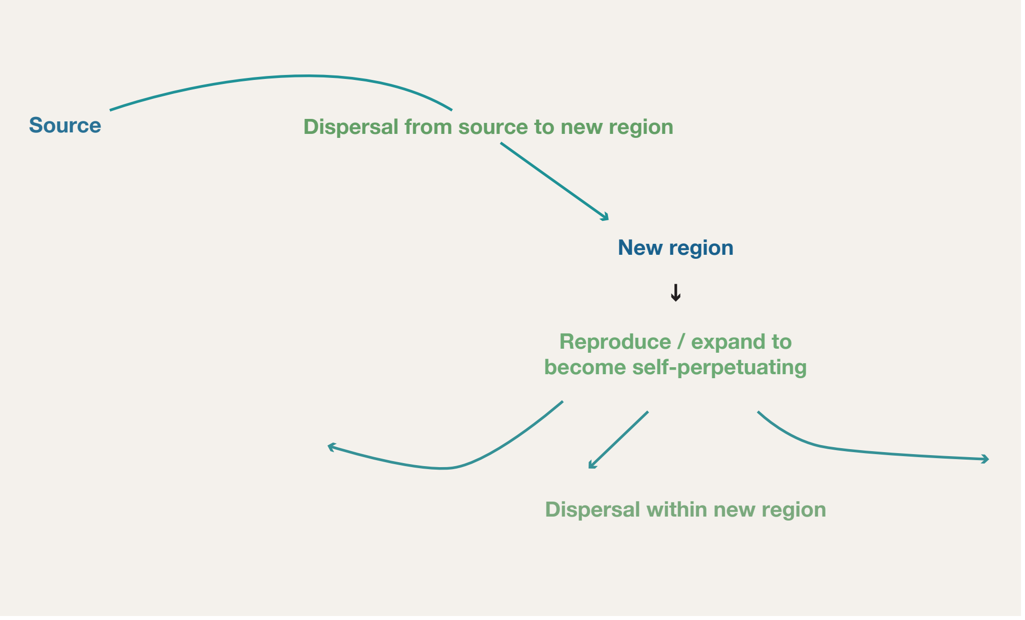
- source
- dispersal from source to new region (i.e. transport)
- dispersal within the new region (i.e. spread).

Source

Source, as used here, is more than location: it refers to conditions and circumstances prior to dispersal.

Propagules at a source can only be a threat in a new region if they are viable when they arrive. Hence viability prior to dispersal needs to be considered; and high viability should be considered a desirable, though not an essential, characteristic in an invasive species.

Figure 6.3: Successful invasion, a geographic model



Phragmites has potentially two types of propagules that can be dispersed from a source: vegetative fragments, and seeds or fruits. Henceforward, the word ‘diaspore’ is used in a restricted sense to mean *Phragmites* seeds or fruits but not vegetative fragments.

Vegetative fragments, particularly rhizome fragments, of *Phragmites* are important in certain types of range expansion but the ecology of fragments is little known. The viability of vegetative fragments is rarely questioned: they are assumed to have high viability. What is essential is that the fragment has live meristematic tissue such as nodes present. Rhizome sections are routinely used for propagation in the field (e.g. Frankenberg 1997) and in pot experiments; failures, when these do occur, are generally attributed to experimental procedure causing water-logging rather than to lack of viability. Probably the greatest threat to effective dispersal of vegetative fragments in arid regions is desiccation of meristematic tissue.

In contrast, the viability of seeds is an issue. Seed viability and related characteristics such as seed set and seed germinability are known to be low to poor in *Phragmites*, and to be quite variable. For example, the number of fertile fruits may range from 0 to about 1000 per inflorescence; by way of contrast, *Typha domingensis* has an estimated 600 000 viable seeds per inflorescence (Roberts 1987). The proportion of shoots that are fertile may range from 0–55% (cited in McKee and Richards 1996). A study of 34 sites in Britain found that seed production averaged 0–100% per site (McKee & Richards 1996): at the Gippsland Lakes, Australia, only 0.5–2% of florets had viable seeds (Clucas & Ladiges 1990); and in Japan seed set ranged from 0.1–59.6% with an average of only 9.7% (Ishii & Kadono 2002). Germination rates are also highly variable and typically low. Germination rates as high as 100% were achieved in prairie wetlands of North America after stratification (Galinato & van der Valk 1986) but this is unusual. A maximum of 20% germination per site was recorded from 34 sites in Britain and France (McKee & Richards 1996). Low germination rates are known also for Australian seeds (Greenwood & MacFarlane 2006) which can make germination experiments difficult.

Reasons for low seed set, low viability and low germinability have been investigated but no universal answer has emerged. It appears to be a site-specific problem, possibly in response to environmental stress. In the British study, for example, low seed set was attributed to temperature during seed development (McKee & Richards 1996), whereas in the Japanese study low seed set was attributed to pollen limitation and insect herbivory, but only after other explanations had been ruled out (Ishii & Kadono 2002). Reasons for low seed set at the Gippsland Lakes were not explored (Clucas & Ladiges 1990) but may have been due to salinity, which was the focus of the study.

Dispersal

The dispersal of propagules from source to new region (i.e. transport) is a critical stage. In the case of *Phragmites* and its initial colonisation of GAB springs in northern South Australia, this would have meant seeds and/or vegetative fragments being transported long distances (hundreds of kilometres) over very dry landscape and arriving at a favourable habitat patch. The distances involved in dispersal within the new region (i.e. spread) are much less and the density of favourable habitat patches is much higher.

The traditional view that *Phragmites* seeds are dispersed primarily by wind (e.g. Alfarhan 2002) is now seen as narrow and overly precise. Instead, it is recognised that most species have multiple means of dispersal, known as polychory (Soons 2006). This means that all dispersal mechanisms and all types of propagules (seed and fragments) must be considered when evaluating dispersal and range extensions.

For an emergent macrophyte such as *Phragmites*, this means considering dispersal by wind (anemochory); water (hydrochory); and animal vectors, principally waterfowl (epizoochory) and stock (endozoochory), as well as humans.

Wind

Diaspores of *Phragmites* do not have specialised appendages for wind dispersal, other than awns and silky hairs, however their small size suggests wind is important as a dispersal agent. Records of average weights for *Phragmites* diaspores are 0.16 mg (Coops *et al*. 1995), 0.11 mg (Ekstam *et al*. 1999), and 0.04 to 0.16 mg per site (McKee & Richards 1996).

The dispersal distances achieved by wind transport are difficult to measure with small-sized diaspores but can be modelled and estimated based on physical properties such as the probable terminal velocity of the diaspore and the height of the inflorescence that releases the diaspore. This type of modelling shows that *Phragmites* is in the 'top' category for wetland non-woody plants, along with *Typha*, and this is due to being relatively tall and to having diaspores with terminal velocities less than 0.3 m/sec which makes them easily uplifted (Soons 2006). Wetland plants in this top category have a dispersal distance described as 'upper limit of at least several kilometres under highly convective or stormy conditions'. Even in the absence of thermals, *Typha* and *Phragmites* can potentially disperse over relatively 'large areas', quantified as 83 ha and 2.6 ha, respectively (Soons 2006).

The effective distance achieved by wind, its indiscriminate nature and the probable low abundance of viable seeds together suggest that wind dispersal of *Phragmites* diaspores is likely to be effective relatively rarely at the transport stage. It is more likely to be effective at the spread stage. Wind dispersal of vegetative fragments over any distance is highly unlikely, other than by extreme events such as tornados.

Water

Diaspores of *Phragmites* can float for at least a few days, and water-dispersed seeds of *Phragmites* have been collected from lowland streams in the Netherlands (Boedeltje *et al*. 2004). Floating time, when investigated in the laboratory, was in the order of 2 to 3 days: 50% of seeds in beakers with gentle water movement sank after 40.9 hours, and 90% sank after 65 hours (Coops *et al*. 1995). This may be long enough to transport seeds several kilometres down a river system.

Although springs appear well separated (Figure 2.1), hydrological connectivity does occur and can be quite common within a spring group and between springs (Volume IV (Lewis *et al.* 2013)). Springs on drainage lines may interconnect by surface flows in response to unusual or extreme rainfall, similar to how river floods connect riverine wetlands. Such connections are infrequent or even rare events, and not specific to any particular season. Hydrochory must be considered largely irrelevant for the transport stage under current climates, but possible at the spread stage, including the few rare situations where tails of neighbouring artesian springs coalesce or both flow into the same wetland depression within a spring complex or group. Site-specific knowledge is needed to make a conclusive evaluation of the importance of local hydrochory. The importance of periodic hydrological connections is becoming increasingly recognised in speciation and genetic diversity studies of obligate aquatic fauna of the springs (e.g. Murphy *et al*. 2009).

Waterbirds

Endozoochory, meaning internal transport by ingestion, appears to be more important for plant dispersal than epizoochory, meaning the external transport by adhesion. Currently, research interest is on endozoochory rather than epizoochory, about which very little is published. This review of the potential role of endozoochory in *Phragmites* dispersal focuses on diaspores

Photo: Travis Gotch

as previously defined (seeds and fruits): viable vegetative fragments are assumed to be too large for waterbirds to ingest.

Endozoochory is emerging as a significant means of dispersing diaspores of aquatic, amphibious and terrestrial plant species. Several studies have collected fecal pellets and droppings of water birds and waders, and then germinated them (e.g. Brochet *et al*. 2009; Green *et al*. 2008; Sanchez *et al*. 2006). The number of plant species identified has now reached 223 (Brochet *et al*. 2009) and includes *Phragmites* seeds, which were recorded in just one study and not in great abundance (Brochet *et al*. 2009). Only one endozoochory study has been published for Australia, and this was done in the Macquarie Marshes. It did not find *Phragmites* seeds in the droppings of grey teal, black swans and Eurasian coot even though *Phragmites* forms extensive reed beds in the area (Green *et al*. 2008).

As it is not certain that seeds will survive ingestion and gut passage and retain viability, recovery has been assessed. Recovery rates established by feeding captive birds, usually ducks, are generally high. For most plant species germination is reduced by gut passage, for example to 2–57% of initial germination rate (Wongshriphuek *et al*. 2008). In captive mallards, the retention time varies little between plant species and varies little between ducks. Most seeds are voided within four hours of feeding and nearly all seeds are voided within 12 hours (Wongshriphuek *et al*. 2008, Chlarambidou *et al*. 2003). Assuming a flight speed of 10 to 70 km/h, this gives a dispersal range of 40 to 280 km if a bird takes flight immediately after eating (Chlarambidou *et al*. 2003). A retention time of 4 to 12 hours sounds short but satellite tracking of grey teal movements in inland and central Australia (Roshier *et al*. 2006) shows that this could be enough to achieve long-distance dispersal: one bird flew 285 km overnight. *Phragmites* seeds do survive ingestion and gut passage but their germinability is reduced (Soons *et al*. 2008). However, the same study found that small-seeded species were potentially dispersed much further than large-seeded species and estimated that the dispersal distance for *Phragmites* was 300 to 700 km (Soons *et al*. 2008).

Dispersal by waterbirds differs from dispersal by wind in not being indiscriminate but targeted, meaning waterbirds will fly from one wetland or GAB spring to another and, in particular, move between sites depending on the type of habitats available, whether pool or tail. Waterbirds move around inland and central Australia (Roshier *et al*. 2006) and waterbirds such as ducks, brolgas, swans and waders occur frequently at some springs, notably Dalhousie Springs, Francis Swamp, Freeling Springs and Hermit Hill (Travis Gotch, pers. comm., September 2010).

Waterbird dispersal is likely to be effective over both long and short distances, at both the transport and spread invasion stages; in other words,when dispersing from source to new region as well as within the new region.

Mammals including stock

Transport of diaspores by external adhesion to animals (epizoochory) was once thought to be restricted to diaspores with spines, hooks or sticky hairs but this is now known to be too simplistic (Romermann *et al*. 2005). Instead, the likelihood of a seed attaching and adhering to an animal coat is determined by its mass and its morphology, with mass being more important for a coat with straight hair such as cattle, and appendages being more important for a coat with curled hair such as sheep (Romermann *et al*. 2005).

In the context of GAB springs, epizoochory by cattle is likely to be significant only when animals move from one spring to another for forage and water (at the spread invasion stage). As with waterbirds, such movements are potentially significant as they are not indiscriminate. Long-distance dispersal (transport) seems unlikely because it would require seeds remaining adhered for several days.

Figure 6.4: Recovery mechanisms following management control

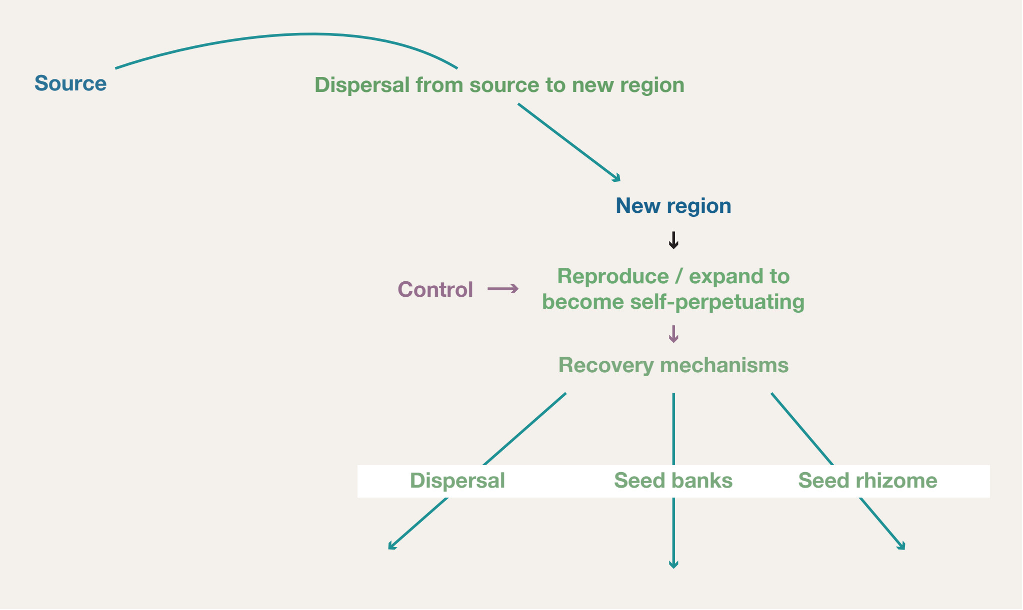


Table 6.4: *Phragmites* and seed banks (with data for *Typha* as a comparison)

Author and site details	Findings
Boedeltje *et al*. (2003)	
Netherlands	*Phragmites*: 25 seeds per sample (*Typha*: 67 seeds per sample)
Canal system	
Phragmites vegetation present	
Gurnell *et al*. (2006)	
UK	*Phragmites* found in transported sediment water but not in seedbank
Constructed channel and adjacent land	
Phragmites vegetation nearby	
ter Heerdt and Drost (1994)	
Netherlands	*Phragmites*: only 171 seeds, present in 27.8% of 216 samples (*Typha*: 22 7525 seeds, present in 93.4% of samples)
Phragmites vegetation nearby	
van der Valk and Davis (1979)	
USA	*Phragmites* seeds: none (*Phragmites* seeds absent from all six types of emergent macrophyte vegetation).
Prairie wetland	
Small recently-established patch of *Phragmites* vegetation	
Wilson *et al*. (1993)	
Canada	*Phragmites*: no seeds in seed bank
Freshwater marsh	
Phragmites vegetation present	

6.3.3 Recovery

Recovery as used here means the re-establishment of *Phragmites* on a GAB spring following control management or elimination. Three recovery mechanisms can be identified: dispersal, seed banks and rhizome (Figure 6.4).

In Figure 6.4, dispersal means the arrival of viable propagules at the site, corresponding to the spread stage in the Invasion Timeline (Table 6.3). Seed banks means the presence of viable seeds in a seed bank that will germinate and establish following management actions. Rhizome means the persistence of underground parts, despite the management activities.

Only two of the three mechanisms for recovery are considered in this section—seed banks and rhizome. Recovery by dispersal was covered in Section 6.3.2.

Seed banks

Phragmites tends not to form abundant and persistent seed banks (Ekstam *et al*. 1999). The view from North America is that *Phragmites* is classified as a VD-1 type, meaning it reproduces vegetatively but does not form a seed bank so is dependent on propagules arriving from outside (van der Valk 1981).

Table 6.5: *Phragmites* and seed banks in Australia

Author and site details	Findings
Britton and Brock (1994)	
5 wetland 'lagoons' Northern Tablelands New South Wales	No *Phragmites* amongst germinating seeds 66 taxa
Capon and Brock (2006)	
Cooper Creek floodplain Queensland	No *Phragmites* amongst germinating seeds 99 taxa *Phragmites* probably not in area
Finlayson *et al*. (1990)	
Magela Creek floodplain Northern Territory	No *Phragmites* amongst germinating seeds
James *et al*. (2007)	
Narran Lakes floodplain New South Wales	No *Phragmites* amongst germinating seeds 77 taxa
McIntyre (1985)	
9 ricefields, Colleambally New South Wales	No *Phragmites* amongst germinating seeds 42 spp *Typha* present in seedbank and probably present in area
Nicol (2004)	
Menindee Lakes New South Wales	No *Phragmites* amongst germinating seeds Up to 32 spp per lake *Typha* occasional in seedbanks
Nicol *et al*. (2003)	
Bool Lagoon South Australia	No *Phragmites* amongst germinating seeds; present in area. 31 taxa *Typha* in seedbank and in area
Nicol *et al*. (2007)	
Thegoa Lagoon, Murray floodplain New South Wales	No *Phragmites* amongst germinating seeds 17 taxa *Typha* present in seedbank
Porter *et al*. (2007)	
9 arid wetlands Paroo and Bulloo River catchments	No *Phragmites* amongst germinating seeds 40 spp
Robertson and James (2007)	
Kanyapella Basin, Murray floodplain Victoria	No *Phragmites* amongst germinating seeds 59 taxa *Typha* present in seedbank and in area

Phragmites is not often detected in seed bank studies but when present, as determined by the emergence technique, then it is usually in very low numbers, especially compared to other species (Table 6.4), even when samples are collected from within or near a stand of *Phragmites*.

In general, seeds in the seed bank are most abundant at the surface (Boedeltje *et al*. 2003). In the case of *Phragmites*, depth is critical. Germinating seeds have little capacity to emerge if buried, and burial by just 1 cm of soil can reduce germination from 71% to 20% (Galinato and van der Valk 1986).

Reasons why *Phragmites* does not form abundant and persistent seedbanks are probably due to low seed set and low seed viability (Ekstam *et al*. 1999). In addition, its capacity to germinate in the dark (Ekstam *et al*. 1999) and on moist soil (Coops and van der Velde 1995) must deplete seed bank numbers even further.

Within Australia, there has been a surge of interest in the seed banks of wetlands and floodplains, from a number of different floodplains and habitats across eastern Australia (Table 6.5). *Phragmites* was not detected in any of these studies.

Although these results are consistent with overseas studies, it would be unwise to assert categorically that *Phragmites* does not form seed banks in Australia. Nearly all samples were collected from wetlands and habitats that did not have *Phragmites* growing nearby. At best, these studies indicate that *Phragmites* is not dispersing into new regions (relating to the spread stage) and forming a seed bank.

Rhizome

The rhizome is an underground stem, usually about 60–90 cm within the soil (Hocking 1989a, Roberts *et al*. 2006) but sometimes as deep as 1.5 m (Lissner & Schieurup 1997).

The rhizome is important as a starch reserve and as a reservoir of buds. It is the starch reserve that facilitates the very rapid growth of shoots in spring and helps to give *Phragmites* a competitive advantage. The starch reserve combined with the bud reserve mean that *Phragmites* stands can re-establish a new canopy of shoots following disturbances that remove shoots, wholly or partly, such as mowing, grazing or fire. The bud reservoir can be quite abundant. In western New South Wales, the bud reservoir numbered 3325 m^{-2} in February, of which 576 (approximately 17%) were swollen and beginning to develop into new shoots whilst the remainder (2749 buds or 83%) appeared dormant (Hocking 1989a).

Unlike the shoots, which live for about one year at the most, rhizomes are relatively long-lived. Rhizomes extend each year, such that the youngest part is at the tip and the oldest furthest back, thus at any time, the rhizomes underground are a multi-aged population. Rhizomes can be aged, relatively, by placing them in an age sequence, based on morphological characteristics such as discolouration, presence of scale leaves, and presence of adventitious roots. In the Czech Republic, this resulted in five age-classes (Klimes *et al*. 1999). In Japan, a similar approach verified the use of colour and by also considering rhizome branching and the state of shoots and sheaths (Karunaratne *et al*. 2004), was able to determine that rhizomes were up to six years old (Asaeda *et al*. 2006). Both these estimates were for *Phragmites* rhizomes growing in seasonally inundated and continuously moist conditions in temperate climates.

No comparable work has been done for *Phragmites* rhizomes under Australian conditions, however there is anecdotal evidence from the Great Cumbung Swamp in New South Wales to suggest that rhizomes can survive in the substrate under persistent dry conditions, remaining viable for five years.

The Great Cumbung Swamp is the terminal wetland on the Lachlan River in south-western New South Wales and normally has extensive reed beds of *Phragmites*. The extended drought and lack of river flow resulted in the wetland drying up. The stands of *Phragmites* senesced, lodged and disintegrated, and no shoots were evident above ground. Heavy rainfalls in autumn of 2010 triggered growth in *Phragmites* after five years of complete senescence, indicating that the rhizome persisted underground over that time (Paul Packard, Wetlands Officer, NSW DECCW, pers. comm. April 2010). Note that Serag (1996), quoting a Russian source, says that *Phragmites* can survive 'long-term drought' and 'its rhizomes remain viable in dry soil for a period of eight to nine years'; however, without consulting the original source, it is not known what the substrate conditions were in terms of temperature and moisture, or what climate is the context.

On GAB springs, it is evident that *Phragmites* can persist for a while, even after conditions have changed such as drying or change in vent. This resistance in the face of dramatically depleted resources is presumably due to the rhizome.

Symon (1985) visited 19 GAB springs in 1978 and made the following observations:

- Elizabeth Springs: 'simple cone, now dry, with remnant *Phragmites* surviving'
- Outside Springs #2: 'simple cone, almost dry, remnant *Phragmites*'
- Horse Springs:'*Phragmites* seemed to be dying out'.

6.4 Growth of *Phragmites*

6.4.1 Context

The majority of field studies of *Phragmites* growth have been done at mid-latitudes and in temperate climates. Only a few studies have been done in hot dry climates comparable to northern South Australia and most of these are descriptive rather than investigative or hypothesis-testing, so contribute little ecological knowledge directly. Similarly, although growth models of *Phragmites* have been developed (Asaeda & Karunaratne 2000) and other modelling approaches trialled (e.g. Karunaratne *et al*. 2003), their direct application to northern South Australia is limited because the latitudinal range for which they have been validated goes to 35° S and not below, whereas GAB springs are at 28–29° S.

Photo: Travis Gotch

Without specific understanding of how *Phragmites* responds to hot dry environments and with only very limited field data of *Phragmites* performance on GAB springs, it is not feasible to address the second question in Section 6.1.2: 'Is it possible that *Phragmites* has reached its maximum or near-maximum extent on some GAB springs?' with confidence.

