Great Artesian Basin Springs: a Plan for the Future

Evidence-based Methodologies for Managing Risks to Spring Values

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COVER PHOTO: McLachlan Springs, an example of the sand mound spring type. (Photo: C Harris)

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EXECUTIVE SUMMARY

Artesian springs of the Great Artesian Basin (GAB) are unique environmental assets of international ecological value, as well as being water assets of immense economic and social value to communities, mining and pastoralism in the desert region of the GAB. Consumptive use of Basin water is estimated to return about $13 billion of production annually, including $4 billion in stock, $6 billion in mining, $2 billion in gas and $1 billion from tourism.

The continued survival and well-being of GAB springs are at risk from the twin threats of diminishing artesian pressure which is in turn reducing outflows from the springs, and disturbance of the surface vents from various land uses, particularly as water points for stock.

Securing the future survival of the GAB springs requires sound governance arrangements and bi-partisan commitment to ongoing management programs and secure funding. The second 15-year GAB Strategic Management Plan (2018-2033) provides a general policy basis for sound governance. Each of the Basin states has relevant supporting legislation and regulations.

Various programs since the 1970s have addressed the primary issue of reducing artesian pressure, working to cap and control flows from uncontrolled bores. The most recent bore-capping program was the GAB Sustainability Initiative (GABSI) program, which invested $300 million from 1999-2018 and was a key driver changing management of artesian bores and springs in the pastoral industry. GABSI and other programs successfully rehabilitated 759 flowing bores and converted 31,553 km of open bore drains to piped systems, saving an estimated 235,640 ML of water every year and reducing pressure loss. However, the job is not complete; work needs to continue in order to sustain pressure at a Basin scale and similar programs will need to continue into the future. More than 535 uncontrolled bores and 6,700 km of open bore drains have not yet been replaced by closed delivery systems.

The second threat to artesian springs, that of surface disturbance, has received less coordinated attention. The threats include physical excavation of spring vents, impacts of stock grazing on native vegetation, increased nutrient loads from stock manure, pugging damage to pools and aquatic habitats affecting spring fauna, invasive weeds and visitor impacts. The vast majority of GAB springs are on lands managed for stock production or other agricultural activity.

Scientific knowledge of the Basin resource and its connectivity to other surface and groundwater systems has significantly increased since the 1980s. New knowledge on the structure, hydrogeology and water chemistry in the Basin was generated by Queensland researchers for the Geoscience Australia *Hydrogeological Atlas of the Great Artesian Basin*, culminating in the GAB Water Resource Assessment.

In the South Australian section of the GAB, more than $14 million was invested in research projects into the physical, hydrological and biological characteristics and processes of mound springs. *The Allocating Water and Maintaining Springs in the Great Artesian Basin* (AWMSGAB) project in 2013 and the *Lake Eyre Basin Springs Assessment* (LEBSA) project in 2015 improved knowledge through field investigations to inform future decision making and management for GAB springs.

This Adaptive Management Plan and Template presents evidence-based methodologies to assess and to manage identified risks to spring groups across the GAB. These include requirements to install and maintain closed water delivery systems for GAB springs. There is also a key recommendation for a coordinated, Basin-wide monitoring program to inform management of GAB water sources.

Much of the evidence is South Australian based, as the south-western zone of the GAB has the most artesian springs. However, the principles of the approach in the Template are applicable to any springs in all states across the GAB.

A well-designed and presented web-based digital platform, the '*GAB Springs Stewardship Initiative*' is proposed as the best method to help ensure that the desired outcomes for the springs are achieved. The purpose of the GAB Springs Stewardship Initiative (GABSSI) is to provide access to information about springs and their values; and to present a template for managing the risks created by human activities that threaten those values. GABSSI will provide ready access to attractive, interesting and compelling information about GAB springs, why they need to be cared for and the best way to care for them.

The collation of existing databases into a GAB-wide database will provide the basis for the GABSSI information portal, allowing access to relevant information for any individual spring or spring group. The Queensland government already has a database and portal in development, and the South Australian investigations have created a coordinated database to be linked in.

This GAB Adaptive Management Plan and Template brings together relevant evidence and provides a decision framework for assessing the risks and determining appropriate management actions to address those risks. It is recommended that the Plan and Template be adopted as an implementation strategy as part of the Implementation Plan for the updated National GAB Strategic Management Plan (2018-2033).

GREAT ARTESIAN BASIN SPRINGS ADAPTIVE MANAGEMENT PLAN

Great Artesian Basin (GAB) springs, the natural surface expressions of the GAB aquifers, have important geological and ecological features and iconic cultural values that are recognised nationally and internationally. Human use of GAB water introduces threatening processes that risk compromising these important spring values. The GAB Springs Adaptive Management Plan (the Plan) aims to maintain artesian pressure that sustains spring flows and to encourage land use practices in and around springs while minimising disruption to current uses and users of Basin water resources.