Instead, this question is considered indirectly, by considering environmental factors known to be growth-limiting for freshwater emergent macrophytes, including latitude, high temperatures, inadequate soil moisture, water depth, and salinity.

This section opens with a description of annual growth *Phragmites*, as a baseline for understanding the effects of environmental constraints.

6.4.2 Growth and production

Wherever its production has been documented, the growth of *Phragmites australis* is strongly seasonal. This is true for countries that are high latitude with cool temperate climates such as Denmark and Scotland (Anderson 1976, Ho 1979) as well as for countries that are low latitude such as Hong Kong (Lee 1990) or hot and dry or Mediterranean climate, such as Egypt (Eid *et al*. 2010a and 2010b; Serag 1996). It is also true in semi-arid western New South Wales and Victoria (Hocking 1989a, 1989b; Roberts *et al*. 2006). It seems likely, therefore, that this will also be true for *Phragmites* growing on GAB springs in hot arid northern South Australia. This assumption can be readily confirmed by appropriate observations.

All these production studies considered the whole plant, which can only be done by sampling below-ground material. Sampling and processing the below-ground parts of a relatively large wetland plant growing in mud is dirty, laborious work but it is necessary to understand the vigour, resilience and productivity of *Phragmites*. As indicated in Section 6.3.3, the underground parts and the above-ground parts have quite different life-spans, as well as quite different roles.

The role of shoots is energy capture and competition (for example through shading). The roles for the rhizome are energy storage, for shoot growth in spring or recovery, and space occupancy and habitat foraging, through lateral expansion. The rhizome is thus important in persistence and resilience. It lives about five times longer than shoots, and usually has much greater biomass. Due to its capacity for lateral

Table 6.6: Maximum biomass, annual production and allocation dynamics for *Phragmites australis* at Mirrool Creek, western New South Wales, 35° S

Growth	Quantity
Maximum biomass	
Above ground	Approx. 9890 g/m² (Mar–Apr)
Below ground	21 058 g m⁻² (Aug)
Annual production	
Above ground	12 898 g/m²/y
Below ground	6338 g/m²/y
Whole plant	14 945 g/m²/y
Internal allocations and losses: Above ground	
Shoot mortality and leaf shedding (includes some from previous year)	9914 g
Upward translocation from rhizome	4291 g
Internal allocations and losses: Below ground	
Received by downward translocation from shoots during senescence	2984 g
Translocated down from shoot photosynthesis	3354 g
Root and rhizome mortality	1053 g
Seasonal production	
Winter	13% of annual total
Spring	32%
Summer	42%
Autumn	13%

expansion and for internal subsidy (transfer of carbohydrates or water between rhizomes), the current distribution of *Phragmites* is not a reliable indicator of where it first established, or even under what conditions.

The population of shoots above ground is analogous to twigs with leaves forming the canopy in a tree. Field studies of the growth of clonal herbaceous plants such as *Phragmites* thus have the option of documenting growth by periodic harvesting or by tracking shoot demography. Studies that use both can be very informative.

Modelling and carbon budgets (e.g. Eid *et al*. 2010b) have now overtaken empirical approaches to growth and proved valuable in exploring dynamics and growth patterns at temporal and spatial scales beyond the capacity of single field studies, such as latitudinal gradients and temperature effects.

Seasonal pattern

The seasonal growing pattern of *Phragmites* described here is a general one that parallels studies in Europe, Japan and Australia. The description follows a field study from western New South Wales (Hocking 1989a, 1989b).

This was a landmark study. The biomass and production data it generated (Hocking 1989a, 1989b) are still referred to in the international literature and still useful on account of the detail recorded and the meticulous nutrient and micro-nutrient budgets. The data have been used repeatedly to calibrate growth models (e.g. Asaeda & Karunaratne 2000), to test the validity of modelling outputs (e.g. Karunaratne *et al*. 2003), and in comparative studies of latitudinal effects (e.g. Karunaratne *et al*. 2003).

Both above-ground (shoots) and below-ground (rhizome) parts of the plant have a strong seasonal pattern of growth. However, the two seasonal patterns are not synchronised and their peak biomasses are offset by about three months. Because of this offset, the ratio of above-ground to below-ground biomass changes through the year. One-off comparisons that fail to place this ratio in an appropriate time phase are common in the literature and are quite misleading.

Spring is a suitable point to commence a description of the annual cycle. Young shoots that have been above ground all winter but not growing much, if at all, begin to elongate and grow very rapidly (September through October) until late summer (February, March). Flowering appears to be determined by photoperiod: panicles emerge about 2 to 6 weeks after maximum daylength (Asaeda & Karunaratne 2000), after which shoots cease to grow. In autumn, the shoots begin to senesce, and are all dead by the end of winter (August). Shoots thus live for a year or less.

Climate is important in controlling shoot growth. In western New South Wales, the next generation of shoots emerges above ground in autumn and winter, but these grow little, if at all, over winter. In cold conditions, there are no live young shoots over-wintering, because any young shoots emerging before winter are likely to be killed by frosts. Thus, the annual cycle is tightly defined. In warm climates such as western New South Wales, shoot cohorts from different years may co-exist, briefly, in autumn. *Phragmites* in coastal habitats at the Gippsland Lakes, Victoria had a similar pattern, with new shoots appearing in June and reaching 1 m before winter, then becoming inactive (Clucas & Ladiges 1990). A key to production of *Phragmites* on GAB springs will be whether shoots die off over winter or not.

The dead shoots remain standing and, unless removed by floods, fire, stock trampling or other disturbance, tend to accumulate. Thus, in February 2006 on the Wimmera River, dead shoots consistently outnumbered live shoots: the ratio of dead to live shoots ranged from 1. 9:1 to 3.5:1 (Roberts *et al*. 2006) whereas at Mirrool Creek live shoots just exceeded the number of dead shoots (Hocking 1989a). The ratios of live to dead shoots can be interpreted as surrogate information about disturbance, but more as a guide rather than a measure. Eventually, the dead shoots either decompose or fall over, being broken down through mechanical damage such as wind, or fire, or river flooding. In isolated waterbodies such as GAB springs, removal rates are likely to be low and decomposition potentially limited by nutrients.

The underground plant parts are mainly rhizome: at Mirrool Creek, the roots accounted for about only about 20% of biomass and show little seasonal variation (Hocking 1989a). In contrast, the rhizome shows considerable seasonal variation. Maximum biomass is in late winter (August–September), then decreases very rapidly in spring as the starch storage is mobilised and used above ground by the elongating shoots. From about late spring, rhizome biomass begins to increase due to the photosynthetic activity of the young shoots, which are now translocating photosynthate downwards. Rhizome biomass continues to increase until, in autumn/winter, starch storage is mobilised to supply the young shoots, and the cycle is repeated.

Production

Production means the quantity of organic material produced over a given period of time (usually a year). Conventionally, these data are collected by harvesting a number of quadrats (directly) or may be estimated from shoot density by weight by height estimates (indirectly). Results are usually reported as dry weight (DW) per unit area (metre or hectare) but sometimes

Table 6.7: Max biomass or production estimates for *Phragmites australis* in different parts of the world

Author and Site Details	Biomass / production
Australia	
Wimmera River, Victoria Approx. 36° S Roberts *et al*. (2006)	Max biomass (from 3 sites) 1100 to 2290 g/m^2
Denmark	
Lake Aresso 56° N Andersen (1976)	Biomass in Aug–Sept Above ground 780–880 g/m^2 Below ground 2480–3600 g/m^2
Egypt	
Lake Burullus 31° N Eid *et al*. (2010b)	Biomass in Dec–Feb Above ground: 4591–7026 g/m^2 Below ground: 1384–2210 g/m^2 Production Above ground approx. 5400 g/m^2
Egypt	
Nile Delta 31° N Serag (1996)	Max. biomass 44 MT ha/ y (above) 55 MT ha/ y (total)
Hong Kong	
Mai Po Marshes Approx. 22–23° N Lee (1990)	Max biomass 21 983 g/m^2/y (above) 2884 g/m^2/y (total)
Japan	
Saitama Prefecture 31° N Karunaratne *et al*. (2003)	Production Above ground: 1980 g/m^2/y Below ground: 1240 g/m^2/y
Scotland	
Three lochs 56° N Ho (1979)	Max biomass (from three sites) 669 to 3978 g/m^2

as ash-free dry weight (AFDW) or converted to carbon (grams of carbon). Production is best estimated by taking multiple harvests from above and below ground at short (e.g. 4-weekly) intervals.

Details of annual biomass and production estimates for *Phragmites* growing beside Mirrool Creek, New South Wales are given in Table 6.6. The Mirrool Creek data can be seen as a general guide to *Phragmites* growth, but are more than that. First, these are the only whole-of-plant production data known for Australia. Second, these can be treated as a guide to potential growth of *Phragmites* on GAB springs, assuming no nutrient limitations there. The rationale for this includes: broad similarity in climate conditions; best approximation in terms of latitude; lack of stressful conditions at Mirrool Creek as reported by Hocking (1989a, 1989b) and another study (Roberts & Ganf 1986), videlicet—substrate always water-logged or shallow inundated; not fired; no evidence of stock or insect herbivory; fresh water quality; unlikely to be nutrient limited.

Compared with other sites, annual production of *Phragmites* at Mirrool Creek is considerably higher, except for possibly Egypt (Table 6.7).

Lake Bullurus, Egypt is closest to GAB springs in terms of latitude and arid climate and could be an alternative candidate for representing a potential maximum production for GAB springs (e.g. Eid *et al*. 2010b).

At the time of the study, this difference between Mirrool Creek and other production studies was attributed to climate (Hocking 1989a). Subsequent modelling (Asaeda & Karunaratne 2000, Karunaratne *et al*. 2003) has confirmed and refined this. Current understanding is that the high productivity evident in western New South Wales at 35° S is due to combined effects of longer growing season, greater radiation load and warmer temperatures (Asaeda & Karunaratne 2000).

Disregarding the possible inhibitory effects of high temperature on photosynthesis, *Phragmites* growing in permanent shallow water areas of GAB springs could be expected to be also very productive, as these environmental conditions are true for northern South Australia, where GAB springs occur at about 28–29° S. However high respiratory demands that are usually associated with higher temperatures could mean that the rhizome biomass is not as high as at Mirrool Creek.

Shoots

Growth can also be described in terms of shoot dynamics (temporal patterns through time) and their allometric characteristics (density, height, diameter, number of leaves). These tend to co-vary (e.g. Eid *et al*. 2010a) and in response to water depth (see below), disturbance and resources. Examples of shoot densities are given below, standardised to month of maximum above-ground biomass where feasible (Table 6.8).

Disturbance response

Any activity such as harvesting, grazing and burning that severely damages or removes a living shoot during the growing months will trigger the reserve buds on the rhizome to grow. The secondary shoots have different morphology and allometric characteristics, in that they are generally less dense, are smaller in diameter and may even be shorter. Even disturbances outside the growing season can affect growth. Firing part of the *Phragmites* stand at Mirrool Creek in the non-growing period, e.g. in August 1981, resulted in shoots with significantly less biomass than an unburnt area the following summer (Hocking 1989b). (Note that in this case, the treatments 'burnt' and 'unburnt' were not replicated so the finding is indicative only.)

Repeated disturbances lead to rhizome depletion and this means less subsidy for spring growth. Persistent shoot removal means that changes to allometric characteristics become more pronounced through time.

Table 6.8: Live shoot density

Author and site details	Live shoot density at time of maximum biomass (February or August)
Australia	
Mirrool Creek	February
Hocking (1989a).	Approx. 220 shoots/m^2 (read from plot)
Australia	
Wimmera River	February
(five river reaches)	61, 46, 84, 58 and 40 shoots/m^2
Roberts *et al*. (2006)	
Egypt	
Lake Burullus	(in Dec–Feb)
Eid *et al*. (2010b)	76 to 228 shoots/m^2
Japan	
Karunaratne *et al*. (2003)	August 132 m^2 (comprising 120 primary and 12 secondary shoots)
Sweden	
Three sites around a lake	August
Andersen (1976)	50.6, 54.0 and 89.4 shoots/m^2

Original data include dead shoots and sometimes give standard errors

This is nicely illustrated by an example from Maputaland, South Africa. Here *Phragmites* is an important resource and 'access to this natural capital provides a crucial contribution to their livelihood and is a buffer against poverty and an opportunity for self-employment' (van Rooyen *et al*. 2004). Continual harvesting has resulted in more and more shoots that are not of suitable quality for use. To be good quality reeds, the shoots must be more than 2.1 m tall and more than 8 mm diameter. The heavily utilised *Phragmites* stands within the park are significantly thinner and shorter than shoots from reed beds that have not been intensively utilised (van Rooyen *et al*. 2004).

6.4.3 Potential constraints

Latitude

One of the principal challenges in plant ecology is understanding how to compare plant growth across latitudes. Latitude itself is not an environmental influence but is a 'surrogate' for a mixture of regional-scale influences on plant growth, notably day length and temperature. Both day length and temperature decline with latitude (e.g. day length gets shorter the further from the equator).

The role of latitude or latitude-related factors in influencing growth is particularly interesting in the case of *Phragmites* as the plant is so widespread. This question has been addressed in different ways: experimentally, by growing plants of different provenances from across a latitudinal range of 40–66° N under standard conditions (Clevering *et al*. 2001; Lessmann *et al*. 2001); analytically, by correlating growth data from different latitudes (Karunaratne *et al*. 2003); and by modelling. None of these growth or comparative or modelling studies included *Phragmites* from environments as hot and dry as northern South Australia, or from latitudes equivalent to 28–29° S. Hence the findings are

Table 6.9: Maximum depth penetration by *Phragmites*

Author and site details	Max depths (m)
Netherlands	
Estuarine lake	0.65 m
Coops *et al*. (1994)	
Sweden	
Lake	0.85 m to 1.21 m
Andersen (1976)	
Sweden	
Lake	1.6 m, 2.0 m
Strand (2002)	
Sweden	
Eutrophic lake	0.4 m to 1.6 m
Weisner (1987)	

guidance only, in terms of helping to understand how to extrapolate mid-latitude studies to *Phragmites* on GAB springs.

The experiments measuring net growth and production (Clevering *et al*. 2001) found differences in some aspects of phenology (flowering, shoot initiation) and resource allocation (number and height of shoots, length and thickness of rhizomes), but not in others (the timing of maximal growth rate, seed size, allocation to underground biomass). A re-analysis of the data (Clevering *et al*. 2001) using degree days suggested that temperature was the driver, a finding confirmed in a separate study (Karunaratne *et al*. 2003).

In contrast, the experiment measuring growth and photosynthesis (Lessman *et al*. 2001) did not find a latitude-related effect in various photosynthetic and respiration measures, and instead concluded that in *Phragmites*, photosynthetic plasticity is far greater than genetic variability.

High temperatures

The occurrence of *Phragmites* in GAB springs in northern South Australia is not unusual because it occurs in regions and other countries under similar hot and dry conditions in permanent water bodies: artesian springs of western Queensland (Fensham *et al*. 2004), springs in Death Valley, California (Pearcy *et al*. 1974), oases in Saudi Arabia (Al Kahtani *et al*. 2007), and soaks in the Sonoran Desert (Leon de la Luz 2006). In hot climates such as these, heat stress is a potential growth constraint particularly for C3 plants such as *Phragmites* (Antonielli *et al*. 2002) as it has peak uptake of CO_2 at about 30ºC (Pearcy *et al*. 1974).

Knowledge of heat stress and its effects comes from the agricultural sector where there is concern about climate change and its effects on food production. Important points that have been established (e.g. Wahid *et al*. 2007) are: heat stress is a function of temperature and duration of exposure to high temperatures; species vary enormously in thermotolerance;

Table 6.10: Occurrence of *Phragmites* in brackish to saline habitats.

Author and Site Details	Brackish and saline conditions
Australia	
Gippsland Lakes	Tolerance limits given as: Water 0.36 to 0.73 % Substrate 0.75% to 1.20%
Coastal lakes open to sea	
Bird (1961)	
South Africa	
Estuaries	Dense beds Salinity < 15 ppt
Adams *et al*. (1992), cited in Adams and Bate (1999)	
Denmark	
Coastal habitats (27)	Salinities recorded down soil profile from 10 to 1.5 m below surface
Lissner and Schierup (1997)	

and thermotolerance is amenable to genetic control and manipulation. Heat stress can cause cellular and intra-cellular damage, result in leaf senescence and abscission, reduced yield, reduce fruit set and affect overall vigour and performance (Wahid *et al*. 2007).

The effects of high temperatures on *Phragmites* have not been studied, but two mechanisms of thermotolerance have been identified: transpirational cooling and isoprene emission. Transpirational cooling is quite effective in reducing the leaf internal temperature. It achieved a cooling effect for the leaves of 5–8°C relative to desert air, throughout a mid-summer day in Death Valley, California (Pearcy *et al*. 1974). Isoprene is a gas that is emitted within the leaf in increasing amounts as temperature and/or radiation load increases, and appears to have a role in mitigating the negative effects of heat stress on photosynthesis (Velikova & Loreto 2005).

In summary, there are at least two mechanisms that allow *Phragmites* to grow effectively in hot dry conditions and avoid (or minimise) heat stress. One relies on presence of abundant and freely-available water in the immediate environment, whereas the other relies on the plant itself. The distribution of *Phragmites* in small isolated water bodies in hot and dry environments in a number of countries including Australia is empirical evidence that *Phragmites* can cope with such conditions, even if the mechanisms are not fully understood.

Inadequate soil moisture (water stress)

The effects of inadequate soil moisture and the subsequent water stress may be a standard subject for desert species but is not much investigated in relation to wetland plants and emergent macrophytes. Only two water stress and drought studies were located for *Phragmites* (Pagter *et al*. 2005; Saltmarsh *et al*. 2006). Both are pot experiments, using relatively young plants established from seed. Both focus on standard physiological questions regarding short-term effects (11 days, 46 days respectively) of an imposed water stress (withholding water, watering at a reduced rates) on photosynthesis, growth and production. The effects of sustained stress on life cycle, persistence or reproduction have not featured in the literature.

Not surprisingly, given its distribution and strong association with aquatic habitats, these experiments found *Phragmites* shoots were quite sensitive to water deficit. Leaf production and leaf growth, and hence also leaf area, were reduced when watering was reduced to only 60% (Pagter *et al*. 2005). Although

Phragmites could increase its osmolality, which is an adaptive response typically involving glycinebetaine or proline, this response was not evident until too late (Saltmarsh *et al*. 2005).

Although interesting, these pot experiments give little information that can be readily transferred to GAB springs. The plants used were relatively young, (between 15 and 100 cm tall) rather than well-established (e.g. 2–3 m tall) shoots. Plants were stressed relatively briefly, for either a short period under temperate conditions, such as 46 days in a growth cabinet at 18–22ºC (Pagter *et al*. 2005) or else for very short period under warm-hot conditions, such as 8 to 11 days at 16.8–38.5ºC (Saltmarsh *et al*. 2006). The conditions and set up used in these experiments focused on leaves and do little to inform the question of survival and persistence of water stressed *Phragmites* in a field situation in central Australia.

Water depth

Established stands of *Phragmites* can grow in water as much as 1.6 m deep (Table 6.9). Maximum depths determined experimentally tend to be shallower (e.g. 80 cm (Coops *et al*. 1996) and 95 cm (Squires & van der Valk 1992)).

The maximum depth at which an emergent macrophyte such as *Phragmites* can grow is determined by its capacity to provide oxygen to its rhizome, which is a species characteristic, modified by site characteristics.

Phragmites is one of several species of tall emergent macrophytes that does not rely on air diffusing downwards to the rhizome but that actively pressurises air within the plant and creates a downward convective flow (Brix *et al*. 1992, Vretare & Weisner 2000). *Phragmites* is particularly effective at this because its internal structure is fairly open and so offers little resistance to the movement of air from the leaf sheath down the culm and into the rhizome (Brix *et al*. 1992).

In *Phragmites*, this capacity is not plastic. Unlike some emergent macrophytes, it does not modify its internal structure as water gets deeper (White *et al*. 2007) although it does change its resource allocation patterns in response to water depth. In deeper water, the shoots are taller but fewer (less dense) and the rhizome does not penetrate so deeply into the substrate (Vretare & Weisner 2000, Coops *et al*. 1996). The maximum depth at which *Phragmites* can grow is reduced by factors such as wave exposure (Coops *et al*. 1994).

Water depth, in particular submergence, is important at early stages in life cycle of *Phragmites*. Germination is significantly reduced under water compared with on moist soil (Coops & van der Velde 1995) and seedlings cease growing when submerged (Coops & van der Velde 1994, Weisner *et al*. 1993). The length of time that seedlings can survive being totally submerged and remain alive is not known but within their first year it is at least four weeks (Mauchamp *et al*. 2001).

It is clear that water depth in the pools and on the tails of GAB springs is unlikely to stress established *Phragmites,* as only rarely (e.g. large pool at Dalhousie Springs) is it deep enough to be limiting. Water depth is also unlikely to stress seedlings, because these already have an in-built tolerance of being submerged. The presence of surface water may reduce seed germination.

Salinity

Salinity (the saltiness of water) and conductivity are often used interchangeably for convenience, although this is not strictly correct. Salinity can be expressed using different units, (i.e. mS/cm, ppm etc.).

Although it is generally described as a freshwater macrophyte, *Phragmites* also occurs in middle and upper reaches of estuaries and in brackish habitats, including salt marshes and estuaries: examples of salinity levels for such field sites are given below (Table 6.10).

In coastal Denmark, *Phragmites* was found growing in salinities of up to 15 ppt in the substrate: it also occurred at higher salinities but at these salinities *Phragmites* died before flowering (Lissner & Schieurup 1997). In estuaries, surface water is a poor indicator of salinities around the roots (Lissner & Schieurup 1997, Adams & Bate 1999). In coastal Denmark, salinity tended to decrease down the profile such that salinities around the stems, which were bathed by sea water, were much higher than salinities in the root zone. Thus, although *Phragmites* has been recorded growing in lower reaches of estuaries in salinities close to seawater, e.g. 35 ppt (Adams and Bate 1999), this was actually an observational artefact: in fact, the water in the root zone was fresher than water round the stems, (i.e. *Phragmites* was on a freshwater seepage site). Testing these findings in a growth experiment showed that *Phragmites* growing in a root-zone salinity of 20 ppt had shorter stems and more dead leaves than *Phragmites* with a root-zone salinity of 0 ppt (Adams & Bate 1999).

Increasing salinity affects different aspects of growth at different levels of salinity. When *Phragmites* is grown from rhizome cuttings, relative growth rates based on weight show a strong optimum at 5 ppt then decline at higher salinity levels; leaf production is highest at 2.5 ppt, and then declines; growth rates based on height or number of shoots are the same at 0 ppt and 5 ppt but then decline. Seedlings show similar symptoms and growth responses but are more sensitive to salinity (Lissner & Schieurup 1997).

Phragmites is believed to have two mechanisms for tolerating salinity: osmotic adjustment and cation adjustment, which is active exclusion of sodium ions (Brix 1999). Osmotic adjustment can be effective up to 22.5 ppt but is not so effective for seedlings and juvenile plants which suffer salt stress at 10 ppt and above (Lissner and Schieurup 1997). Osmotic adjustment may be effected through water loss (acting to concentrate solutes) rather than by synthesising metabolically expensive solutes (Lissner *et al*. 1999a). This has implications for *Phragmites* in warm and hot climates, for it suggests that salt tolerance may increase under high transpiration (Lissner *et al*. 1999b).