The Plan:

- focuses on fostering a cultural change among user groups whose activities may impact spring condition (health);
- emphasises the need to develop increased understanding of the GAB and the importance of protecting and sustaining these unique features in the arid landscape; and,
- recognises the need to support continued water extraction and associated land uses that provide benefits to the community within a framework that helps protect springs that are at risk of degradation.

The GAB Springs Adaptive Management Plan provides a framework for sustainable spring management. It aims to use the best science and local knowledge available to articulate the importance of GAB springs and present options for management that protect spring values while supporting continued productive use of the water and surrounding landscape. The balance between productive use and protection of spring geology and ecology is achieved through the application of a template that can be applied across the Basin to evaluate springs and negotiate water extraction practices. This template is evidence based, relying on both research data and on-ground management experience.

An 'adaptive' approach to spring management is necessary because spring characteristics including surface conditions, groundwater dependent ecosystems, land tenure and management activities are highly variable between spring complexes. This means that the risks generated by water extraction and land-use require an approach tailored to the spring complex. Simply recommending buffer zones to maintain pressure or fencing as a barrier to animals using springs as a water source may not be suitable solutions for a number of practical reasons. There are three essential requirements for effective implementation of the Adaptive Management Plan to improve spring management practices:

1. robust science that accurately characterises the nature and condition of spring complexes;
2. effective legislation and regulation to protect springs that defines the rights and commensurate responsibilities of water users and land managers; and,
3. a culture of willing compliance that sees the water users and land managers actively protecting (agreed) spring values while supporting the productive use of GAB water and surrounding land-systems.

The Plan proposes a range of on-ground management options that can be applied once the condition of the springs is assessed. Appropriate management responses can be negotiated between landholders and regulators pertinent to the particular circumstances.

The Great Artesian Basin

The Great Artesian Basin (GAB) is Australia's largest freshwater resource and one of the largest fresh groundwater aquifer systems in the world [1]. It has an area of 1.7 million km^2 underlying parts of Queensland, South Australia, New South Wales and the Northern Territory.

The Basin's significance as a water resource is magnified by its location – it underlies arid and semi-arid landscapes to the west of the Great Dividing Range. Basin groundwater provides a climate-independent water supply in areas which often receive low or intermittent supply of rainfall [2]. The GAB is still the only reliable source of water over much of the Basin to support almost all human activity. Consumptive use of Basin water is estimated to return about $13 billion of production annually, including $4 billion in stock, $6 billion in mining, $2 billion in gas and $1 billion from tourism [3].

The GAB provides a reliable supply of groundwater under pressure which emerges at the surface through flowing springs and over 50,000 constructed bores [2]. In some areas in the far western part of the Basin the overlying strata are thin enough for water to come to the surface. GAB groundwater supports an estimated seven thousand individual springs in 450 spring groups scattered across the Basin extent.

Natural flowing artesian springs originating from the Jurassic – Lower Cretaceous aquifers and Upper Cretaceous aquifers occur throughout the GAB, but mainly on the margins of the GAB. Springs occur in twelve large supergroups: the Barcaldine, Springsure, Bogan River, Bourke, Eulo, Lake Frome, Lake Eyre, Dalhousie, Mulligan River, Springvale, Flinders River and Cape York [4, 5] (Figure 1).