6.5 Invasion theories and invasiveness

6.5.1 Factors driving colonisation

This section discusses the three principal drivers of colonisation and their components (listed in Section 6.2.3) in the PABH framework (Catford *et al*. 2009) in terms of *Phragmites* ecology and biology.

Propagule pressure (P)

Only three of the five components of propagule pressure are considered here:

- number of propagules per introduction
- frequency of introduction
- dispersal modes and avenues.

One of the other two components relates to the potential for human interference and the other refers to assumed or default characteristics.

Although there are no data quantifying the numbers of seeds or vegetative fragments reaching the GAB springs, or their timing or their pathways, a qualitative but informed judgement can be made based on the preceding review.

In terms of number of propagules per introduction arriving, the reproductive biology of *Phragmites* suggests this is likely to be very low. Evidence for this is that the seed set is

Photo: Travis Gotch

variable but generally low, and is reduced by stresses such as thermal conditions; the number of flowering stems is also variable, and is also reduced by stressful conditions such as low water availability and increasing salinity.

The frequency of introduction is likely to be annual for seeds, assuming that *Phragmites* at the source stage flowers each year, but restricted to a few months only. Mature seeds are normally shed in late winter or spring and this restricts dispersal to a particular time of year.

Dispersal modes and avenues are diverse, with wind, waterbirds and humans implicated for the transport stage, and wind, water, waterbirds, stock and other animals as well as humans implicated for spread stage. However, although *Phragmites* seeds can be dispersed by different means, the requirement for seeds to travel considerable distances over an intervening landscape that is generally inhospitable for a water plant, suggests there is very little chance of seeds arriving successfully by non-targeted dispersal strategies. Numbers of seeds arriving is assumed to be much higher through targeted by agents such as water birds and human interference. People carrying plant parts, whether accidentally or deliberately, is seen as the only effective means of transporting vegetative fragments.

In summary, propagule pressure from *Phragmites* on GAB springs is probably very low.

This finding is not surprising. It is consistent with the general understanding about the reproductive strategies and resource allocations of herbaceous clonal plants and of rhizomatous emergent macrophytes, in particular (Clevering & Lissner 1997). It is also consistent with empirical studies of genetic diversity in Europe and in North America. These have found little to no evidence of sexual recruitment, except in the specific case of the novel genotype in North America.

Abiotic characteristics (A)

All four components of abiotic characteristics are considered here, albeit briefly.

For resource availability, the critical resource for *Phragmites* in the arid climate of northern South Australia is water. Water is needed for metabolic processes such as photosynthesis and respiration throughout its life cycle. If inadequate, the plant experiences stress, loss of vigour and may die. Although difficult to quantify what ‘adequate’ means in field terms, water needs to be present in sufficient abundance, such as shallow water or permanently saturated soil, to meet the apparently high transpiration demand that *Phragmites* has for it to be a cooling mechanism and saline-tolerating mechanism.

The second component, conditions and regime, considers to what extent changes to the GAB spring environment are facilitating the 'invasion' of *Phragmites* on GAB springs. *Phragmites*, especially its young growth, is highly palatable to cattle hence excluding them would certainly provide the opportunity for *Phragmites* to establish, gain vigour and persist, whether as germinating seeds or as shoots from existing rhizomes.

The third component, episodic disturbance, is potentially very relevant to *Phragmites*. Episodic water level drawdown that exposes un-vegetated mudflats is widely recognised as providing the conditions appropriate for large-scale regeneration of wetland plants such as *Phragmites* (Clevering & Lissner 1999, van der Valk 1981). Such circumstances do occur on GAB springs and within spring groups where there can be considerable flow variation and fluctuation down the tail, leaving soils saturated 'for considerable lengths of time' (see Volume IV (Lewis *et al.* 2013) for more detail).

The fourth component, geographic location, is the temporal and spatial distribution of critical resources in the landscape. GAB springs are permanent and therefore reliable patches of water although relatively tiny in a landscape where surface water availability is low, brief and uncertain.

In conclusion, the abiotic characteristics of GAB springs are clearly significant for *Phragmites*, although as these vary at fine temporal and spatial scale, the challenge is to 'locate' where the favourable and unfavourable conditions are predictably and with confidence.

Biotic characteristics (B)

Of the six components under biotic characteristics, only one, invader traits, is considered here. The other five components, although linked to *Phragmites* success, relate to its interactions with other species and ecosystem consequences, topics that have not been considered in this review.

The rhizome is without doubt the key to success of *Phragmites*. Its large carbohydrate storage and bud reservoir, its seasonal growth that results in yearly renewal and multi-aged populations, its life expectancy of about five to six years, and is position safely at depth within the substrate, in combination confer both resistance and resilience.

In terms of biotic characteristics, the rhizome is a formidable ecological trait.

6.5.2 Relevance of leading hypotheses

The PABH framework synthesised by Catford *et al*. (2009) effectively dispensed with individual models and theories of invasion success by focusing instead on their emergent properties which were recognised as the four driving factors of propagule pressure, abiotic characteristics, biotic characteristics and human interference. Despite this conceptual advancement, it is instructive to revisit, briefly, the 29 leading hypotheses that were identified, as an individual theory may prove useful in framing a null hypothesis for experimental research. The hypotheses are listed in Appendix 5 and summarised below.

Photo: Travis Gotch

Based on the evaluation of propagule pressure, abiotic characteristics and biotic characteristics given above, the following points can be made:

- hypotheses based on propagule pressure are unlikely to be relevant to understanding invasion success of *Phragmites* on GAB springs (PP, GC, SP and IW: numbers 1 to 4 in Table A5.1, Appendix 5)
- hypotheses based on modified abiotic conditions (i.e. natural conditions no longer exist) are not relevant (ADP: number 27 in Table A5.1, Appendix 5)
- hypotheses based on abiotic factors as high supply of resources (water) are very relevant (IRA, DS, DE, OW, R-ER, N: numbers 22, 23, 24, 26, 28 and 29 in Table A5.1, Appendix 5)
- hypotheses based on abiotic factors as environmental conditions at the time are relevant (HF, EVH, ADP: numbers 20, 21, 27 in Table A5.1, Appendix 5)
- hypotheses based on biotic factors such as invader traits are relevant (GC, SP, IW and EICA: numbers 2, 3, 4 and 11 in Table A5.1, Appendix 5).

Note that this list is not exhaustive. Other leading hypotheses such as those relating to community interactions (a component of biotic factors) may also be relevant but are not included here as these were not part of the review.

Human interference (H)

A shortcoming of the 29 leading hypotheses is, with the exception of PP which is number 1 in Table A5.1, Appendix 5, their failure to explicitly identify or test for human interference.

GAB springs have a long history of usage as a resource, especially as a water resource, first by Aborigines (e.g. Badman 2000) and later by settlers following European settlement. Settlement has seen a succession of different types of ‘users’: pastoralists and drovers, missionaries, railway workers, travellers and, more recently, conservation and tourists (e.g. Anonymous undated; Lewis 2001).

These users should all be considered as candidates for human interference on account of their potential to modify the three driving factors. Preparing a robust and comprehensive list of these opportunities and evaluating the likelihood of each is a necessary step when undertaking a retrospective or ‘forensic’ analysis of invasion success. For this, it would be helpful to distinguish between deliberate (intended) and non-deliberate (i.e. not the focus, equivalent to co-lateral damage) alterations to propagule pressure, abiotic characteristics and biotic characteristics.

Potential examples of human interference relevant to the GAB springs are:

- propagule pressure—deliberate propagation, assuming that *Phragmites* is or has been useful; inadvertent dispersal by travellers
- abiotic characteristics—changes to spring morphology due to stock trampling; changes to spring discharges due to utilisation; changes to water quality through contamination and faecal pollution
- biotic characteristics—presence of large herbivore altering ecological interactions.

6.5.3 PABH framework

The PABH framework departs from considering individual hypotheses by emphasising that it is the coincidence, in space and time, of all three driving factors that makes an invading species successful rather than a single factor. This is illustrated as the point of overlap, designated as successful invasion in Figure 6.5.

A successful invasion is when all three drivers provide favourable circumstances at a particular point in time and space. The temporal or spatial characteristics of the intersection may be shaped by the fourth driving factor, human interference (not shown). The diagram is based on Figure 1 in Catford *et al*. (2009).

6.6 Responses to the three questions

6.6.1 Question 1

The first part of Question 1, ‘Are GAB springs that are currently grazed by cattle and apparently free of *Phragmites* at risk of being colonised by *Phragmites* if cattle are removed?’, is about the colonisation process for *Phragmites* on GAB springs.

The geographic colonisation model (Figure 6.3) makes a clear distinction between the transport stage and spread stage. For *Phragmites* and GAB springs, transport is the initial stage, and

Figure 6.5: Successful invasion as an intersection in space and time

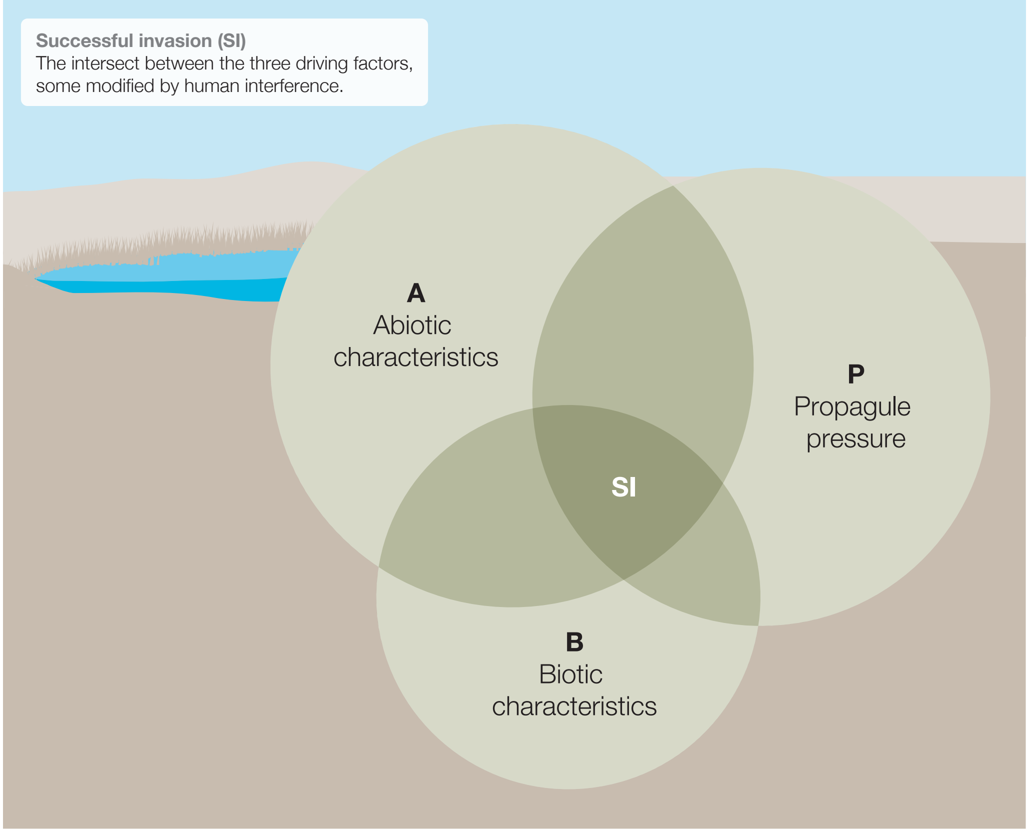


Figure 6.6: *Phragmites* patch on banks of Murrumbidgee River

A 3–4 m tall stand of *Phragmites australis* protected from cattle grazing by fallen trees on the banks of the Murrumbidgee River near Redbank Weir, NSW. Contrast the height of shoots protected by large fallen timber (centre) with shoots that are not so well protected (left).

Not shown (and hard to photograph effectively) are residual shoots found further back on the floodplain, away from fallen trees, that were completely unprotected and reduced to 5 cm tall brown brittle 'stumps'. Photograph: Jane Roberts, 27 March 1990

targeted dispersal such as by waterbirds to GAB spring habitats suitable for *Phragmites* is more likely to contribute viable propagules than random and non-targeted dispersal. However, physical factors (such as the distances involved and the relatively low occurrence of *Phragmites* seeds in droppings of nomadic and migratory waterbirds) combined with some distinctive traits (notably low fertility and low fecundity in *Phragmites*) collectively suggest that remote and isolated GAB springs are at a very low risk of being colonised as a result of transport by waterbirds.

Dispersal by people is the only other means by which viable propagules could arrive at GAB springs in a targeted way over such distances. Whilst it is impossible to envisage the full range of potential pathways for dispersing propagules, transport by people is considered, on balance, to also present a low risk.

Similar arguments and considerations apply to the spread stage, which is more localised dispersal over shorter distances, but with the notable exception that water-dispersal and stock-assisted dispersal may be relevant in certain circumstances.

In summary, GAB spring colonisation by external propagules is considered a very low but not impossible risk. This assumes that *Phragmites* is no longer present and has definitively been eliminated from the GAB spring in question.

Assumptions

Two assumptions are embodied in Question 1. One (explicit) is that an area is 'apparently' free of *Phragmites*; the other (implicit) is that there is a linkage between cattle removal and the successful establishment of *Phragmites*.

Table 6.11:Growth measures or observations of *Phragmites* on GAB springs

Author and site details	Habitat
Coward Springs	
Symon (1985)	'Down the side of the mound is a large breakaway from whence most water flowed. This part was once protected by a fence now derelict. However, where access by stock was a little more difficult *Phragmites* reaches 2 m high …'
Dalhousie Springs in 19th century	
Cohen (1989) reporting on Giles comments on arriving at Dalhousie Springs in December 1870.	'… an almost illimitable expanse—welcome sight!—waving green reeds, with pools of water at intervals, and dotted with island cones topped with reeds or acacia bushes …' Cohen (1989) reports that the reeds grew 'thickly' and were up to 18 feet or 5.5 m tall.
Dalhousie Springs in 19th century ?	
Symons (1984), citing Richards (1914).	'The reeds where we struck the springs—(I measured one) were 17 feet high and as thick as your finger.'
Hermit Hill Springs	
HHS 131 mound Fatchen (2001)	Spring selected for monitoring in 1987 on account of not being dominant by *Phragmites*. Within five years, *Phragmites* has expanded, reached its peak and effectively capped the vent.
Hermit Hill Springs	
(Travis Gotch, pers. comm. September 2010).	In November 2004, shoot height was 4.9 m at the vent.
Of mound springs fenced in 1984–1988	
Lewis (2001)	'During the last two to three years there has been evidence of senescence in the stands of *Phragmites* and *Typha*.'
Hermit Hill Springs	
Davies (2001)	Shoot biomass values in excess of 10 kg m^{2} were calculated for the centre of the monitored springs.
The Fountain	
Big Cadna-owie Anonymous, Undated	*Phragmites* up to 3 m high. Growth up to 4 m tall.

Young leaves of *Phragmites* are highly palatable to cattle and therefore it must be assumed that any *Phragmites* present on a GAB spring that is open to cattle will be subject to grazing pressure, unless the plant is inaccessible due to fencing or other impediment (Figure 6.6). Grazing can severely reduce the above-ground biomass and cover of *Phragmites* stems to the point where its cover is negligible, having been eaten down to a few insignificant and anonymous stumps. However, even if all shoots are completely eliminated, there is still the rhizome, which is much longer lived, and is likely to be still present in the ground. In this case, the GAB spring may appear 'free of *Phragmites*' but is actually only free of above-ground material.

The second part of Question 1, 'If *Phragmites* can be controlled to the point of being eliminated, then is it likely to re-establish?', is effectively already covered above (and assumes that elimination includes the rhizome and does not just refer to the canopy).

Photo: Travis Gotch

6.6.2 Question 2

Answering the second question, 'Is it possible that *Phragmites* has reached its maximum or near maximum extent on some GAB springs?', requires information, in the form of data, on growth and distribution of *Phragmites* on the GAB springs, expressed in terms that convey vigour and context.

Such data are not currently available, and the question is not answered.

Information that is available on *Phragmites* growth on GAB springs in South Australia is very sparse (Table 6.11). There are also photographs and transects where cover is recorded (e.g. Fatchen 2001a).

Points to note from Table 6.11 are:

- information is generally sparse and semi-quantitative
- only one growth measure is used at a time, usually height
- instances of heights of 3–4 m indicate locations favourable to *Phragmites* growth
- early records of heights greater than 3 m are interesting but their accuracy and precision is not assured
- indirect estimates of *Phragmites* biomass at Hermit Hill as 'in excess of 10 kg m^2' are similar to maximum biomass recorded for Mirrool Creek (Table 6.6) of 9.8 kg m^2
- cover is useful for monitoring gross changes in distribution through time but is an insensitive measure of *Phragmites* vigour.

None of these comments are linked to habitat characteristics, whether pool or tail.

6.6.3 Question 3

The third question 'Why is *Phragmites* invading GAB springs?' does not have a single answer. The PABH framework makes it clear that the presence and persistence of an invading species, such as *Phragmites* on GAB springs, is the outcome of a set of favourable conditions that have coincided in time and space (Figure 6.5).

However, it seems unlikely that *Phragmites* is actually invading at present, and it is more likely that it *Phragmites* is in fact re-establishing, in a manner well-anticipated by Symon (1985) who considered that *Phragmites australis* 'is one of the plants likely to respond spectacularly if areas are protected from grazing'.

6.7 Possible management actions

This section outlines some straightforward activities that would put future management of *Phragmites* on GAB springs onto a firmer base. These activities are all relatively minor, so are distinct from investigations or monitoring programs.

6.7.1 Action 1: Investigate colonisation risk

In the case of a specific GAB spring where it may be planned to remove cattle but colonisation by *Phragmites* is feared, then the likelihood of this happening could be investigated by:

- identifying distances and orientation to existing stands of *Phragmites*
- documenting and evaluating possible dispersal pathways and avenues, considering both seeds and fragments; for example, direction of prevailing winds, movements by people (connecting roads, tracks), movement by stock and by water-dependent feral animals
- establishing whether the risk is spread or transport, in the sense used in this review.

The factors driving dispersal during the transport stage may be quite different from the factors driving dispersal during the spread stage, and the catalytic role of human interference may be quite different.

6.7.2 Action 2: Investigate possibility of present but not noticeable risk

The likelihood that *Phragmites* is already present but grazed to such an extent that it is not contributing to estimates of plant cover, can be evaluated by:

- checking all forms of historical records for mention of tall reeds (herbarium specimens, visitors accounts, previous studies not just of plants but any reliable natural history observer, photographs, Aboriginal importance, historical information such as station records, bore logs)
- setting up temporary exclosures in likely habitat patches (solar-powered electric fencing, or re-assembled portable robust barriers)
- closely inspecting ground surface at the time of year when new shoots are likely to be emerging.

6.7.3 Action 3: Investigate the risk of viable seeds being present

The risk that a GAB spring apparently free of *Phragmites* may have seeds present can be checked by:

- application of the emergence technique to sediment samples to check for the presence of viable *Phragmites* seeds.

This action is suggested only for completeness. The generally low numbers of *Phragmites* seeds usually recorded in seed banks present sampling problems and this action is not expected to be a reliable indicator.

6.7.4 Action 4: Determine vigour by investigating habitat quality

Habitat quality for *Phragmites* on a GAB spring can be considered in terms of resource gradients, by focusing on the most critical resource—water. A spatial conceptualisation of how *Phragmites* vigour (height, density, biomass, flowering stems) might be distributed based on a simple concept of a GAB spring (Figure 6.7) is given below.

The model is indicative only and would merit being refined and improved. Records of vigour should be done at a time of year when the plant is expected to be vigorous (notionally spring, or September through October).

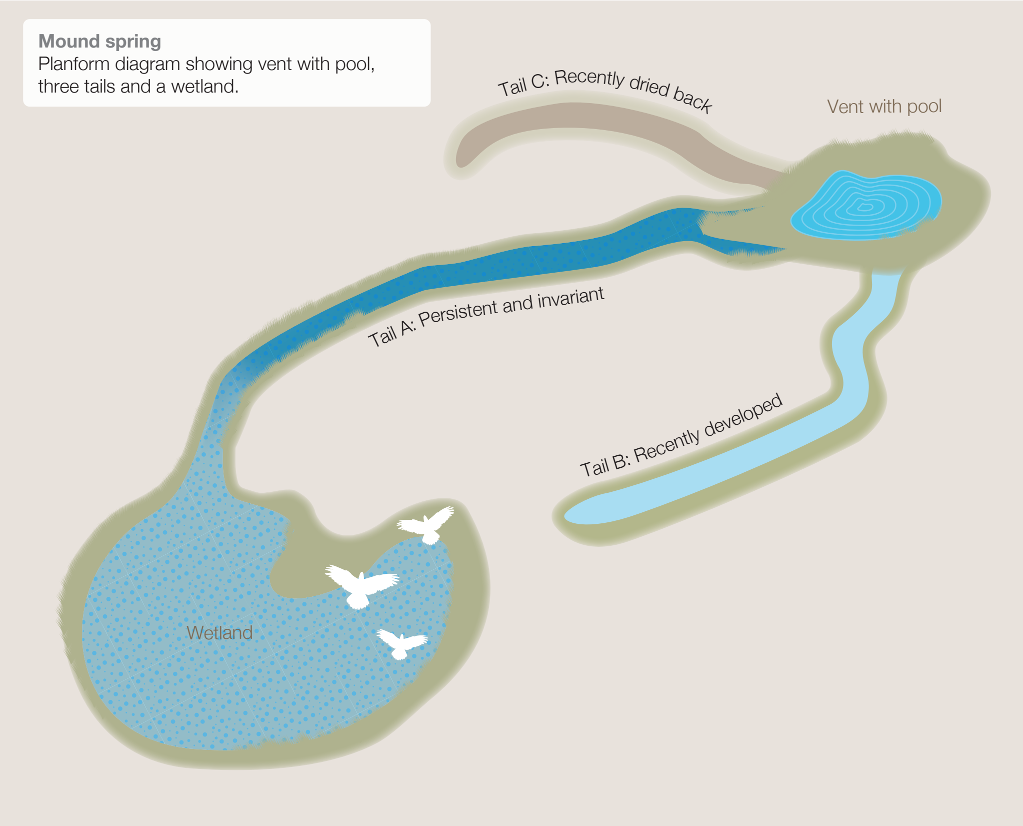


Figure 6.7: *Phragmites* habitats on a GAB spring

- Pool associated with vent: high vigour and high quality if shallow (to 35 cm), trending to sub-optimal (to 75 cm) and too deep (if > 150 cm).
- Tail supplied persistently and reliably from main vent (Tail A): high vigour and high quality but possibly trending to medium or sub-optimal, depending on flow volume; rending depending on flow downslope (i.e. high availability).
- Tail that has recently formed (Tail B): young growth, potentially high quality, depending on discharge; if a trickle, then low quality and *Phragmites* unlikely to expand into this.
- Tail that is weakening or has recently ceased to flow (Tail C): old growth, senescing, losing vigour as habitat quality degrades.
- Wetland receiving spill from main vent: quality, as a *Phragmites* habitat is dependent on reliability and volumes, and whether salinising.

7

Grazing management

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7. Grazing management

7.1 Background

This chapter summarises a review of the effects and impacts of grazing in riparian and spring environments along with a community survey into the values of Great Artesian Basin (GAB) springs involving a wide range of stakeholders. The full review and community survey are available by application to the South Australian Arid Lands Natural Resources Management Board (SAALNRMB).

7.2 Summary of SAALNRMB grazing management of desert waterholes and springs report, as it relates to GAB springs

On the whole, grazing has the potential to negatively impact on spring vegetation, as demonstrated by the loss of focus group flora diversity as grazing pressure increases (Chapter 5). However, the majority of GAB springs on the western margin of the GAB are located on pastoral leases (Figure 7.1) and it is therefore important that grazing management and strategies around minimising stock impacts on springs be considered. Also important is the management of nutrient loads and vegetation regrowth after the removal of grazing. As noted in Chapter 6, Symon (1985) was correct in his prediction of the spectacular recovery of *Phragmites* after grazing pressure was removed. This has resulted in impacts on spring endemic and relict fauna being reported (Davies *et al*. 2010).

There are very few studies on grazing on artesian springs, particularly on GAB springs. To date, all have reported significant loss of biodiversity as a result of heavy grazing (Kovac & Mackay 2009; Lewis & Harris 2009; Davies *et al*. 2010; Chapter 5). However, Kovac and Mackay (2009) and Section 5.2.3 found that low levels of grazing positively increased the diversity and abundance of some invertebrate groups and flora respectively.

Based on general grazing practices, stakeholder input (Lewis & Lay 2010) and observations of grazing pressure and impacts (Gotch pers. obs.), a number of recommendations for best-practice grazing management have been developed to reduce the impact of grazing. In summary, they are that:

- fenced exclosures should include the whole ecological focus zone, or more
- introduction of new stock in a paddock should be located near a bore or dam rather than on a spring
- stock should not be moved directly from areas with known wetland weeds into areas with relatively weed-free springs
- grazing impacts can be minimised using a low stocking rate or pulsed grazing where the rate of pulse grazing is modified according to the stock density.

Photograph on facing page: Travis Gotch

Photo: Travis Gotch

Further research is recommended to establish optimum grazing regimes, including sustainable carrying capacity, any differential seasonal impacts and recovery times for pulse grazing. This would be assisted through collection of additional on-ground data on actual stocking rates, and time of grazing, and the density and spatial arrangement of springs in a management area. Clarke *et al.* (Section 5.2.3) identified that floristic diversity increased with the number of active vents. This needs to be examined further, as observations by the author (Gotch) and feedback from pastoralists (Greenfield, Sims, Crozier pers. comm.) have indicated that the spatial arrangement of spring groups influence the grazing behaviour of cattle. This is most evident at spring groups such as at Francis Swamp, Billa Kalina and Hawker Springs, as grazing impacts tend to be greatest at the outer springs and diminish further into the group.

Grazing and spring management are not mutually exclusive and, given the number of springs on pastoral leases, this is a good thing. However, grazing (like any impact) must be carefully managed, especially in GAB springs where large diversities of short-range endemics exist.

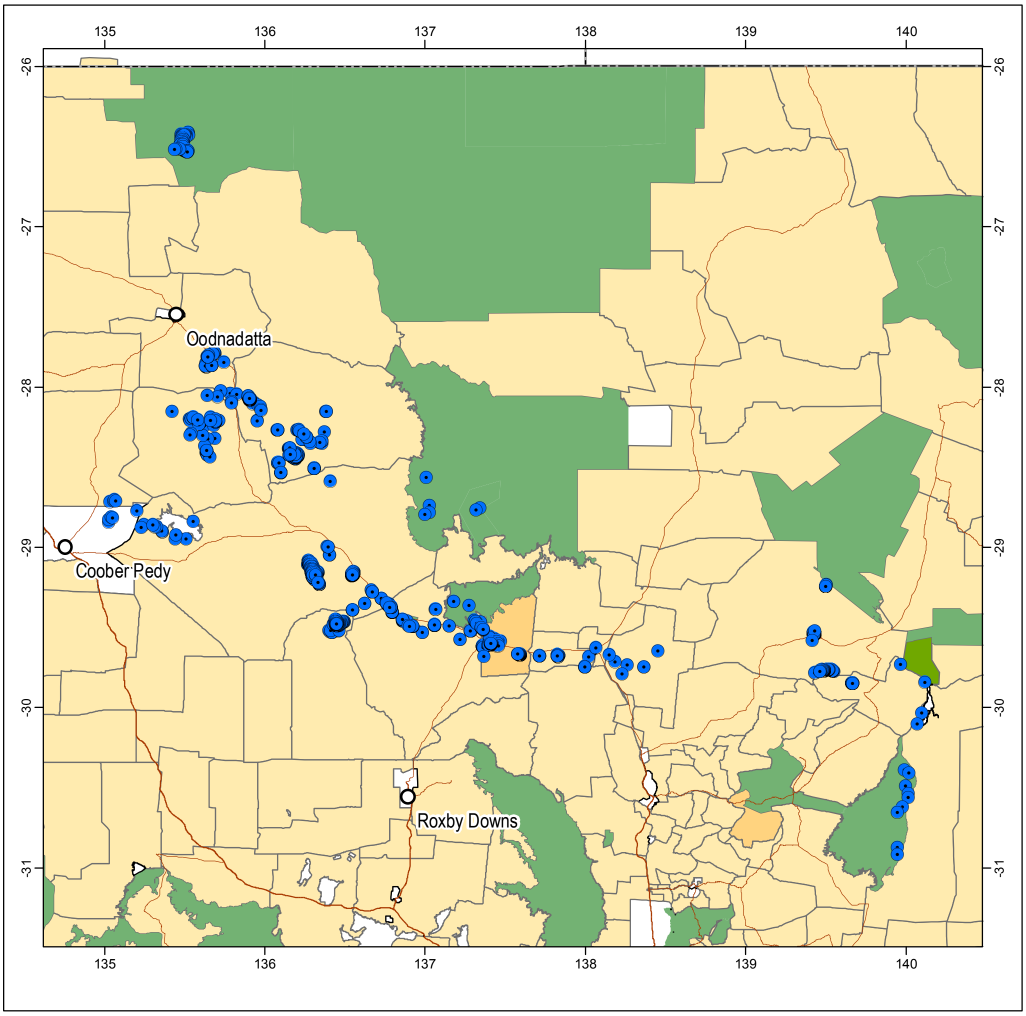


Figure 7.1: Spring distribution and land tenure

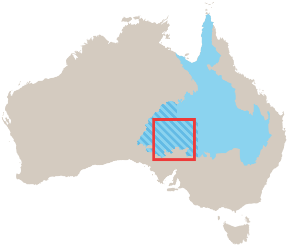
Legend
- ● GAB Springs
- ○ Town
- — Primary Road
- — Secondary Road

Land Tenure
- ▨ Pastoral Lease
- 🟩 National Parks Reserve
- 🟩 Fossil Reserve
- ▨ Aboriginal Reserve
- ☐ Other

0 40 80 120 160
Kilometres

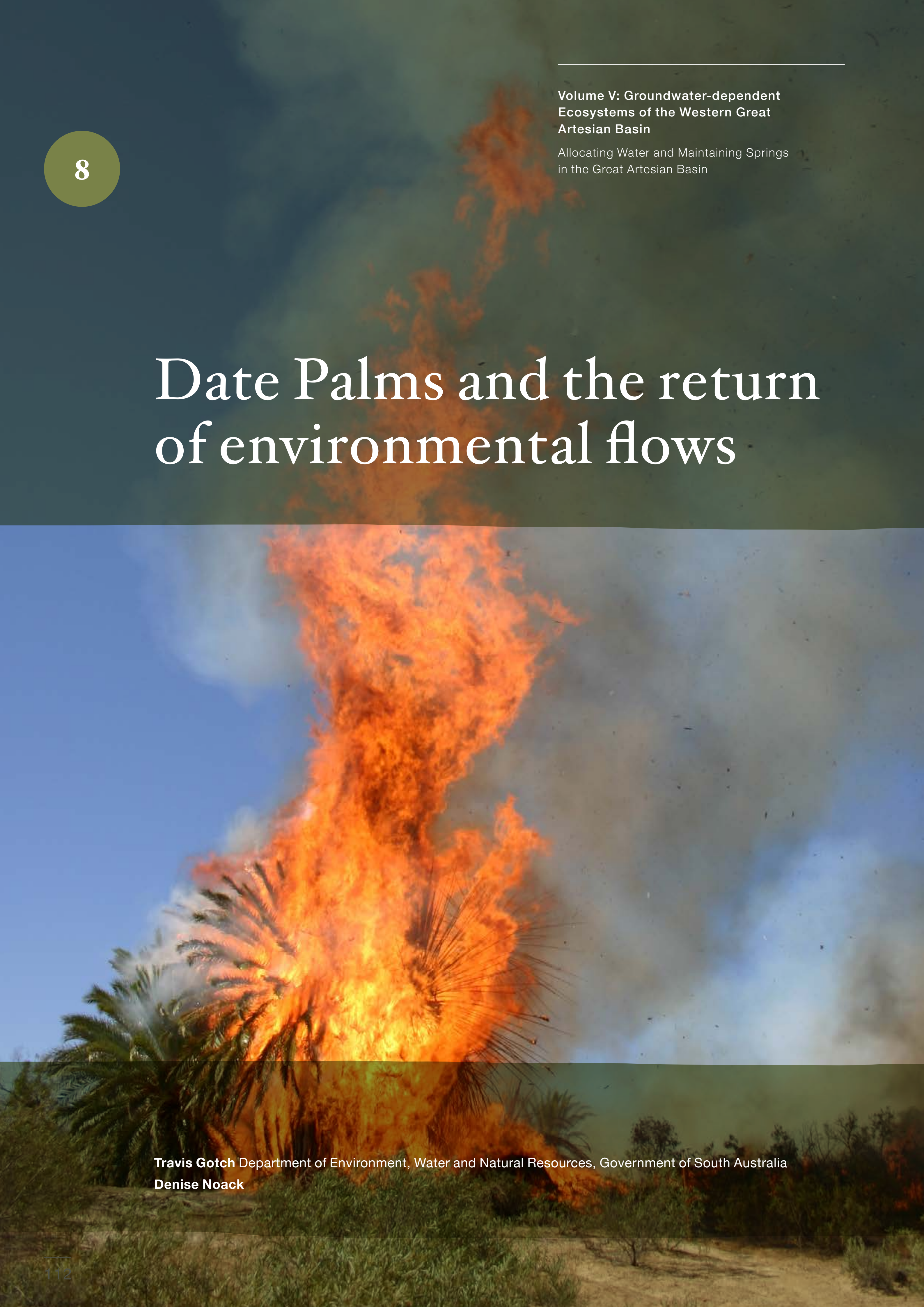
N

Produced by SAALNRMB
Map Projection: Lambert Conformal Conic
Map Datum: Geocentric Datum of Australia 1994
Date: February 2012



8

Date Palms and the return of environmental flows



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8. Date Palms and the return of environmental flows

This report shows that by removing Date Palm (*Phoenix dactylifera*) from the National Heritage listed Dalhousie Springs site, significant returns of environmental flows were achieved. In addition, removing invasive trees provided significant positive benefits for this unique habitat. This work contributed to National Water Initiative outcomes by returning environmental flows to a significant groundwater-dependent ecosystem of high conservation value.

8.1 Introduction

8.1.1 Dalhousie Springs

Dalhousie Springs, located at Witjira National Park in the north of South Australia, is one of 13 supergroups located around the margins of the Great Artesian Basin (GAB) (Figure 8.1). It is also the only supergroup to contain a single complex of springs. The Dalhousie Springs are considered to be of extremely high geological, biological and cultural conservation significance (Harris 1981; Zeidler & Ponder 1989; Harris 1992; Morton *et al*. 1995).

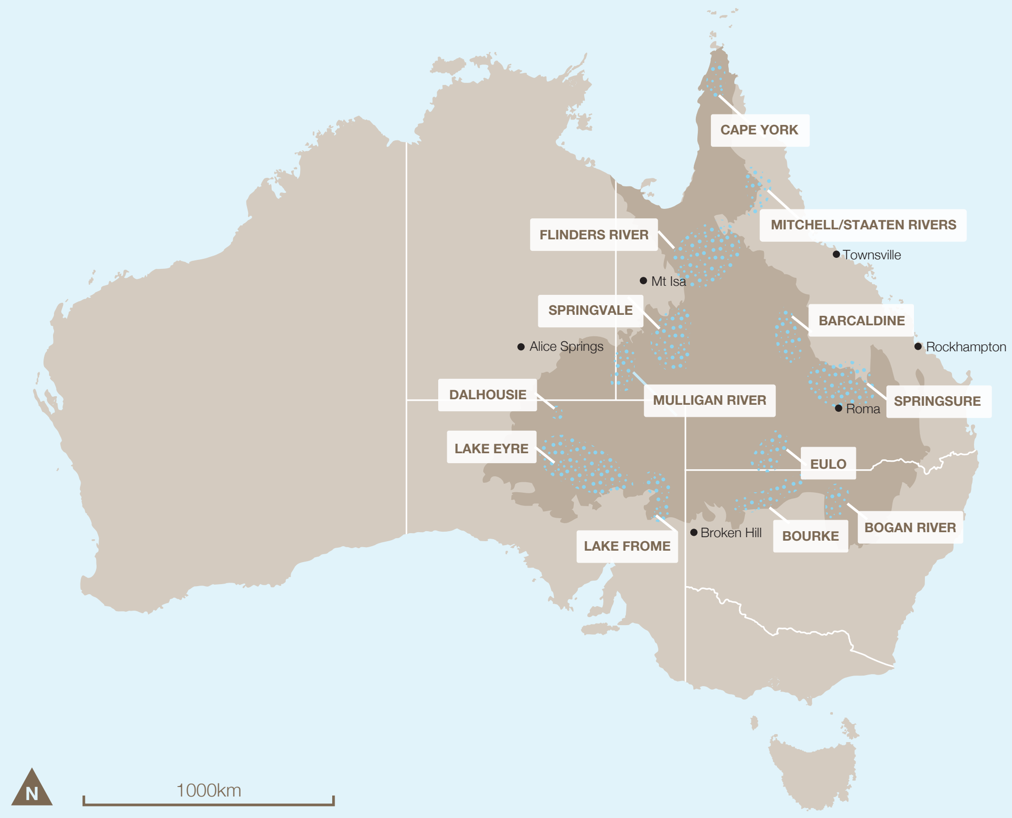

Figure 8.1: Distribution of spring supergroups of the GAB (adapted from Habermehl 1982; Cox & Barron 1998; Fensham & Fairfax 2003)

Photograph on facing page: Travis Gotch

Dalhousie is the most biologically significant spring complex in Australia, with 32 confirmed relict, rare or endemic species (Gotch 2005). It also has one of the highest levels of short-range endemism-against-area recorded (Gotch *et al*. 2008). As a permanent source of water, the springs were and continue to be an important site for the traditional owners. The springs at Dalhousie are important features of many *Altyerre* (secret/sacred cultural stories and song-lines) and extensive archaeological deposits around the springs are evidence of their long-term use (Ah Chee 2002). Because of this, the Dalhousie Springs were listed on the National Heritage register in 2009 and more recently were ranked the highest conservation priority aquatic ecosystem in the Lake Eyre Basin (Hale 2010) despite the ranking system not including invertebrates.

There are a total of 148 spring vents distributed across 13 spring groups at Dalhousie Springs (Figure 8.2); see Volume IV: Spatial Survey and Remote Sensing of Artesian Springs (Lewis *et al.* 2013) for more information. The wetland created by these spring vents has an area of approximately 1200 ha, though this can vary slightly as a result of fluctuations in flow (White & Lewis 2011). Sibenaler (1996) estimated flows at Dalhousie to be around 54 ML/day but, using the tool developed by White and Lewis (2011), flows for the entire spring complex are estimated at 60 ML/day.

The vegetation of Dalhousie Springs is much more complex compared to other GAB Springs in South Australia. Including the between-spring habitat, Mollemans (1989) identified 82 species of plant in 44 plant communities based on the dominant species in the tallest stratum and vegetation structure. This shows *Phragmites australis* reed lands as the most dominant wetland vegetation community accounting for an estimated 75% of the spring-related vegetation in terms of its aerial extent. A detailed inventory of the plant species at Dalhousie has subsequently recorded 104 species (Noack 2005). Other spring vegetation includes *Melaleuca glomerata* woodlands, rushes (*Juncus krausii*), sedges (*Baumea arthrophylla, B. juncea, Bolboschoenus caldwellii, Cyperus laevigatus, C. gymnocaulis, Eleocharis geniculata, Fimbristylis sieberana, Isolepis cernua*) and the bulrush, *Typha domingensis*. Many of these species are restricted in their distribution in central Australia (Social and Ecological Assessment 1985; Mollemans 1989; Noack 2005).

There are 32 species of significance (endemic, relict or rare) listed within the Dalhousie Complex (Gotch 2005).The springs support a range of invertebrate species including endemic crustaceans (amphipods, isopods, ostracods, cladocerans, shrimps and crayfish), molluscs (hydrobiid snails) and five endemic fish (Gotch 2005). A total of 155 native bird species have been reported at Dalhousie, including 56 species of waterbird and several species of migratory waders (Noack unpublished data 2004). Vertebrate species include two frogs, numerous reptiles and several mammal species. It is this diverse and unique flora and fauna that make Dalhousie one of the great biological treasures of the world.

8.1.2 Date Palms

The Date Palm (*Phoenix dactylifera*) is one of the most widely cultivated food crops in the world, second only to citrus in overall production (Zaid 2002). Native to the area around the Persian Gulf and across North Africa, they have been in continuous cultivation for over 7000 years (Potts 2002). *Phoenix dactylifera* is a large dioecious palm that reaches up to 30 m in height. It has a relatively thick trunk covered with persistent woody leaf bases which provide protection from water loss and fire. After the first few years of growth numerous suckers arise from the base of the tree, creating thick clumps of palms with multiple canopies.

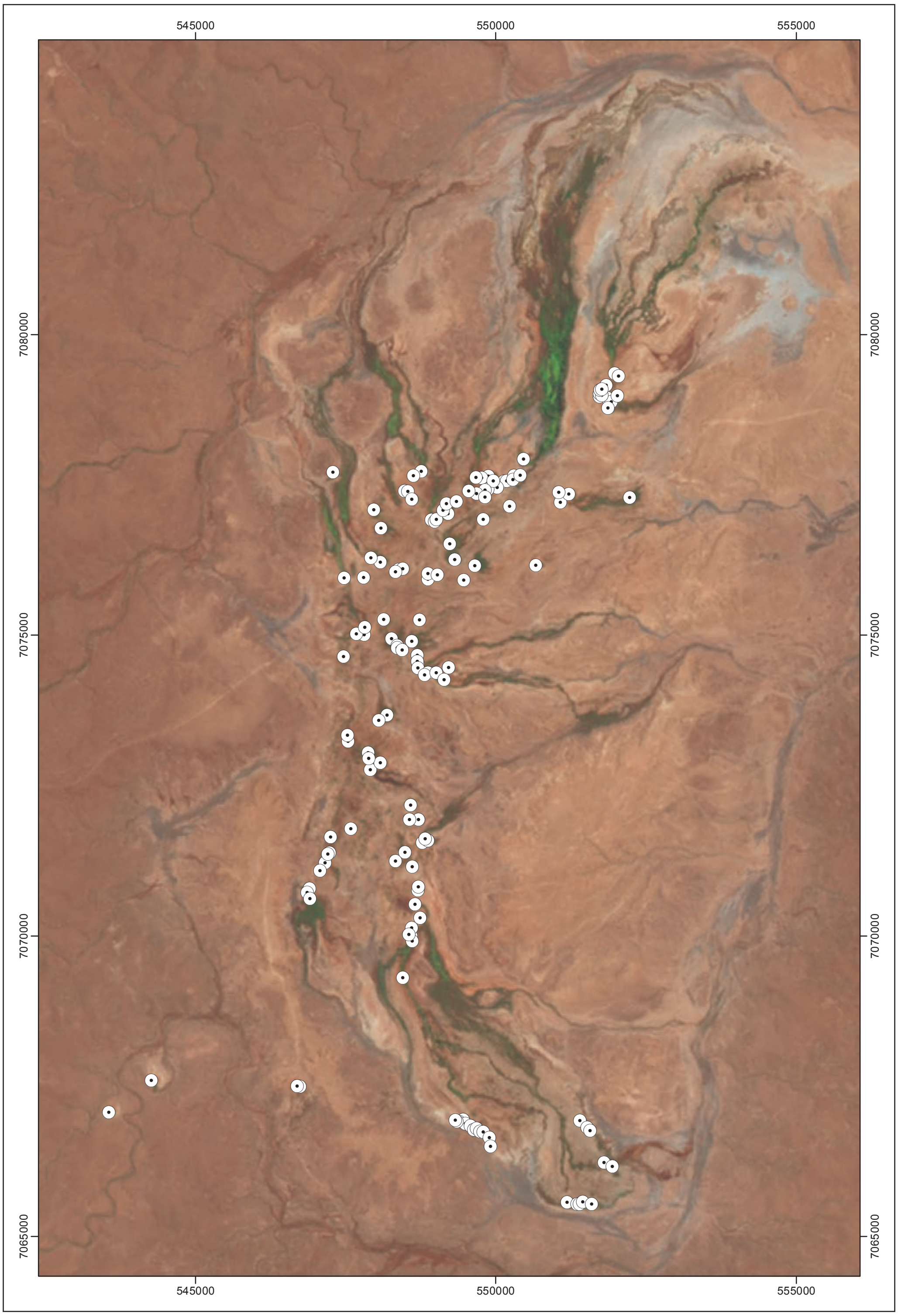

Figure 8.2: Distribution of spring vents at Dalhousie Springs

Legend

⊙ Spring Vents

0 1 2 3 4
Kilometres
N

Background image: Landsat 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: January 2012

Photo: Travis Gotch

Figure 8.3: Date Palm seeds in dingo faeces

Upon reaching sexual maturity at about five years, the female plant blossoms once per year producing small fragrant flowers. Female flowers are whitish in colour and borne on a branched spadix while the male inflorescence is a waxy cream colour. The palms are pollinated by wind and one large inflorescence may comprise of 6000 to 10 000 flowers. On an individual tree there can be more than a dozen inflorescences. Due to the hit-and-miss nature of wind pollination, some seasons produce a lot of fruit while others produce very little.

The date fruit is cylindrical in shape, measuring 5 cm in length and 2 cm in width and contains a single hard seed. Annual fruit yield per adult tree can vary from as little as 5 kg to more than 150 kg. The seed is often transported long distances by birds and animals. At Dalhousie Springs, the major vector for dispersal is the dingo, which eats large volumes of Date Palm fruit. Male dingos often defecate at high points—which at Dalhousie Springs is often at a spring vent (Figure 8.3).The palms live well over 100 years and can continue to produce fruit for a long time, ensuring a large seed supply for re-colonisation.

Date Palms prefer arid to semi-arid environments and can tolerate temperatures ranging from -6°C to in excess of 56°C provided they have access to water (Zaid & de Wet 2002). Optimal growth occurs between 32°C and 40°C while the plant becomes dormant and ceases growth below 7°C (Zaid & de Wet 2002).