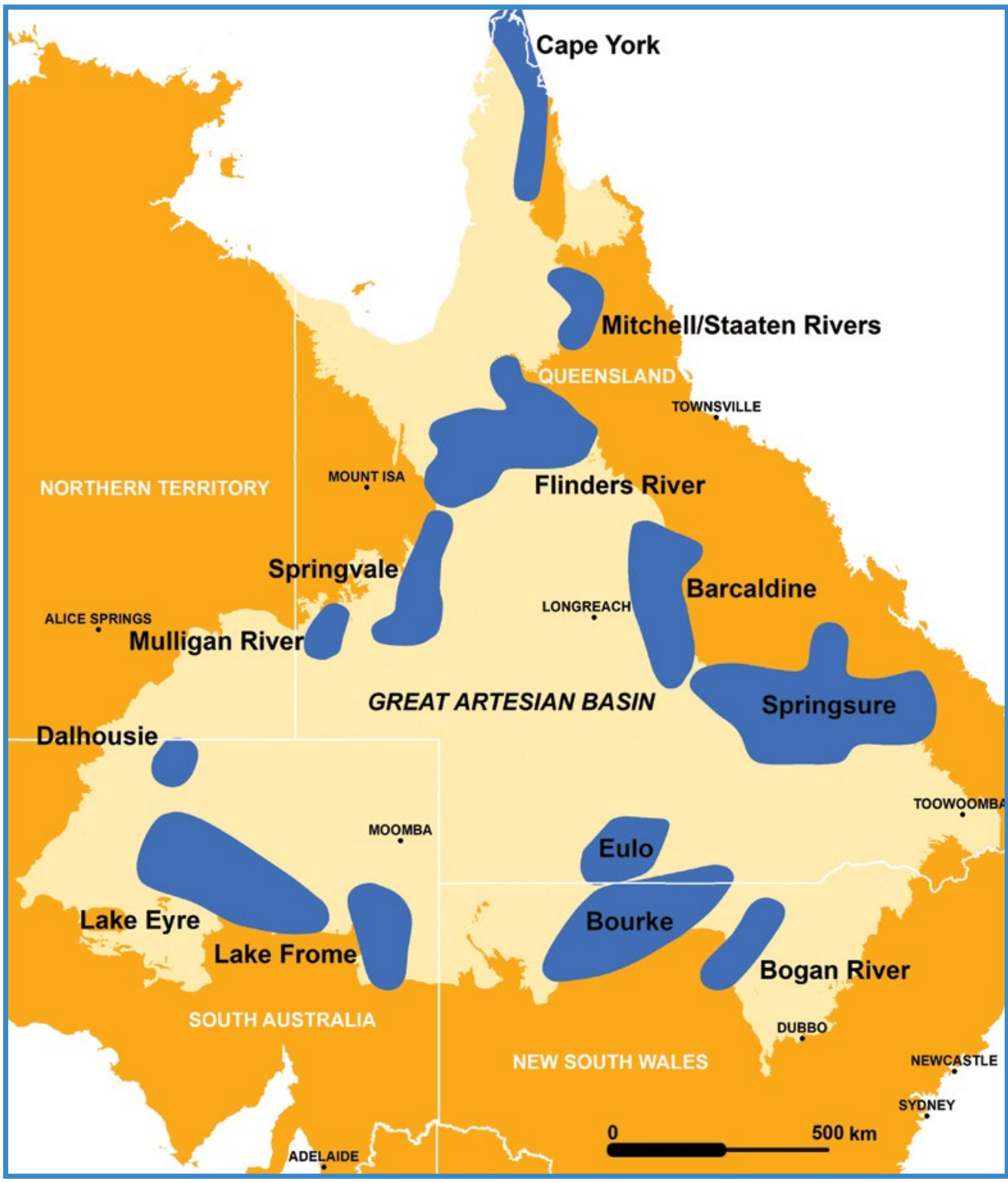
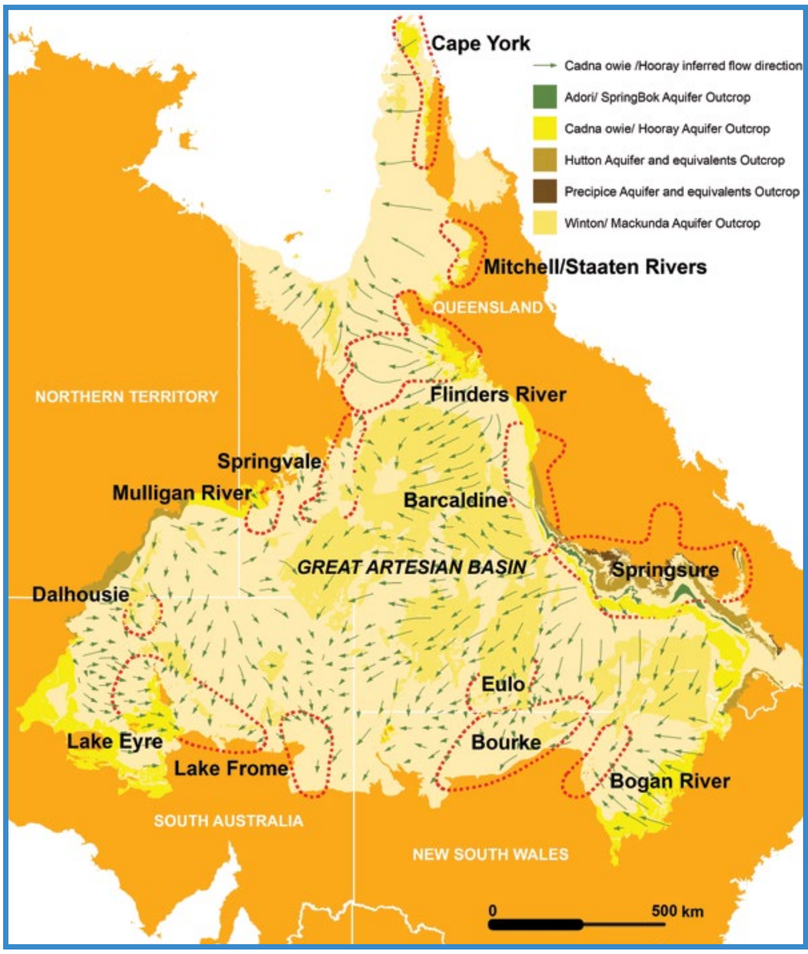