Date Palms are prodigious users of water. Water usage by Date Palms in horticulture was reviewed in Liebenberg and Zaid (2002). For climates similar to that at Dalhousie Springs (South Africa, Iraq and California), Date Palms were found to consume between 25 ML/ha/yr and 36 ML/ha/yr. This is derived using standard plantings of 200 palms per hectare. In these studies, regular irrigation practices were used and varied from dripper to flood irrigation methods. Date Palms at Dalhousie occur on spring mounds, at vents and within tails. This provides them with access to water limited only by the actual flow of the spring vents they are located on. Because of this, water consumption estimated using figures derived from irrigation studies will be conservative.

Date Palms are very hardy. They can survive a wide range of salinity and have natural adaptations that protect them from fire. Given their fecundity, resilience and an absence of natural controls, they are well suited to become a major invasive weed in the GAB springs.

8.1.3 Date Palms at Dalhousie Springs

Date Palms were introduced in Australia for their fruit and were widely planted in Australia and throughout much of northern South Australia. In most locations where the Date Palm has been deliberately introduced it is not considered to be an environmental weed (Noack 2002). However, there are a number of locations in Australia where Date Palms have become environmental weeds such as in the Pilbara region of Western Australia along the Fortescue River and further north at Lake Kunnanura (Noack 2002). National Parks and Wildlife (Western Australia) have removed an estimated one million Date Palms in an effort to save the endemic palm *Livistona alfredii* (Gotch *et al*. 2006). In South Australia, Date Palms have been planted at a number of GAB spring sites. Outside of Dalhousie Springs, palms planted at Old Nilpina spring in northern South Australia are now spreading and their impacts are the cause of some concern (Fatchen 2000). Palms have also been planted at Big Perry Springs, Freeling Springs, Wandillinna Springs and also near the Bubbler and Blanche Cup at Coward Springs Bore (Gotch 2005).

There has been much conjecture as to when Date Palms were first introduced at Dalhousie Springs. A common myth is that they were planted by the Afghan cameleers as a food supply while travelling through the area; however there is no evidence to support these claims. In 1888, the South Australian Parliament authorised the South Australian Woods and Forests department to plant Date Palms at Dalhousie Springs, but there are no records to suggest that such plantings took place (Figure 8.4). There is written evidence provided by the Lewis family estate indicating that Dalhousie Station staff were responsible for planting Date Palms at the Springs in the late 1800s. A direct account of the planting of at least some of the Date Palms is given in letters between John Lewis and his son Essington in March 1899 referring to date seeds sent up to Dalhousie, '… I sent up a box some time ago. I want the

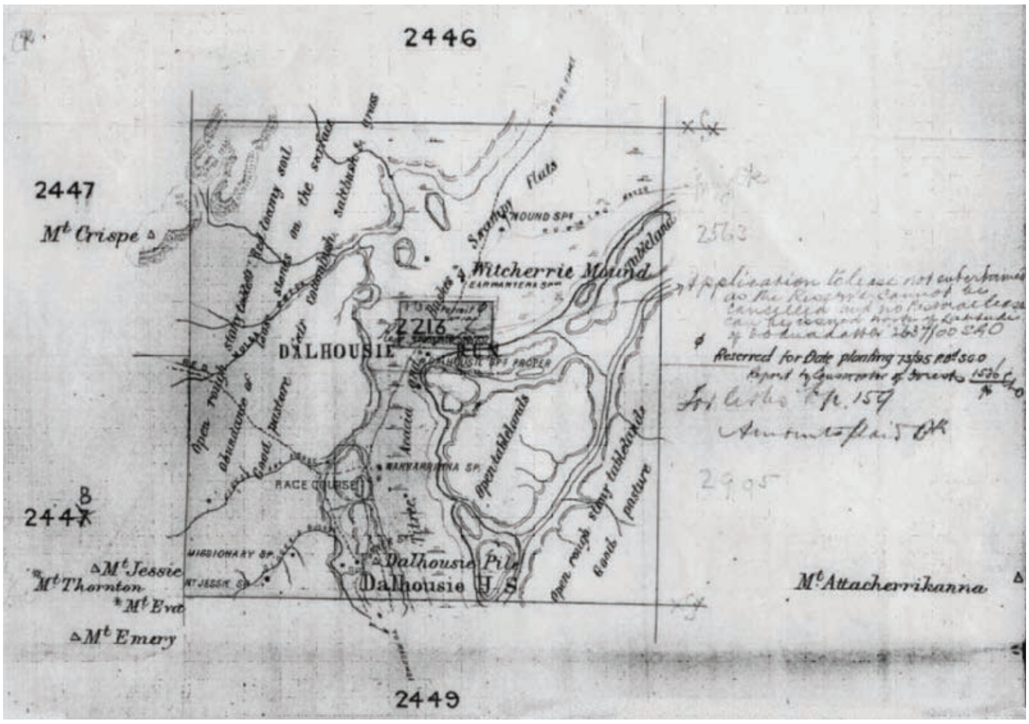

Figure 8.4: Lease map plan 1888

Figure 8.5: Green Date Palms on fire at Old Man Spring, Dalhousie South Australia

Photo: Travis Gotch

seeds planted about … they should grow well at the Mission spring' (Lewis 1899). In further correspondence, '… I am glad you have some young ones growing. It will be well to sow them in all suitable places and protect them' (Lewis 1899).

The exact location of the original Date Palm plantings at the Dalhousie Springs area is not clear. Samuel White, after his expedition through Central Australia in 1913, reported on the exploration of a great many springs in the Dalhousie area, but at only one spring was there any reference to Date Palms, and this reference was to a single plant. White also mentions that there were several palms 'flourishing' at the Homestead (White 1914). Over the following 100 years, Date Palms have progressively established on many of the springs in the complex. At a number of these springs, the Date Palm infestations currently have, or have the potential to, seriously threaten the ecological integrity of the springs. Mollemans (1989) also reports the presence of *Washingtonia robusta* at the Dalhousie Ruins Springs, however by 2005 this palm was no longer present (Gotch unpublished data).

8.1.4 Impacts of Date Palms

Date Palms are aggressive invaders of wetland habitats. They have the ability to grow in high densities, forming a continuous and dense canopy effectively excluding light, with the roots forming a dense mat that is both extensive and invasive. Roots can extend considerable distances into water bodies (Kendrick 2000). Date Palms inhibit the establishment of endemic species beneath the canopy and compete with those species already present (Kendrick 2000).

As noted in Section 8.1.2, Date Palms are prodigious users of water. Many of the GAB springs in the Dalhousie Springs complex have low water flows, and these springs are at most risk of impacts by Date Palm infestation. The aggressive and extensive root system and high transpiration rates of the Date Palms leads to a reduction and in some cases cessation of free-water flows to the detriment of all water-dependent species (Noack 2002). In managed prescribed groundwater zones, groundwater used by introduced weed species can have significant impacts on water available for environmental flows. The return of flow into the natural system through reduction of water use from invasive species can be of benefit to environmental flows.

Date Palms have the potential to threaten wetland species along the spring tails, including *Baumea arthrophylla, Bolboschoenus caldwellii, Eleocharis geniculata, Fimbristylis sieberana* and *Isolepis cernua* (Noack 2002). Date Palms have impacted on and may have caused the localised extinction of several tree species in the spring complex including *Eucalyptus coolabah* ssp. *arida*, *Santalum lanceolatum* and *Codonocarpus cotinifolius* (Noack 2002). Date Palms also threaten GAB spring ecology through altered fire regimes. Masses of dead fronds and high oil contents in the living fronds result in high-intensity fires (Figure 8.5) that can kill endemic species, particularly where palms occur in dense clumps around or adjacent to melaleuca or eucalyptus trees. The exotic palms are rarely killed by wildfire. Burnt palms sprout green leaves from the crown of the trunk (Kendrick 2000; Noack 2002; Gotch *et al*. 2006).

Date Palms pose a serious threat to endemic fish. Fish have not been observed feeding in waters overshadowed by palms (Bryan Pierce pers. comm. to SANPWS 1991). It is speculated that shade from the palms inhibits the growth of phytoplankton, disrupting the food web. What is certain is that the abundance of most species is reduced in areas of high palm cover.

Date Palms have been shown to significantly reduce the biodiversity and heterogeneity of flying invertebrates, as shown in Figure 8.6 (Gotch unpublished data). Malaise trap data collected during 2003 show total of 33 taxonomic units are present at the undisturbed Old Woman Spring (DAA001) while only 15 taxonomic units were present at the disturbed Old Man Spring (DAA005) site. A quick overview of Figure 8.6 shows clearly the dominance of Diptera and in particular Chironomids in the sample. It should be noted that this is not a true reflection of the total invertebrate diversity but is an artefact of the methodology used. What the data accurately show is the variation in species diversity and abundance between

Photo: Travis Gotch

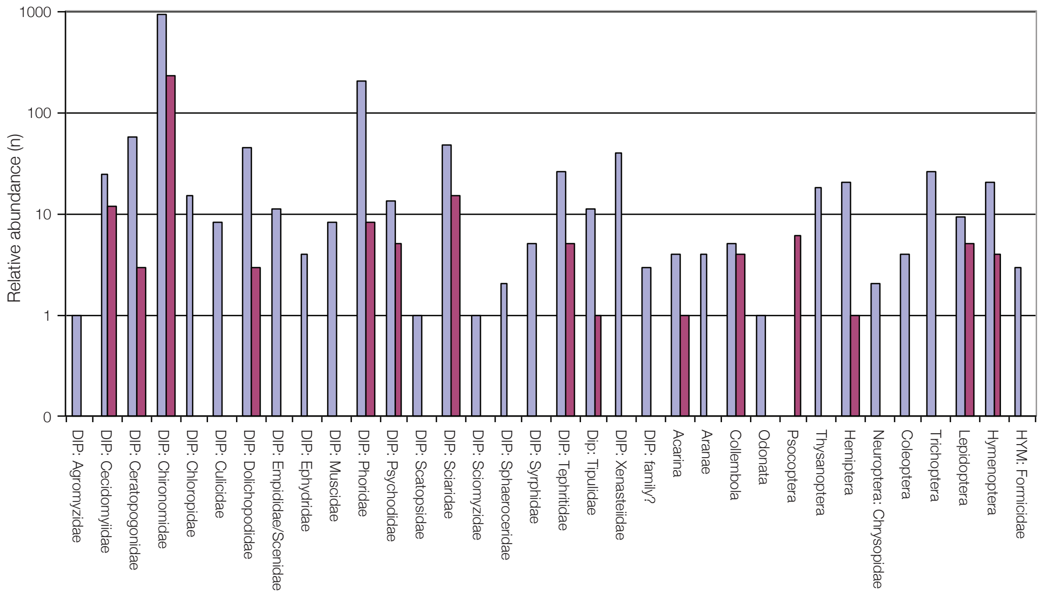

Figure 8.6: Relative abundance of invertebrates from malaise traps in two different spring habitats on a logarithmic scale

Old Woman Spring has minimal disturbance from Date Palms, while Old Man Spring is heavily impacted.

☐ Old Woman

■ Old Man

undisturbed sites and disturbed sites. Shannon-Weiner estimates of species heterogeneity show significantly higher species heterogeneity in Old Woman Springs compared to Old Man Springs (Old Woman H’ 1.743 ± 0.032; Old Man H’ 1.119 ± 0.04). The Shannon-Weiner Index was chosen over Simpson’s Index as it weights rare species more than common species. This is appropriate in this data set due to the high abundance of Chironomids relative to other taxonomic units (Krebs 1999). Soil nematodes were also examined and indicate that the palms were having an effect on their diversity and abundance. However, the sample size was too small to draw any statistically based conclusions (Davies pers. comm. to Travis Gotch 2003).

This data was originally published in Gotch *et al*. (2006) but has been reproduced here as part of a concise report on the impact of the Date Palms.

8.2 Date Palm distribution

Based on the reports of White (1914) and the letters between John and Essington Lewis (1899), it can be surmised that the first palms were planted at the Ruins Springs (DHA001 and DHA002) and at springs in the Kingfisher group (DAA) including Old Man Spring (DAA005). From there, it is evident they have spread and continue to colonise throughout the spring complex. Mollemans (1989) barely mentions the Date Palms in the text but lists them as ‘fairly common’ in the attached plant list. By 1999, Date Palms were present on 23 springs (Noack 2002). A ground survey of Date Palms in 2003 reported the presence of Date Palms on 21 springs (Gotch *et al*. 2006), however by 2005 a more detailed survey using helicopter and Omnistar^{TM} DGPS found palms on 25 springs (Noack 2005).

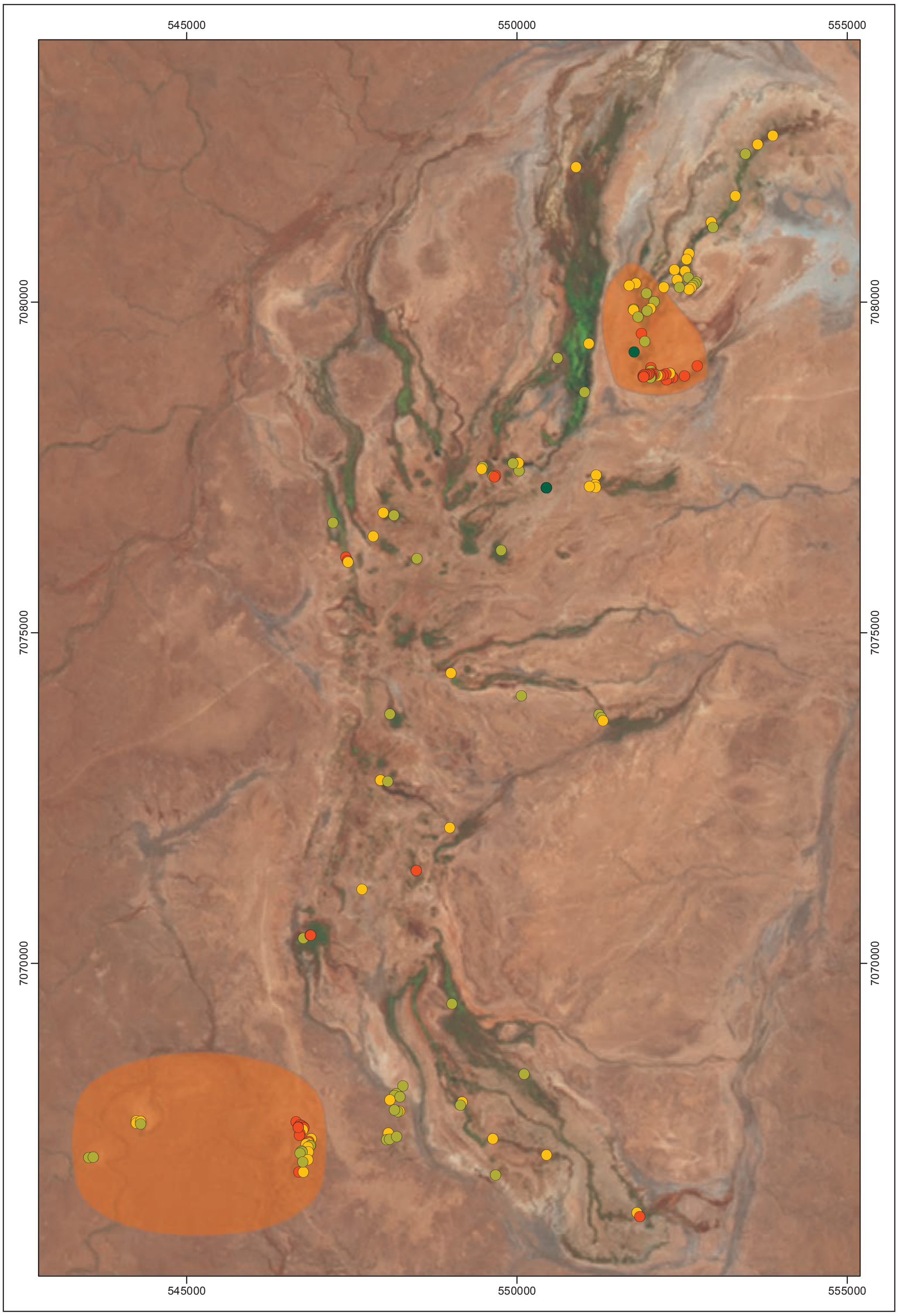

Figure 8.7: Distribution of Date Palms at Dalhousie Springs, July 2010

Date Palm Distribution

- ● 5+ palms
- ● 2 - 4 palms
- ● Individual
- ● Shoot
- ▨ Date Palm Control Zones

0 1 2 3
Kilometres

N

Background image: Landsat 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: March 2012

Figure 8.8: Heritage value Date Palms left after the removal at the Dalhousie Ruins site

A second helicopter survey was conducted in 2010 as part of this work and a comprehensive map of Date Palms produced (Figure 8.7). This survey identified 39 springs at the Dalhousie site with Date Palms present. Subsequent to this, major infestations at two sites were removed.

8.3 Control methods

Because of the diverse values of the area, control of the Date Palms required a number of considerations. At the Ruins Springs, the palms are considered part of the heritage of this site. The Dalhousie Homestead Ruins are entered on the State Heritage Register under Criteria (a), ‘demonstrated important aspects of the evolution or pattern of the State’s history’. However, individual Date Palms at the ruins have not been identified as having heritage significance and are not specifically included on the Register. The Heritage Branch has advised that only the Date Palms immediately adjacent to the Dalhousie Homestead Ruins have heritage value as they provide a context for the ruins (Figure 8.8).To ensure the protection of the heritage values of the springs it is considered that any suckers from these palms or further recruitment of palms which could damage the buildings need to be controlled.

Aboriginal occupation of Dalhousie Springs extends back thousands of years (Hughes & Lampert 1985) and cultural sites are evident everywhere. Many of the sites with Date Palm infestations are adjacent to Altyerre. Witjira is a jointly managed between traditional owners and the Department of Environment, Water and Natural Resources (DEWNR) of South Australia. All decisions relating to the removal of palms have been made in consultation with the traditional owners via the joint board of management. Assessments of Aboriginal cultural sites were undertaken by the traditional owners and Aboriginal heritage site clearances obtained prior to the commencement of on-ground works.

The methods available for control of Date Palms were reviewed and evaluated in Gotch *et al*. (2006). In summary, they include:

- felling with chainsaws
- removal with a machine
- pulling with rope and truck
- chemical control
- removal by commercial operators
- biological control
- using fire to clear fronds and allow access for chainsaws.

Due to the high cost of machine removal, the first phase at Old Man Spring (DAA005) used fire to remove the excess palm fronds then used chainsaws to remove the palms. This method was successful and resulted in the removal of over 700 palms. Post-removal monitoring (Figure 8.9) documented the recovery of the spring which was surprisingly rapid. Within one week *Phragmites australis* was resprouting along the tail, while after one month numerous tadpoles (*Limnodynastes tasmanensis*) had colonised the free water and dragonfly naiads were observed in the vent pool. These organisms are voracious predators and were conspicuously absent while the palms dominated the spring. They are an excellent indicator of a return of spring health.

The second phase of palm removal utilised a large logging machine capable of grabbing the palm trunk and cutting it off at the base at the same time. This machine was able to handle the biggest palms and significantly increased the speed at which palms were removed (Figure 8.10).

Photo: Denise Noack

Photo: Travis Gotch

1: Dense palm infestation prior to control, 2005

2: One week after the control took place; note increase in flow

Photo: Karl Newport

3: Same point in 2010

Figure 8.9: Date Palm control at Old Man Springs

Figure 8.10: Logging machinery used to remove palms in 2010

8.4 Summary of return of environmental flows

The volumes of water returned as environmental flows are estimates based on the best available data relating to water use by Date Palms. These water usage figures are derived from irrigation settings where water supply is limited. It is reasonable to assume that at Dalhousie Springs, where there is unlimited access to water, the estimates of date palm water use calculated here are conservative and the volumes of water returned may be greater than those reported.

As stated in Section 8.1.2, water use by Date Palms in similar climates to Dalhousie Springs has been shown to be between 25 ML/ha/yr and 36 ML/ha/yr (Zaid & de Wet 2002). Using these values, daily rate per palm was calculated as ranging from 0.125 ML/day to 0.18 ML/day. Since the commencement of the control works, 2458 palms have been removed. Extrapolating from these figures, the amount of water now available for the natural environment is estimated to be between 307.25 ML/yr (roughly 0.85 ML/day) which is the equivalent of a medium-flow pastoral bore. At the upper end, it is 442.44 ML/yr (roughly 1.2 ML/day), which is similar to the flow of the Bubbler (CBC002). This is summarised in Table 8.1.

At Old Man Spring (DAA005) in the Kingfisher Group, removal of the palms resulted in the spring wetland doubling in area within a day of the removal being carried out. This led to the linking of the spring tail with the Two Boys Spring (DAA001) and the recolonisation of wetland taxa previously absent within the spring. After two years, the area of wetland had contracted such that the tails were no longer permanently linked but was still more than 50% larger than it was prior to control. The spring at DAA008 was

Table 8.1: Summary of the return of environmental flows resulting from the removal of Date Palms at Dalhousie Springs.

Total number of palms removed	
	2458
Water use per palm per year (ML/day)	
Lower scale	0.125
Upper scale	0.18
Water returned (ML/yr)	
Lower scale	307.25
Upper scale	442.44
Water returned (ML/day)	
Lower scale	0.84
Upper scale	1.21
Upper scales are flows calculated from water use experiments undertaken in Southern California while lower scales are flows calculated from water use experiments undertaken in South Africa (Liebenberg & Zaid 2002).	

previously dry and only supported a few large palms prior to the removal. This spring had not had any flow for the past 20 years (B. Lowe pers. comm. 2003). Within hours of the removal of the palms, the spring began to flow and continues to do so two years later despite recolonisation by *Phragmites australis* and *Cyperus gymnocaulis*.

The volume of water returned as environmental flow is quite significant. Water that was previously supporting Date Palms is now supporting native vegetation and fauna along with a significant increase in habitat diversity and area.

9

Conclusions and recommendations

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9. Conclusions and recommendations

The work undertaken as part of this volume can be divided into three broad types: original research, review and analysis, and on-ground works.

9.1 Original research component

Original research has confirmed and extended knowledge of the high genetic diversity and high degree of endemism present at the Great Artesian Basin (GAB) springs. How biodiversity and genetic diversity is arranged spatially through the GAB springs has been uncertain, and therefore it has been unclear whether there are areas of higher value and at what scale the springs should be managed. The information in this volume has provided new information about the geographic distribution of biodiversity and genetic diversity that can be used to support population-scale conservation planning.

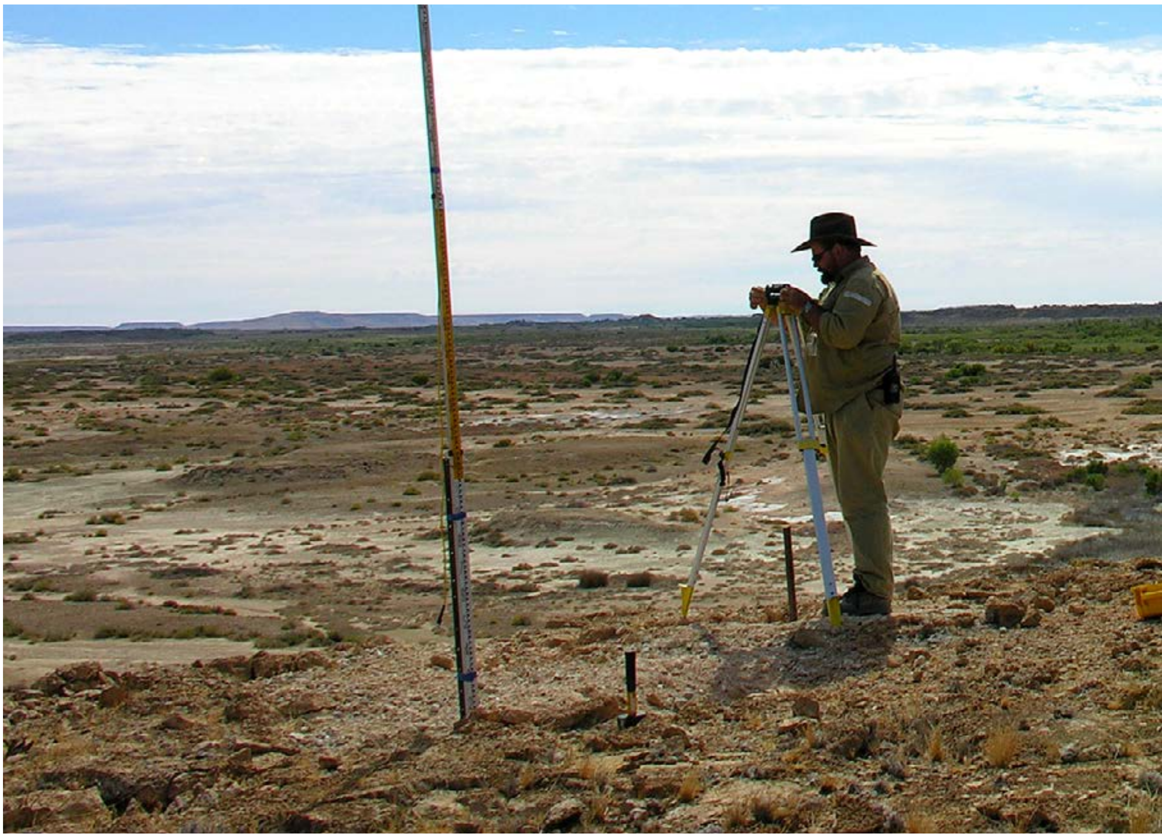
Guzik and Murphy's genetic analysis of aquatic invertebrate fauna at GAB springs (Chapter 4) has identified up to 42 evolutionary significant units (ESUs), most of which are likely new short-range spring endemics. They conclude that the biodiversity represented by cryptic species has been vastly underestimated. They confirm that there is little dispersal of these species between springs and that this is controlled by geographical features in the landscape and dependent on the dispersal mechanisms of individual species. Their work identified some specific locations of high vulnerability. Of particular note—the evidence suggests that aquatic species in springs are very likely to be cryptic and endemic. This is particularly important, as it demonstrates just how limited knowledge of the biodiversity of springs in the GAB really is.

Based on the outcomes of the research undertaken as part of this project (Guzik & Murphy in Chapter 4; Clarke *et al*. in Chapter 5), it is recommended that the optimal management scale for springs to protect biodiversity is the spring-group level. The spring group is also considered to be the optimal scale to assess impacts on springs arising from water allocation planning, and this scale of management may also be the most operationally pragmatic when engaging with land managers.

GAB spring fauna are extremely localised in their distribution. This may result in them being highly adapted to their local spring environment, making particularly vulnerable to rapidly changing conditions arising as a result of management actions or reductions in flow. Equally, spring relict flora has been shown to be highly isolated. Clarke *et al*. (Chapter 5) has shown that the loss of GAB spring *Gahnia trifida* populations would see the loss of a large proportion of the genetic diversity of *G. trifida* in South Australia. Before any attempts to manage spring endemics and relicts by translocating threatened species from spring populations in other regions, further work must be conducted to understand how variations in water chemistry and the rate of change in these conditions effect spring endemic populations.

Clarke *et al*. (Chapter 5) found a range of physical and chemical factors influence the abundance and diversity of vegetation at the GAB Springs. Importantly, they demonstrate that focus group flora are more abundant at springs

Photograph on facing page: Travis Gotch



with high flow rates and that species richness is positively associated with springs that have flowing water in their tails. Their findings confirm that reductions in flow, as well as loss of flow, are major threats to spring ecosystem biodiversity.

Species-specific associations with conductivity were also found by Clarke *et al*. (Chapter 5). This has important implications for preserving suites of species associated with different conductivity conditions across spring groups and complexes. It is also a significant finding for management at the local spring scale, as conductivity can vary in the different zones present at a spring, with fresher water occurring in the central vent and slightly more saline conditions occurring in the outer wetted perimeter and tail. Changes to the flow rate at a spring have the potential to alter the extent of each zone of conductivity (Volume IV: Spatial Survey and Remote Sensing of Artesian Springs (Lewis *et al.* 2013)). These findings also need to be considered when fencing to exclude grazing from springs, so that fences are not constructed tightly around the freshwater vent zone, leaving more saline zones unprotected.

Testing of plant species richness and abundance against stock presence showed some species-specific associations. Plant richness was highest at lightly grazed sites, suggestive of a possible role for controlled grazing in managing for biodiversity (Clarke *et al*. in Chapter 5). However, the mechanisms underlying this finding need to be examined before making a broad recommendation for grazing treatments at GAB springs. Significantly, focus group species were generally negatively associated with the presence of stock, and a number of weed species were positively associated with grazing (Clarke *et al*. in Chapter 5).

Both of these research projects were asked to consider the appropriate spatial scales at which ecosystems should be managed to maintain genetic diversity in endemic and relict spring

Photo: Dylan Koerner

species. For fauna, the range varied from the complex to spring-group level, while for flora complex level units were suitable. Spring spatial hierarchy is fully explained in Chapter 2, Volume IV (Lewis *et al.* 2013). The spring-group level of hierarchy contains clusters of spring vents that share similar water chemistry and source their water from the same fault or fracture (Table 2.2, Volume IV (Lewis *et al.* 2013)). Combined with this being the smallest range for some endemic species and the minimum unit to manage genetic diversity in springs, it is recommended that the appropriate scale for management of spring biota is at the group level.

9.2 Review and analysis

Biologically and ecologically, the GAB springs are by any measure one of the special places in Australia's diverse landscapes. In Chapter 2, the literature around spring environments was examined and the critical finding is that, despite significant inroads in the last ten years, very little is yet known about the spring environment. Managers are just beginning to have sufficient information to form baselines on which monitoring can be based. Equally important is the need for managers and decision-makers to have a basic understanding of the principles behind metapopulation theory when implementing on-ground actions that have the potential to impact spring environments.

Roberts (Chapter 6) documented the biological basis for the vigour of *Phragmites australis* and outlined techniques that can be used to assess the risk of its proliferation at individual sites under changed management. Importantly, this work demonstrates that *Phragmites australis* is a naturally occurring element of spring ecology. This investigation was undertaken in response to the findings of monitoring of grazing exclosures and the anecdotal reports of land managers that find *Phragmites australis* grows strongly in the lifting of grazing pressure, apparently to the

Photo: Travis Gotch

detriment of other species, notably the nationally endangered spring endemic *Eriocaulon carsonii*. Chapter 6 systematically examines the available literature on the reproduction and dispersal of *Phragmites australis* to show that the possibility of it invading sites from which it has been eliminated is low (though not impossible), and that it is unlikely that *Phragmites australis* is actively colonising new sites, but much more likely to be re-establishing its canopy. A series of field-based actions are outlined in Chapter 6 that would confirm the findings of the desk-top review. Re-casting the role of *Phragmites australis* from that of a nuisance plant, to that of a species that is a natural part of spring ecology, albeit one that is out of balance due to inappropriate land-use practices, is a major contribution to the science underpinning on-going management of GAB spring ecology.

Chapter 7 identified a number of recommendations for best-practice grazing management of springs that are designed to reduce the impact of grazing, including:

- fenced exclosures should include the whole ecological focus zone, or more
- introduction of new stock in a paddock should be located near a bore or dam rather than on a spring
- stock should not be moved directly from areas with known wetland weeds into areas with relatively weed-free springs
- grazing impacts can be minimised using a low stocking rate or pulsed grazing where the rate of pulse grazing is modified according to the stock density.

These practices need to be further investigated, particularly stocking levels and timings of pulse grazing as these will vary from site to site. Other recommendations were made about the need to examine the spatial arrangement of springs and the effect this has on grazing pressure.

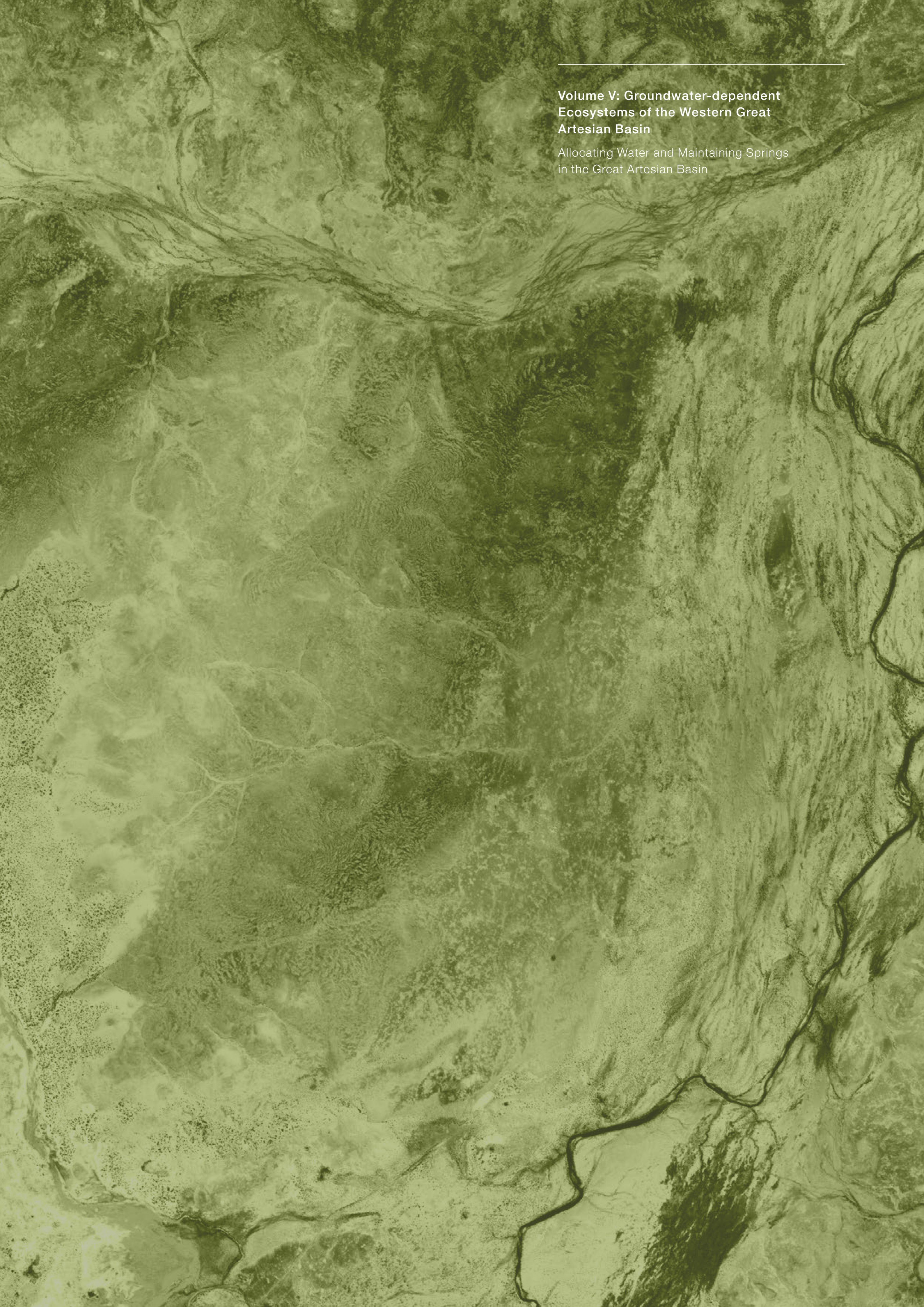
9.3 On-ground works

Invasive Date Palms (*Phoenix dactylifera*) were removed at Dalhousie Springs resulting in the return of significant environmental flows. Over the duration of the project, nearly 2500 Date Palms were removed. In addition to this, the locations of outlying palms were mapped to facilitate further removals. Conservative estimates of the return of environmental flow show between 307 and 442 ML/yr, equivalent to the flow of a moderate bore drain or a spring the size of the Bubbler (CBC002) at Wabma Kadarbu Conservation Park.

Future work in this area includes the development of remote sensing techniques to identify Date Palms from above. This is important as *Phragmites australis* at Dalhousie Springs can grow up to 5 m high, obscuring smaller palms until they are well established.

9.4 Summary

While all work undertaken as part of this research has enhanced the understanding of GAB spring ecology, it has also stressed the requirement for ongoing active management of springs on multiple spatial scales to protect their unique values that are vulnerable to environmental change and the pressures of land use. A number of key findings have been identified, including the establishment of optimal management scales for springs, key information to assist in the management of *Phragmites* (especially after grazing pressure is removed), guidelines around grazing practices on springs and the return of over 1 ML of water a day to Dalhousie Springs.



Volume V: Groundwater-dependent Ecosystems of the Western Great Artesian Basin

Allocating Water and Maintaining Springs in the Great Artesian Basin

Appendix 1: Palaeo-ecology spring cores

Table A1.1: Palaeo-ecology spring cores

Spring name	Spring code	Core Length (cm)	General description	Suitability for future palaeo-ecological research?	Photograph of main sediment type within core
Beresford Spring	BBS001	310	High organic content comprised of grey to dark brown sediment. Also a noticeable clay component. Evidence of aeration within sediment.	YES, however pugging by livestock in top 1.5 m to consider.	
Blanche Cup	CBC001	330	High organic content comprised of brown to dark brown sediment. A noticeable coarse sand fraction is also evident which requires further analysis.	YES, however site has been impacted by tourism which will need to be considered during further research. Lack of stratification of sediments indicates likely sediment mixing.	
The Fountain	NTF001	370	High organic content. Dark brown to black sediment. Light sand and clay fraction also evident.	YES, however signs of bank collapse and possible pugging to 1.5 m on this spring will need to be factored into further research on this site.	
Jersey	CJS001	210	90 cm of organic material at top of core (0–90 cm). The remainder of core (90–210 cm) is composed of yellow-brown coarse sand.	NO, There is strong evidence of sediment mixing at this site. The sand likely originates from the artesian aquifer below it.	
Coward Springs Campground Bore Drain	NA	50	High organic content. Dark brown to black in colour.	YES, potentially useful site for the study of diatoms in an artificial bore drain system Corer could not penetrate sediment past 50 cm. This barrier may be the clay liner installed during construction of the bore drain.	

Appendix 2: Diversity of evolutionary significant units in spring groups and complexes

The diversity of evolutionary significant units (ESUs) in spring groups and complexes with endemic (only from a particular location) versus total (ESUs per location). Colour indicates an alert to high (red > 10) and moderately high (orange 5–10) ESU diversity. Results for *Ngarawa* are only represented in this table, the phylogenetic data is still preliminary.

Table A2.1: Diversity of evolutionary significant units in spring groups and complexes

	Spring complex	Springs sampled	No active springs	Chiltoniid			*Phreatomerus*			*Trochidrobia*
				ESU	TOT	END	ESU	TOT	END	ESU
Beresford		4	4	A2	1	1	W-IV	1	0	TS - E
	BBH	1	1	A2	1	0	W-IV	1	0	TS-E
	BWS	3	3	A2	1	0	W-IV	1	0	NA
Coward		66	355	A1, A3, A5-A8/j	7	7	W-IV	1	0	TS -D, TP- A
	CBC	5	19	A1	1	0	W-IV	1	0	TS-A
	CBS	1	1	A1	1	0	W-IV	1	0	NA
	CCS	3	14	A1	1	0	W-IV	1	0	TS-A
	CHS	3	5	A1	1	0	W-IV	1	0	TS -D, TP- A
	CHW	1	2	A1	1	0	W-IV	1	0	NA
	CEN	24	179	A3/J	2	2	W-IV	1	0	TP-A
	CES	13	75	A6/A8	2	0	W-IV	1	0	TS-D, TP-A
	CJS	5	9	A5	1	1	W-IV	1	0	TP-A
	CKH	11	51	A7/A8	1	0	W-IV	1	0	TP-A
Strangways	CSS	9	13	C	1	1	W-I, W-III	2	1	TS-E

**Fonscochlea ESUs and Trochidrobia ESUs are as per data generated by Ponder et al. 1995). Results for Ngarawa are only represented in this table as the phylogenetic data is still preliminary.

			Ngarawa			*Fonscochlea***			Total	
	TOT	END	ESU	TOT	END	ESU	TOT	END	ESU	Endemic ESU
	1	O	A3	1	1	FAq1, FZ3, FV2	3	1	7	3
	1	O	A3	1	1	FAq1, FZ3, FV2	3	1	7	2
	NA	NA	NA	NA	NA	NA	NA	NA	2	0
	2	2	A1,C	2	0	FAq1, FZ2, FV1,FV2	4	1	16	10
	1	0	A1,C	2	0	FAq1, FZ2, FV1	3	1	8	1
	NA	NA	A1,C	2	0	NA	NA	NA	4	0
	1	0	NA	NA	NA	FAq1, FZ2, FV2	3	1	6	1
	2	0	A1,C	2	0	NA	NA	NA	6	0
	NA	NA	A1,C	2	0	NA	NA	NA	4	0
	1	0	A1,C	2	0	NA	NA	NA	6	2
	2	0	NA	NA	NA	FAq1, FZ2, FV2	3	1	8	1
	1	0	NA	NA	NA	FAq1, FZ2, FV2	3	1	5	2
	1	0	A1,C	2	0	FAq1, FZ2, FV2	3	1	8	1
	1	0	A2	1	O	FAq2, FZ5, FBK	3	2	8	4
	**Fonscochlea ESUs and Trochidrobia ESUs are as per data generated by Ponder et al. 1995). Results for Ngarawa are only represented in this table as the phylogenetic data is still preliminary.									

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Table A2.1: Diversity of evolutionary significant units in spring groups and complexes

	Spring complex	Springs sampled	No active springs	Chiltoniid			*Phreatomerus*			*Trochidrobia*	
				ESU	TOT	END	ESU	TOT	END	ESU	
Peake	EFS	5	49	H	1	1	W-II	1	1	TM, TI**	
Francis Swamp	FFS	8	120	G	1	1	W-I	1	0	TS-E	
Hermit Hill		28	933	A4	1	0	S-VI	1	1	TP-B	
	HBO	2	30	A4	1	0	S-VI	1	0	TP-B	
	HDB	2	8	A4	1	0	S-VI	1	0	TP-B	
	HHS	5	429	A4	1	0	S-VI	1	0	TP-B	
	HOF	5	265	A4	1	0	S-VI	1	0	TP-B	
	HOW	3	45	A4	1	0	S-VI	1	0	TP-B	
	HSS	6	30	A4	1	0	S-VI	1	0	TP-B	
	HWF	5	126	A4	1	0	S-VI	1	0	TP-B	
Neales		18	117	B/I	6	6	F-A, F- B, F, C	3	3	TS-C, TM	
	NBS	1	7	B4	1	1	F-C	1	0	TS-C	
	NFS	3	6	B3	1	0	F-C	1	0	TS-C	
	NHS	6	89	B1	1	1	F-C	1	0	TS-C	
	NOS	3	6	I	1	1	F-A	1	0	TS-C, TM	
	NTF	1	1	B2	1	1	F-C	1	0	TS-C, TM	
	NMI	1	1	NA	NA	NA	F-A	1	0	NA	
	NTM	3	7	B3	1	0	F-B	1	1	TS-C	
Wangianna		6	83	A4	1	0	S-VII	1	1	TP-B	
	WDS	5	75	A4	1	0	S-VII	1	0	TP-B	
	WWS	1	8	A4	1	0	S-VII	1	0	TP-B	
Lake Eyre South	LES	1	1	NA	NA	NA	W-IV	1	0	NA	

**Fonscochlea ESUs and Trochidrobia ESUs are as per data generated by Ponder et al. 1995). Results for Ngarawa are only represented in this table as the phylogenetic data is still preliminary.

		Ngarawa			*Fonscochlea***			Total	
TOT	END	ESU	TOT	END	ESU	TOT	END	ESU	Endemic ESU
2	1	A6	1	1	FAq4, FZ6, FE2	3	2	8	6
1	0	A2	1	0	NA	NA	NA	4	1
1	0	A1,B,C	3	0	FAc, FZ1, Fv1	3	0	9	1
1	0	A1,B,C	3	0	NA	NA	NA	6	0
1	0	A1,B,C	3	0	FAc, FZ1, Fv1	3	0	9	0
1	0	A1,B,C	3	0	NA	NA	NA	6	0
1	0	A1,B,C	3	0	FAc, FZ1, Fv1	3	0	9	0
1	0	A1,B,C	3	0	NA	NA	NA	6	0
1	0	A1,B,C	3	0	NA	NA	NA	6	0
1	0	A1,B,C	3	0	NA	NA	NA	6	0
2	1	A4,A5,A7	3	3		3	2	17	15
1	0	NA	NA	NA	NA	NA	NA	3	1
1	0	A7	1	0	NA	NA	NA	4	0
1	0	A7	1	0	NA	NA	NA	4	1
2	0	A4	1	1	FAq3,FE1	2	0	7	2
2	0	A5	1	0	NA	NA	NA	5	1
NA	NA	NA	NA	NA	NA	NA	NA	1	0
1	0	A5, A7	2	0	FAq3, FZ6,FE1	3	0	8	1
1	0	A1,B,C	3	0	FAc, FZ1, Fv1	3	0	9	1
1	0	A1,B,C	3	0	FAc, FZ1, Fv1	3	0	9	0
1	0	NA	NA	0	NA	NA	NA	3	0
NA	NA	A1	1	0	NA	NA	NA	2	0

**Fonscochlea ESUs and Trochidrobia ESUs are as per data generated by Ponder et al. 1995). Results for Ngarawa are only represented in this table as the phylogenetic data is still preliminary.

Appendix 3: Vulnerability of springs estimated from the number of Evolutionary Significant Units

Vulnerability of springs as estimated by the number endemic evolutionary significant units (ESUs) per spring group and complex. 'X' indicates presence of an ESU. Colour indicates an alert to high (red < 10) and moderately high (orange 10–50) endemism. Results for *Ngarawa* are only represented in this table, the phylogenetic data is still preliminary.

Table A3.1: Vulnerability of springs estimated from the number of evolutionary significant units

		Beresford		Coward									Strangways	Peake	Francis Swamp	Hermit Hill	
		BBH	BWS	CBC	CBS	CCS	CHS	CHW	CEN	CES	CJS	CKH	CSS	EFS	FFS	HBO	HDB
Chiltoniid	A1			X	X	X	X	X									
	A2	X	X														
	A3								X								
	A4															X	X
	A5										X						
	A6									X							
	A7											X					
	A8									X		X					
	B1																
	B2																
	B3																
	B4																
	C												X				
	G													X			
	H														X		
	I																
	J								X								

						Neales							Wangianna		Lake Eyre South	Possible maximum habitat size (Based on Appendix 4, Fensham *et al.* 2007)	
	HHS	HOF	HOW	HSS	HWF	NBS	NFS	NHS	NOS	NTF	NMI	NTM	WDS	WWS	LES	Number of springs	Wetland extent
																10-50	>1
																<10	>0.1<1
																100-200	>0.01<0.1
	X	X	X	X	X								X	X		>1000	>1
																<10	>1
																50-100	>0.1<1
																50-100	>0.1<1
																100-200	>0.1<1
								X								50-100	>1
										X						<10	>0.1<1
							X					X				10-50	>0.1<1
						X										<10	>0.1<1
																10-50	>0.001>0.01
																100-200	>1
																10-50	>1
									X							<10	>1
																100-200	>0.01<0.1

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Table A3.1: Vulnerability of springs estimated from the number of evolutionary significant units

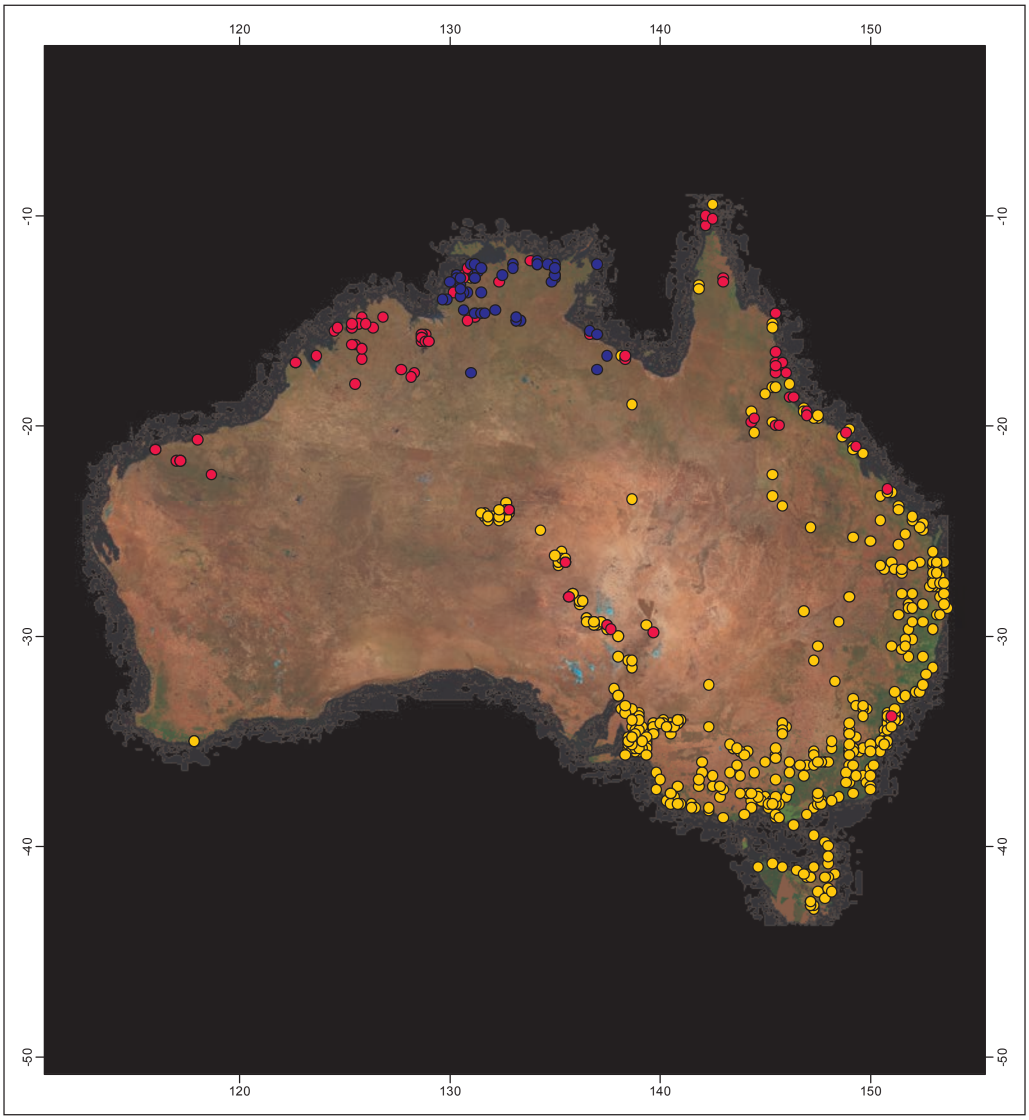
		Beresford		Coward									Strangways	Peake	Francis Swamp	Hermit Hill	
		BBH	BWS	CBC	CBS	CCS	CHS	CHW	CEN	CES	CJS	CKH	CSS	EFS	FFS	HBO	HDB
Phreatomerus	WI												X		X		
	WII													X			
	WIII												X				
	WIV	X	X	X	X	X	X	X	X	X	X	X					
	SVI															X	X
	SVII																
	FA																
	FB																
	FC																
Trochidrobia	TP-A			X	X	X	X		X	X	X	X					
	TP-B															X	X
	TS-C																
	TS-D						X			X							
	TS-E	X	X										X		X		
	TM													X			
	TI**													X			
Ngarawa	A1			X	X		X	X	X			X				X	X
	A2												X		X		
	A3	X															
	A4																
	A5																
	A6													X			
	A7																
	B															X	X
	C			X	X	X		X	X	X						X	X

						Neales							Wangianna		Lake Eyre South	Possible maximum habitat size (Based on Appendix 4, Fensham *et al.* 2007)	
	HHS	HOF	HOW	HSS	HWF	NBS	NFS	NHS	NOS	NTF	NMI	NTM	WDS	WWS	LES	Number of springs	Wetland extent
																100-200	>1
																10-50	>1
																10-50	>0.001>0.01
															X	300-400	>1
	X	X	X	X	X											900-1000	>1
													X	X		50-100	>1
									X		X					<10	>1
												X				<10	>0.1<1
						X	X	X		X						100-200	>1
																300-400	>1
	X	X	X	X	X								X	X		>1000	>1
						X	X	X	X	X		X				100-200	>1
																50-100	>0.1<1
																100-200	>1
									X	X						50-100	>1
																10-50	>1
	X	X	X	X	X											>1000	>1
																100-200	>1
																<10	>0.1<1
									X							<10	>1
										X		X				<10	>0.1<1
																50-100	>1
							X	X				X				100-200	>1
	X	X	X	X	X								X	X		>1000	>1
	X	X	X	X	X								X	X		>1000	>1

Appendix 4: Distribution of *Phragmites* in Australia

Distribution of herbarium records for *Phragmites* identified to species. The distribution of herbarium records for three species of *Phragmites* in Australia: *P. australis* (green), *P. karka* (blue) and *P. vallatoria* (pink). Map excludes several records identified only to genus. Total number of herbarium records for all *Phragmites* specimens is 1055. Information downloaded from Australia's Virtual Herbarium (AVH) on 25 April 2010.

Figure A4.1: Distribution of *Phragmites* in Australia



Vegetation data: Australian National Herbarium.
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

Appendix 5: Leading hypotheses in invasion ecology

Table A5.1 presents 29 leading hypotheses in invasion ecology, as identified in Tables 2 and 3 in Catford *et al*. (2009).

Table A5.1: Leading hypotheses in invasion ecology.

	Hypothesis (abbreviation)	Description
1	Propagule pressure (PP)	High supply and frequency of plant propagule introduction increase chance of successful invasion due to high genetic diversity, seed swamping, continual supplementation, higher probability of introduction to favourable environment.
2	Global competition (GC)	Based on propagule pressure but noting that with an increasing number of species introduced, the higher the likelihood that a competitive species will be in the invading species pool.
3	Sampling (SP)	Like global competition, but interspecific competition rather than propagule pressure drives invasion. Species identity is more important than species richness of the recipient community and invasion occurs when invading species are able to exploit resources and avoid enemies more effectively than resident species.
4	Ideal weed (IW)	Life history, characteristics and traits of the invading species facilitate invasion by enabling them to outcompete indigenous species.
5	Reckless invader (RI)	Species characteristics that facilitate invasion under certain environmental conditions may be disadvantageous to invader when conditions change. Such trade-offs may explain transient invasions.
6	Enemy release (ER)	Upon entry into a new range, invader loses its natural enemies (herbivores, pathogens) that limit its population size in its home range. Two types of enemy release: regulatory and compensatory.
7	Enemy reduction (ERD)	Similar to enemy release in process and outcome, but rather than complete release, it is based on a reduction in the number of enemies.
8	Enemy of my enemy (EE)	Enemies have a stronger effect on indigenous species resulting in apparent competition. Invader accumulates generalist pathogens, which limit the invader's abundance, but limit indigenous competitors more.
9	Enemy inversion (EI)	Invader's natural enemies are also introduced into new range but are less effective, or may have opposite effect, in the new biotic or abiotic conditions.
10	Increased susceptibility (IS)	Low genetic diversity and lack of specific defence of invaders increases their susceptibility to enemies in the invaded community.
11	Evolution of increased competitive ability (EICA)	Similar to compensatory enemy release; release or reduction of enemies that limit population in home range enables invader to allocate freed resources to adapting and enhancing its competitive ability in new ecosystems and community.

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Table A5.1: Leading hypotheses in invasion ecology.

	Hypothesis (abbreviation)	Description
12	Specialist–generalist (SG)	Based on interaction between invader and recipient community, invasion success maximised when enemies in recipient community are specialists (unable to prey on introduced species) and indigenous mutualists are generalists (facilitate invasion).
13	New associations (NAS)	Invading species form new relationships with species in the invaded community which enhance or impede invasion success.
14	Missed mutualisms (MM)	Upon entry into a new range, invading species will lose the beneficial mutualistic relationships that they experience in home range, thereby impeding invasion.
15	Biotic indirect effects (BID)	Includes a range of mechanisms that can facilitate invasion as a result of indirect community interactions (how A alters the effect that B has on C).
16	Invasional meltdown (IM)	Direct or indirect symbiotic or facilitative relationships among invaders cause an ‘invasion domino effect’. Often occurs over a range of trophic levels where one species makes habitat or community more amenable for another.
17	Biotic resistance (BR)	Competitors, herbivores and pathogens in recipient community limit colonisation, naturalisation and persistence of invaders, impeding invasion.
18	Novel weapons (NW)	Invading species release allelopathic chemicals that inhibit and repress potential competitors in new range. Indigenous species are not adapted to the novel chemical weapons, enhancing the invaders competitive ability and success.
19	Limiting similarity (LS)	This predicts that successful invaders are functionally distinct from species in the recipient community, so encounter minimal competition and can fill an empty niche. Limiting similarity causes traits / phylogenetic overdispersion.
20	Habitat filtering (HF)	Invader successful as it is adapted to conditions of ecosystem and able to pass through the environmental filters. Habitat filtering leads to trait underdispersion and phylogenetic clustering.
21	Environmental heterogeneity (EVH)	Habitats with high environmental variability contain a diverse array of niches that can host a variety of species. Invasion will be successful if there are an insufficient number of indigenous species to fill the available niches.
22	Increased resource availability (IRA)	Species require resources for colonisation and establishment so an increase in resource levels provides opportunity for invasion.
23	Disturbance (DS)	Disturbance events increase resource availability and reset succession, giving invading species an equal chance of success at colonisation and establishment.
24	Dynamic equilibrium model (DE)	Disturbance and productivity interact to affect invasion, and each factor can reverse responses driven by the other. Invaders can readily establish in low-disturbance/low-productivity systems but only become dominant in high-productivity systems with high levels of disturbance.

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Table A5.1: Leading hypotheses in invasion ecology.

	Hypothesis (abbreviation)	Description
25	Empty niche (EN)	Due to limited indigenous species pool, the recipient community and ecosystem are unsaturated so invader can use the spare resources and occupy the unused niches.
26	Opportunity windows (OW)	Similar to empty niches but niche availability is dynamic fluctuating through time and space. When opportunity arises, invading species colonises and, once naturalised, invades.
27	Adaptation (ADP)	Invader pre-adapted to ecosystem condition, or adapts post-introduction, enabling it to be successful in new range because of its specialisation and associated competitive ability.
28	Release-enemy release (E–ER)	Combines enemy release (#6) and increased resource availability (#22) but notes that invasion can be accelerated and enhanced when both occur.
29	Naturalisation (DN)	Invasion success attributed to human interferences, high propagule pressure, suitable environmental conditions and favourable community interaction. Habitat filtering (#20) is recognised but focuses on limiting similarity (#19).

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Glossary and shortened forms

AACWMB: Arid Areas Catchment Water Management Board

Actual evapotranspiration: The amount of water that actually evaporates and transpires from a surface.

Adaptive management: A management approach often used in natural resource management where there is little information and/or a lot of complexity and there is a need to implement some management changes sooner rather than later. The approach is to use the best available information for the first actions, implement the changes, monitor the outcomes, investigate the assumptions, and regularly evaluate and review the actions required. Consideration must be given to the temporal and spatial scale of monitoring and the evaluation processes appropriate to the ecosystem being managed.

Adiabatic: Relating to or describing a process or condition in which heat does not enter or leave a system.

Advection: The transport of dissolved constituents (i.e., solutes), particulate/colloidal matter, and/or heat by flowing groundwater.

Aeolian: Pertaining to material deposited by wind.

AFDW: Ash-free dry weight

AHD: Australian Height Datum

AISA Eagle: Airborne hyperspectral (visible–near-infrared) image sensor operated by Specim Spectral Imaging Ltd.

Alluvium: sediments deposited by or in conjunction with running water in rivers, streams, or sheetwash and in alluvial fans.

Ambient: The background level of an environmental parameter (e.g. a measure of water quality such as salinity).

AMS: Accelerator mass spectrometry

AMS ^{14}C: Accelerator Mass Spectrometry (AMS) Carbon^{14}

ANAE: Australian National Aquatic Ecosystem

Analytical model: A type of mathematical model that is composed of a closed-form solution (i.e. the solution can be expressed as a mathematical analytic function).

Andesite: An extrusive igneous, volcanic rock, of intermediate composition, with aphanitic to porphyritic texture.

Anemochory: Dispersal of seeds, fruits or other plant parts by wind.

Anisotropy: The directional variation of a property at a point.

Anoxic: Related to or defined by a severe deficiency in oxygen.

Anticline: A fold formed in strata that is arch-shaped (convex up) in which the strata slope downward from the axis.

Anthropogenic: Caused by humans, in the context of human degradation of the environment.

Aquatic ecosystem: The stream channel, lake or estuary bed, water, and/or biotic communities, and the habitat features that occur therein.

Aquatic habitat: Environments characterised by the presence of standing or flowing water.

Aquiclude: A geologic material, stratum, or formation that contains water (i.e. has porosity) but does not transmit it (i.e. has zero or negligible permeability).

Aquifer: An underground layer of rock or sediment that holds water and allows water to percolate through.

Aquifer, confined: Aquifer in which the upper surface is impervious (see ‘confining layer’) and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer.

Aquifer system: Intercalated permeable and poorly permeable materials that comprise two or more permeable units separated by aquitards that impede vertical groundwater movement but do not affect the regional hydraulic continuity of the system.

Aquitard: A bed of low permeability adjacent to an aquifer; may serve as a storage unit for groundwater.

Aquifer, unconfined: Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure.

ARA: Airborne Research Australia

ARC: Australian Research Council

Arenite: A sedimentary rock that consists of sand-sized particles (0.06–2 millimetres [0.0024–0.08 inch] in diameter).

Arid: A climatic region that receives little or no rain. In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broadacre cropping.

Aridification: Drying of an environment from wet to arid.

Arid lands: In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broadacre cropping.

Artesian: An aquifer in which the water surface is bounded by an impervious rock formation; the water surface is at greater than atmospheric pressure, and hence rises in any well which penetrates the overlying confining aquifer.

ASD: Analytical Spectral Device

ASS: Acid sulfate soils

ASTER: Advanced Spaceborne Thermal Emission and Reflectance Radiometer

Asthenosphere: A portion of the upper mantle that is directly below the lithosphere, in which there is relatively low resistance to plastic flow and convection is thought to occur. This weak zone allows the plates of the lithosphere to slide across the top of the asthenosphere.

ATREM: Atmospheric removal algorithm

Auger: Rotary drilling equipment, used in soils or poorly-consolidated materials, that removes cuttings from a borehole by mechanical means without the use of drilling fluids. Augers operate on the inclined plane or screw principle.

AUSPOS: Online tool for post-processing GPS data.

AVH: Australia's Virtual Herbarium

AWMSGAB Project: Allocating Water and Maintaining Springs in the Great Artesian Basin project

Basinal: Pertaining to a basin.

Bicubic: Of or pertaining to the interpolation in two dimensions using cubic splines or other polynomials.

Biodiversity: (1) The number and variety of organisms found within a specified geographic region; (2) The variability among living organisms on the earth, including the variability within and between species and within and between ecosystems.

Biological diversity: See 'biodiversity'.

Biological integrity: Functionally defined as the condition of the aquatic community that inhabits unimpaired water bodies of a specified habitat as measured by community structure and function.

Bioregion: Geographical region based on IBRA classification.

Bioturbated: The displacement and mixing of sediment particles and solutes by fauna or flora.

BoM: Bureau of Meteorology

Bore: See 'well'.

BP: Before present

Buoyancy: The resultant vertical force exerted on a body by the static fluid in which it is floating or submerged.

Caprock: A harder, more resistant rock type overlying a weaker or less resistant rock type

Carbonaceous: Consisting of or containing carbon or its compounds.

Clastics: An accumulation of transported weathering debris.

cm: Centimetre

CMB: Chloride mass balance

CO1: Cytochrome Oxidase subunit 1

Compaction: The processes by which sediment is densified (reduction of porosity or increase in bulk density caused by an increase in the compressive or total stress). In soil mechanics this term is limited to processes involving the expulsion of air from the voids.

Complexes: Clusters of spring groups that share similar geomorphological settings and broad similarities in water chemistry.

Conceptual model: A descriptive form of model in which concepts and the relationships between them are used to describe an overarching idea or theory.

Cone of depression: A curved water table or potentiometric surface that forms around a pumping well.

Confining layer: A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'.

Conformably: Of or relating to, sedimentary strata that are parallel to each other without interruption.

Connate: Pertaining to fluids (usually water) that were trapped in the pores of sedimentary rocks as they were deposited.

Consequence: The outcome of an event affecting objectives.

Control Point Network: A set of reference points of known geospatial coordinates from which a spatial survey is based.

Critical habitat: Those areas designated as critical for the survival and recovery of threatened or endangered species.

Cross-formational flow: Vertical groundwater flow from one hydrostratigraphic unit to another.

CSIRO: Commonwealth Scientific and Research Organisation

Cyanobacteria: A form of large photosynthetic bacteria. Cyanobacteria can produce thick and extensive mats. Commonly known as “blue-green algae”, but can also be yellow-green, brown, or even reddish-purple.

Darcian flow condition: A condition of groundwater flow in which flow occurs in a non-turbulent way and complies with the predictable conditions assumed in the application of Darcy’s Law of groundwater flow though saturated porous media.

Darcy’s Law: The discharge of water (Q) through a unit area of porous medium is directly proportional to the hydraulic gradient (i) normal to that area (A). The constant of proportionality is the hydraulic conductivity (K). $Q = KiA$

DEH: Department for Environment and Heritage (Government of South Australia)

Deltaic: Pertaining to or like a delta.

DEM: Digital Elevation Model

DENR: Department of Environment and Natural Resources (Government of South Australia)

Density: The mass of a substance divided by its volume.

Denudation: The long-term sum of processes that cause the wearing away of the earth’s surface, leading to a reduction in elevation and relief of landforms and landscapes.

Depocentre: The deepest point of a sedimentary basin, normally at a basin’s centre. Point where thickest accumulation of sediment collects.

Desorption: A process by which solutes, ions, and colloids are released from or through a surface into a liquid of gaseous phase. The opposite of sorption.

DFR: Driving Force Ratio

DFW: Department for Water (Government of South Australia)

DGPS: Digital GPS

Diagenetic: The sum of physical and chemical processes that affect a sediment following deposition.

Diaspore: A plant dispersal unit consisting of a seed or spore plus any additional tissues that assist dispersal.

Diffuse discharge: The discharge of groundwater by molecular movement from zones of high head to zones of low head.

Diffuse recharge: The recharge of groundwater into a groundwater system by molecular movement.

Discharge: (1) The volume of water that passes a given location within a given period of time. Usually discussed with respect to springs, streams or groundwater systems; (2) The water leaving a groundwater system.

Disconformably: Pertaining to a type of unconformity in which the rock layers are parallel.

Diversity: The distribution and abundance of different kinds of plant and animal species and communities in a specified area.

Divide: A topographic high (or ridge) separating surface watersheds (catchments). A groundwater divide is elevated area, line, or ridge of the potentiometric surface separating different groundwater flow systems.

DMITRE: Department of Manufacturing, Innovation, Trade, Resources and Energy (Government of South Australia)

DO: Dissolved oxygen

Domal: Dome-like

Down-warping: A segment of the crust of the Earth that bends downward.

Down-welling: The downward movement of fluid.

DSC: Dalhousie Spring Complex

DSEWPaC: Department of Sustainability, Energy, Water, Population and Communities (Government of South Australia)

DSM: Digital Surface Model

Duricrust: A thin hard layer on or near the surface of soil.

DW: Dry weight

EC: Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (μS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS.

Ecological processes: All biological, physical or chemical processes that maintain an ecosystem.

Ecological resilience: The capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker *et al.* 2004).

Ecological values: The habitats, natural ecological processes and biodiversity of ecosystems.

Ecology: The study of the relationships between living organisms and their environment.

Ecosystem: Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment.

Efflorescence: The crystallisation of a salt from a hydrated or solvated state via the loss of water to the atmosphere on exposure to air.

EFFORT polishing: Empirical Flat Field Optimal Reflectance Transformation; applies a mild adjustment to apparent reflectance data so that spectra appear more like real materials on the ground surface.

EFZ: Ecological focal zones

Elevation head: Head due to the energy that is the result of gravity (the elevation of the water relative to some datum).

Endangered species: Any species in danger of extinction throughout all or a significant portion of its range.

Endemic: A plant or animal restricted to a certain locality or region.

Endogenic: Formed or occurring beneath the surface of the earth.

Endozoochory: Seed dispersal via ingestion by a vertebrate animal.

ENSO: El Nino / Southern Oscillation

ENVI: Software for processing and analysing geospatial imagery.

Environmental water head: The sum of the elevation head and the pressure head calculated using the average density of the water over the whole water column, not just the screened interval. This is used for calculating the vertical hydraulic gradient.

EPBC Act: Environment Protection and Biodiversity Conservation Act 1999

Epeiric sea: A shallow sea that extends over part of a continental landmass.

Ephemeral: (1) Pertaining to a watercourse or body flows or contains water only in direct response to precipitation, and thus discontinues its flow or becomes dry during dry seasons; (2) plants with more than one life cycle, which are often short in duration.

Ephemeral river recharge: A term used to describe indirect recharge resulting from episodic flow events in arid zone rivers.

Ephemeral streams or wetlands: Those streams or wetlands that usually contain water only on an occasional basis after rainfall events; many arid zone streams and wetlands are ephemeral.

Epigenic: Pertaining to a geological change in the mineral content of rock that occurs after the rock has formed.

Epizoochory: Seed dispersal where seeds are transported on the outside of vertebrate animals.

Epoch: Defined periods of time.

ERI: Electrical resistivity imaging

ERR: Ephemeral river recharge

ESU: Evolutionary significant unit

Evapotranspiration: The total loss of water as a result of transpiration from plants and evaporation from land and surface water bodies.

Excess head: The level to which water will rise above ground surface in an artesian well, measured in metres (m).

Facies: A unit or body of rock with definable and specific characteristics that can be used in classification.

FLAASH: Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes. An atmospheric correction algorithm.

Floristic: Of or relating to flowers or flora.

Flow: The rate of water that discharges from a source expressed as a volume per unit time.

Flow line/flow path: The path a molecule of water takes in its movement through a porous medium.

Flow net: A map showing both equipotentials and streamlines of an aquifer or geological system.

Flow regime: The character of the timing and amount of flow in a stream.

Fluvial: Of or relating to inhabiting a river or stream. Produced by the action of a river or stream.

Fluvio-deltaic: Of or relating to streams rivers or deltas.

Fm: Formation

FNPWA: Far North Wells Prescribed Area

Fresh water: Water with salinity < 1000 mg/L; drinkable or potable water is implied.

Fresh-water head: The sum of the elevation head and the pressure head calculated using the density of the fresh water (~1000 kg m^{-3}). This is used for calculating the horizontal hydraulic gradient.

FR FieldSpec® 3: Full range (400–2500 nm) FieldSpec Pro portable field spectroradiometer by Analytical Spectral Devices.

Ga: Billion years

GA: Geoscience Australia

GAB: Great Artesian Basin

GDA94: Geocentric Datum of Australia 1994

GDE: Groundwater-dependent ecosystem/s

Geological features: Include geological monuments, landscape amenity and the substrate of land systems and ecosystems.

Geomorphic: Of or resembling the Earth or its shape or surface configuration.

Geomorphology: Study of landforms and the processes that make them.

Geo-registered: To geographically reference a remotely sensed image or spatial data to an Earth model.

GIS: Geographic information system

GL: Gigalitres

Glacio-fluvial: Of or relating to a glacial rivers or streams.

Glaciogene: Formed by glacial activity.

Glacio-lacustrine: Of or related to glacial lakes.

Glauconated: To be altered into the mineral glauconite. Glauconite is a greenish clay mineral of the illite group, found chiefly in marine sands. Chemical formula is $(K,Na)(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$.

GMI: Gidgealap-Merrimelia-Innaminka

GMWL: Global Meteoric Water Line

GNIP: Global Network of Isotopes in Precipitation

GNSS: Global Navigation Satellite System

gph: Gallons per hour

Graben: An elongated block of the earth's crust lying between two faults and displaced downward relative to the blocks on either side.

Granitoid: A granite or granitic rock.

Groundwater: Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground.

Groups: Clusters of spring vents that share similar water chemistry and source their water from the same fault or structure.

GSD: Ground sample distance

Gypcrete: A gypsum indurated or cemented duricrust.

Gypsiferous: Containing appreciable amounts of the mineral gypsum ($CaSO_4 \bullet 2H_2O$).

ha: Hectare

Habitat: The natural place or type of site in which an animal, plant, or community of plants and animals lives.

Halophytic: Adapted to living in salty soil, particularly plants.

Head: Fluid mechanical energy per unit weight of fluid, which correlates to the elevation that water will rise to in a well.

Headward: In the region or direction of the head.

Heterogeneity: The condition in which the property of a parameter or a system varies with space.

HEVAE: High Ecological Value Aquatic Ecosystem

Hummocky: Lumpy terrain or land which has an irregular shape.

Hydraulic conductivity (K): A measure of the ease of flow through aquifer material: high K indicates low resistance or high flow conditions, usually measured in metres per day.

Hydrochemistry: Science that deals with the chemical characteristics of water.

Hydrochory: Seed dispersal by water.

Hydrogeology: The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also ‘hydrology’.

Hydrology: The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth’s surface and within its atmosphere; see also ‘hydrogeology’.

Hydrostatic pressure: The pressure exerted by liquid at equilibrium due to the force of gravity.

Hydrostratigraphy: Refers to stratigraphic classification with respect to the hydrogeological properties of strata.

HyMap: An airborne hyperspectral image sensor operated by HyVista Corporation.

Hyperspectral: Imagery or ground data derived from subdividing the electromagnetic spectrum into numerous (more than 10) very narrow bandwidths.

IAEA: International Atomic Energy Agency

IBRA: Interim Biogeographic Regionalisation for Australia

Indigenous species: A species that occurs naturally in a region.

Interbedding: Where layers or rock (or beds) of a particular lithology lie between or alternate with beds of a different lithology.

Intercalation: The reversible inclusion of a molecule (or group) between two other molecules (or groups).

Intrabasinal: Pertaining to the interior of a basin

Intracratonic: Pertaining to the interior of a craton

Intraplate: Pertaining to the interior of a tectonic plate

Isopach Map: A map illustrating variation of thickness within a tabular unit or stratum. Each line, or isopach represents where a particular stratum has the same thickness.

Isopotentials: A vector or region in space where every point in it is at the same potential.

Isotropy: The condition in which the properties of a system or a parameter do not vary with direction.

ka: Kilo annum (1000 years)

Kaolinitic: Where the composition has a significant proportion of the mineral kaolin ($Al_2Si_2O_5(OH)_4$).

kL: Kilolitre

km: Kilometre

km^2: Square kilometres

Lacustral: Of, or pertaining to, a lake.

Lacustrine: Of, or pertaining to, a lake.

Lag time: The time between the middle of the precipitation event in a watershed (or catchment) and the arrival of the flood peak at a given location.

LAS: LASer file format exchange

LEB: Lake Eyre Basin

Level of risk: Magnitude of a risk, or combination of risks, expressed in terms of the combination of consequences and likelihood.

LGM: Last Glacial Maximum

LiDAR: Light Detection and Ranging

Limnological: The study of life and phenomena of freshwater.

Lithosphere: The rigid, outermost shell of the Earth. The lithosphere sits on top of the asthenosphere and is that portion of the Earth that interacts with the hydrosphere, biosphere and atmosphere.

Lithostratigraphic: Refers to the stratigraphy with respect to the strata's rock properties.

LMWL: Local Meteoric Water Lines

Loop closure: A check to assess the cumulative error generated from moving sites with multiple base stations.

L/s: Litres per second

Lunette: A sand or sediment dune formed by wind activity that typically takes the shape of a crescent.

m: Metre

Ma: Million years

Macro-invertebrates: Aquatic invertebrates visible to the naked eye including insects, crustaceans, molluscs and worms that inhabit a river channel, pond, lake, wetland or ocean.

mAHD: Metres Australian Height Datum**.** Defines elevation in metres (m) according to the Australian Height Datum (AHD).

Mantle-derived: To be derived from the earth's mantle.

mBNS: Metres below natural surface

MBR: Mountain block recharge

m/day: Metres per day

Meteoric water: Water that is or has recently been a part of the atmospheric portion of the hydrologic cycle.

MF: Matched Filtering

MFR: Mountain front recharge

mg/L: Milligrams per litre

Micaceous: Where the composition has a significant proportion of mica minerals. Mica can be one of any group of chemically and physically related aluminum silicate minerals.

Mining (hydrogeology): This implies extraction of water from a groundwater system which is not currently receiving recharge.

MIS: Marine isotopic stage

mL: Millilitres

ML: Megalitres

mm: Millimetre

m/Ma: Metres per million years

mm/yr: Millimetres per year

MNDWI: Modified Normalised Difference Water Index

MNF: Minimum Noise Fraction

Model: A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions; examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change.

MODIS: Moderate Resolution Imaging Spectroradiometer

MODTRAN: Moderate Spectral Resolution Atmospheric Transmittance

Monocline: A geologic structure in which all layers are inclined in the same direction.

Mountain block recharge: A term used to describe subsurface inflows from a consolidated mountain block.

Mountain Front recharge: A term used to describe infiltration (or seepage) from streams (either perennial or ephemeral), at a mountain front.

Mountain system recharge: A term to used to describe the contribution of groundwater recharge derived from mountains to adjacent aquifers.

mS/cm: milliSiemens per centimetre

MSL: Mound spring line

MSR: Mountain system recharge

mt: Mitochondrial

MTMF: Mixture Tuned Matched Filtering

Multispectral: Images with multiple wavelengths, usually between four to 15, representing broad bandwidths of the electromagnetic spectrum.

m/yr: Metres per year

NASA: National Aeronautics and Space Administration (United States of America)

Natural resources: Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems.

NCSSA: Nature Conservation Society of South Australia

NDSMI: Normalised Difference Soil Moisture Index

NDVI: Normalised Difference Vegetation Index

Neotectonic: Tectonic activity considered to be current or recent in geologic time.

nm: Nanometres

NRM: Natural resource management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively.

NSW: New South Wales

NT: Northern Territory

Numerical model: A form of mathematical model that uses some sort of numerical time-stepping procedure to obtain a modeled behavior over time.

NWI: National Water Initiative

Observation well: A narrow well or piezometer whose sole function is to permit water level measurements.

Orogen: A section of the earth's crust that is subject to the formation of mountains.

Orogenic: In reference to a process in which a section of the earth's crust is folded and deformed to form a mountain range.

Orographic: Of, or relating to mountains, particularly their form and position.

Orthophotography: A digital photograph that has been registered to a Digital Elevation Model that allows for accurate measurement of features directly from the photograph.

OSL: Optically stimulated luminescence

pa: Per annum

Palaeochannel: Refers to the channel of a river or stream, or the sediments contained within a riverbed or streambed that is no longer active.

Palaeoclimate: Climate conditions or events that occurred in the past and is no longer active.

Palaeo-ecology: The study of fossil animals and plants in order to deduce their ecology and the environmental conditions in which they lived.

Palaeohydrological: Hydrological changes or events that occurred in the past and is no longer active.

Palaeorecharge: Groundwater recharge event or condition that occurred in the past and is no longer active.

Palaeo-wind: Wind conditions that occurred in the past and are no longer active.

Paludal: Of or pertaining to marshes, swamps or fens.

Palynology: The study of pollen grains and other spores, particularly those found at archaeological sites or in geological deposits

Paralic: Pertaining to deposits laid down on the landward side of a coast.

PCA: Principal Components Analysis

Pericratonic: Of, or pertaining to the boundary of continental crust and oceanic crust.

Periglacial: Of, or referring to a place at the edges of glacial areas. Can also be used to refer to any place where geomorphic processes related to freezing of water occur.

Permeability: The state or quality of a material that causes it to allow liquids or gases to pass through it.

Petroglyphs: Rock engravings created by removing part of a rock surface by incising, picking, carving, and abrading.

pH: Standard measurement of acidity/alkalinity

Phenological: Plant growth cycle

Phreatic zone: Water in the zone beneath the water table where the fluid pressure is equal to or greater than atmospheric pressure.

Phreatophytic vegetation: Vegetation that exists in a climate more arid than its normal range by virtue of its access to groundwater.

Phylogeography: The study of the historical processes that may be responsible for the contemporary geographic distributions of individuals.

Piezometer: A pressure-measuring device. This typically is an instrument that measures fluid pressure at a given point rather than integrating pressures over a well.

Piezometric surface: See ‘potentiometric head or surface’.

Playa: An arid zone basin with no outlet, which periodically fills with water to form a temporary lake.

pmC: Percent modern carbon

Point water head: The sum of the elevation head and the pressure head calculated using the density of the water at the point sampled.

Polychory: Seed distribution by more than one agent.

Porosity: Pertaining to the voids within a sediment or rock; can also be called void fraction. Effective porosity is the porosity of a sediment or rock available to contribute to fluid flow through the rock or sediment.

Potential evapotranspiration: The amount of water that would evaporate and transpire from a surface if sufficient water was available to meet the demand.

Potentiometric head or surface: The level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface.

PPI: Pixel Purity Index

ppm: Parts per million

ppt: Parts per trillion

Precautionary principle: Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.

Pressure head: Head caused by the pressure (energy) of the fluid.

Probability: Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossible and 1 is absolutely certain.

Proponent: The person or persons (who may be a body corporate) seeking approval to take water from prescribed water resources.

PSM: Permanent survey mark

Pugging: The trampling of wetland soils into mud by livestock often resulting in a very uneven surface of deep hoofmarks in which water pools and becomes stagnant.

QuickBird: Satellite operated by Digital Globe that captures very high-resolution multispectral imagery.

R8: Trimble GPS receiver

RADAR: Radio Detection and Ranging

Radiogenic: Related to a stable element that is product of radioactive decay.

Radionucleide: An atom with a nucleus that is unstable and is characterised by excess energy. The nuclide will disintegrate with the emission of corpuscular or electromagnetic radiations,

Ramsar Convention: This is an international treaty on wetlands titled The Convention on Wetlands of International Importance Especially as Waterfowl Habitat. It is administered by the International Union for Conservation of Nature and Natural Resources. It was signed in the town of Ramsar, Iran in 1971, hence its common name. The convention includes a list of wetlands of international importance and protocols regarding the management of these wetlands. Australia became a signatory in 1974.

Rayleigh Number: The ratio buoyancy forces to viscous resistance and dispersive/diffusive dissipation.

Recharge: The process by which water enters the groundwater system.

Recharge zone: The area of an aquifer or aquifer system where water enters the subsurface and eventually the phreatic zone.

Red Edge Position: The inflexion point (or maximum slope) between the red and infrared wavelength regions.

Residual risk: Risk remaining after risk treatment.

RGR: Relative growth rates

Rheology: The study of the flow of matter, primarily in the liquid state, but also as ‘soft solids’ or solids under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force.

Rhyolite: A pale fine-grained volcanic rock of granitic composition.

Rhythmites: Layers of sediment or sedimentary rock that are laid down with an clear periodicity and regularity.

RINEX: Receiver Independent Exchange Format

Risk: The effect of uncertainty on objectives.

Risk analysis: Process to comprehend the nature of risk and to determine the level of risk.

Risk assessment: Overall process of risk identification, risk analysis and risk evaluation.

Risk avoidance: Informed decision not to be involved in, or to withdraw from, an activity in order not to be exposed to a particular risk.

Risk categories: Overarching categories of risk which may include several sources of risk.

Risk criteria: Terms of reference against which the significance of risk is evaluated.

Risk identification: The process of finding, recognising and describing risks.

Risk management: Coordinated activities to direct and control an organisation with regard to risk.

Risk management framework: Set of components for designing, implementing monitoring, reviewing and continually improving risk management throughout the organisation.

Risk treatment: A process to modify risk.

RMS: Root mean square

RTK DGPS: Real-time kinematic differential global positioning system

Runoff: (1) Water from precipitation, snowmelt, or irrigation running over the surface of the Earth; (2) surface water entering rivers, lakes, or reservoirs; (3) a component of stream flow.

SA: South Australia

SAAE: South Australian Aquatic Ecosystem

SAALNRMB: South Australian Arid Lands Natural Resources Management Board

SA Geodata: State government database containing spatial and geophysical data

Salinity: The amount of solutes (dissolved materials) in water.

SAM: Spectral Angle Mapper

SARDI: South Australian Research and Development Institute

Sedgelands: Vegetation species associated with wetlands that have adapted to extreme environmental conditions such as drought and low availability of nutrients.

Sedimentological: Of, or pertaining to sediments or the study or sediments.

Semiarid: pertaining to climatic conditions in which the precipitation, although slight, is sufficient for growth of short sparse grass.

Senescence or senescent: The growth phase of a plant from maturity to death.

Silcrete: A silica indurated or cemented duricrust.

Siliciclastic: Clastic sediments composed of primarily siliceous minerals.

Sorption: The general process by which solutes, ions, and colloids become attached (sorbed) to solid matter in a porous medium. Sorption includes absorption and adsorption.

SpEC: Specific electrical conductance

Specific yield: The ratio, less than or equal to the effective porosity, indicating the volumetric fraction of the bulk aquifer volume that a given aquifer will yield when all the water is allowed to drain out of it under the forces of gravity.

Specific storage: The volume of water released per unit volume of aquifer for a unit decrease in hydraulic head.

Spectral: Relating to electromagnetic wavelengths; for remote sensing used in this study, spectral covers the region from the visible to the shortwave infrared.

Spectroradiometer: An instrument for measuring the radiant energy distribution in the electromagnetic spectrum.

Speleothem: A mineral deposit of calcium carbonate that precipitates from solution in a cave.

Spring: Individual wetlands comprising one or more vents and tails joined together by permanent wetland vegetation.

Spring complex: Clusters of spring groups that share similar geomorphological settings and broad similarities in water chemistry.

Spring group: Clusters of springs that share similar water chemistry and source their water from the same fault or structure.

Spring supergroup: Clusters of spring complexes.

Spring vent: A conduit or aperture through which groundwater discharges to the surface environment.

SRTM: Shuttle RADAR Topography Mission

SSPCA: Spectrally Segmented Principal Component Analysis

Sst: Sandstone

Stadial: A period of colder temperatures during an interglacial (warm period) separating the glacial periods of an ice age.

Static water level: The level of water in a well that is not affected by pumping.

Steady state: The condition in which properties in a system are not changing with time.

Stochasticity: Refers to systems whose behaviour is intrinsically non-deterministic, sporadic and categorically not intermittent.

Storage: Water contained within an aquifer or within a surface-water reservoir.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of an aquifer per unit change in head.

Storativity: The volume of water released per unit area of aquifer for a unit decline in head. In a confined aquifer, storativity is essentially the specific storage times aquifer thickness. In an unconfined aquifer, storativity is essentially equal to the specific yield or the effective porosity.

Stratigraphical: Of, or pertaining to the study of stratigraphy.

Stratigraphies: Plural layers in sedimentary and layered volcanic rock

Stratigraphy: A branch of geology concerned with rock layers and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks.

Sub-basin: A smaller drainage basin within a larger drainage basin.

Subhydrostatic pressure: The pressure exerted by liquid at equilibrium that is less than the liquid's hydrostatic pressure.

Substrate: A layer of earth beneath the surface soil or subsoil.

Supergroups: Clusters of spring complexes; there are 13 supergroups across the GAB with three found in South Australia.

Superhydrostatic pressure: The pressure exerted by liquid at equilibrium that is greater than the liquid's hydrostatic pressure.

Surface water: (1) Water flowing over land after having fallen as rain or hail or precipitated in any another manner, or having risen to the surface naturally from underground; (2) Water of the kind referred to in (1) that has been collected in a dam or reservoir.

SWIR: Short-Wave InfraRed

SWP: Soil water potential

Synclinal: Of or pertaining to a syncline. A syncline is a trough-shaped fold of stratified rock (convex down) in which the strata slope upward from the axis.

Tails: Wetlands associated with flow away from the vent.

Taxa: General term for a group identified by taxonomy, which is the science of describing, naming and classifying organisms.

TDEM: Time Domain Electromagnetics

TDS: Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity.

Tectonics: A branch of geology that is primarily concerned with the structures within the earth's crust, with particular reference to the forces and movements that have operated in a region to create these structures.

TEM: Transient Electromagnetic

Terrane: A fault-bounded area or region with a distinctive stratigraphy, structure, and geological history.

Terrigenic: To be derived from the land

Tertiary aquifer: A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago).

Thermal conductivity: The rate of heat flow per unit area for a unit thermal gradient normal to that area.

Thermogene: A process that produces heat.

TL: Thermoluminescence

Tomography: A technique for displaying a representation of a cross section through another solid object. In geology, this is usually done with seismic or another geophysical technique.

Total dissolved solids (TDS): The sum of all organic and inorganic dissolved matter in water.

Toxic: Relating to harmful effects to biota caused by a substance or contaminant.

TPS: Temperature, pH, Salinity meter

Tracer: A solute, suspended matter, or heat which is artificially or naturally induced to evaluate the rate and direction of groundwater flow.

Trachyte: A fine-grained volcanic rock consisting largely of alkali feldspar.

Transgressive: Pertaining to a geologic event during which sea level rises relative to the land and the shoreline moves toward higher topographic regions.

Transient: The condition in which properties of a system vary with time.

Transmissivity: The hydraulic conductivity of an aquifer unit, multiplied by its saturated thickness.

Travertine: A name used to describe a terrestrial calcareous sedimentary rock that typically precipitates from springwater.

Tufa: A name used to describe a terrestrial calcareous sedimentary rock that precipitates from springwater. It an be used to specifically describe a fine-grained micritic carbonate with textures highly influenced by microbial activity, precipitated at ambient and sub-ambient water temperatures.

UltraCam: A digital photogrammetric aerial camera.

Underground water: See 'groundwater'.

Unsaturated: The condition when the porosity is not filled with water.

Unsaturated zone: Generically, is considered equivalent to the vadose zone. This is the zone above the water table and the saturated portion of the capillary fringe where the pores are generally filled with both liquid water and air.

Upward leakage: The leakage of groundwater to strata located above the aquifer or to surface.

Upwardly-fining: A decrease in grainsize within a sedimentary unit in proportion to age.

U/Th: Uranium/Thorium ratio

Vadose Zone: In terrestrial environments, the portion of the shallow subsurface that is above the water table.

Velocity head: Head caused by the kinetic energy of the flowing fluid.

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 springs from a legislative perspective and in accordance with water allocation planning. See ‘spring vent’.

VIS-NIR: Visible and Near Infrared

VHR: Very High Resolution

Volcaniclastics: Volcanic material that has been transported and reworked through mechanical action, such as by wind or water.

Volcanolithics: Sediments composed of fragments of volcanic rock.

WAP: Water allocation plan

Water allocation: (1) In respect to a water licence, means the quantity of water that the licensee is entitled to take and use pursuant to the licence; (2) In respect to water taken pursuant to an authorisation under s.11, means the maximum quantity of water that can be taken and used pursuant to the authorisation.

Water allocation plan (WAP): A plan prepared by a catchment water management board or water resources planning committee and adopted by the Minister in accordance with the Act.

Water-dependent ecosystems: Parts of the environment, species composition and natural ecological processes that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems.

Water table: A surface at or near the top of the phreatic zone (zone of saturation) where the fluid pressure is equal to atmospheric pressure.

Well: (1) An opening in the ground excavated for the purpose of obtaining access to groundwater; (2) An opening in the ground excavated for some other purpose but that gives access to groundwater; (3) A natural opening in the ground that gives access to groundwater.

Wetlands: Areas of permanent, periodic or intermittent inundation – whether natural or artificial, permanent or temporary – with water that is static or flowing; and is fresh, brackish or salty (including areas of marine water); the depth of which at low tides does not exceed six metres.

WGS84: World Geodetic System (1984)

WorldView-2: Satellite operated by Digital Globe that captures very high-resolution multispectral imagery.

ZoI: Zone of influence

µm: micrometres

$\delta^{13}C$: Carbon isotopic concentration

$\delta^{x}O$ (e.g. $\delta^{18}O$): Isotopic abundance ratio. Oxygen 18 isotope

σh: Principal maximum horizontal compressive stress

σV: Principal vertical stress

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Cover image:
HyMap airborne image of northern Billa Kalina Springs Complex and tributary of Margaret Creek, HyVista Corporation, 2009

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