FIGURE 1
Twelve large supergroups of springs occur on the margins of the Great Artesian Basin. (Figures constructed from data sourced from Ransley *et al.* (2015)[74])



The main area of GAB recharge is along the Great Dividing Range, where rain soaks into sandstone aquifers confined between impervious mudstone layers (aquitards). As the confined aquifer system continues from the mountain ranges to the western side of the Basin, gravity builds water pressure in the aquifers which causes the water to flow steadily westwards across the Basin (Figure 2). The geological characteristics of the Basin and the aquifer system means that the movement of water in the basin is highly variable. Groundwater can take up to two million years to cross the Basin [1, 2].

FIGURE 2
GAB SPRING SUPERGROUPS.
Diagram showing the main GAB spring supergroups and how water flows from east to west across the Great Artesian Basin, from the Great Dividing Range towards Lake Eyre. (Figures constructed from data sourced from Ransley *et al.* (2015)[74])

Protecting GAB Springs

The GAB springs are one of the few major artesian spring systems in the world that has not been irreparably degraded by over-exploitation of the water-bearing aquifers and/or the impacts of land-use in and around spring vents.

The GAB springs have deep cultural significance for Indigenous Australians. GAB springs have supported periodic occupation by First Nations people for more than 40,000 years. Important cultural stories and practices are linked to springs and associated topographical features. Archaeology in and around spring sites reflects the importance of these permanent water sources in the otherwise dry landscapes. Many springs determined important trade and communication corridors for First Nations people and these connections persist today with communities maintaining cultural, social and spiritual connections with Basin springs and their associated ecological communities and landscapes.

The springs have high cultural and economic value for GAB communities and for the wider Australian population as unique natural assets. Accordingly, the communities of native species which depend on the natural discharge of groundwater have been protected through a declaration as an endangered ecological community under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* [6].

European exploration and early settlement relied on the springs for water sources, determining the route of the Overland Telegraph and associated transport routes such as the Oodnadatta Track and the narrow-gauge Ghan railway to Alice Springs. Over wide areas the GAB springs and bores have provided the only reliable source of freshwater for humans and pastoral stock, as well as mining and outback towns, influencing development of the inland following European settlement. More than 120 towns and settlements in the Basin rely on GAB water for town usage [2].

Springs are at risk from two major threatening processes:

- reduction in artesian pressure from water extraction that reduces flow to springs
- physical disturbance of spring structures and dependent ecosystems resulting in loss of geological features, and spring ecosystems through grazing, trampling, increased nutrients from animal waste, weed invasion and excavation.

Efforts to sustain the springs at the Basin-wide level have focused primarily on maintaining pressure by managing authorised water extractions and eliminating leaking infrastructure and inefficient practices. Changes in and around springs associated with land-use practices are equally important. Both threatening processes require sustained action to ensure that springs are protected while the benefits that accrue from the use of GAB water and land continue.

Scientific knowledge of Basin water resources and their connectivity to other surface and groundwater systems has significantly increased since the 1980s. New knowledge on the structure, hydrogeology and water chemistry in the Basin was generated by Queensland researchers for the Geoscience Australia *Hydrogeological Atlas of the Great Artesian Basin*, culminating in the Great Artesian Basin Water Resource Assessment [7-14].

GAB Springs Characteristics

Healthy springs require a very specific combination of surface structures, geochemical processes and flow regime to sustain their ecologically rare dependent ecosystems. Spring flows are dependent on both groundwater pressure and the condition and conductivity of the spring vents. This section outlines the important characteristics which determine spring types, geomorphic features, flow regimes and dependent ecosystems.

Classification and Typology of Springs

Springs have been classified into a hierarchy consisting of spring vents, groups, complexes and supergroups [15]. Spring vents are clustered into groups that share similar water chemistry and are related to common geological features. These groups then form clusters that share similar geomorphological settings and are referred to as 'spring complexes'. Clusters of spring complexes are referred to as 'supergroups' [16-19]. *The Allocating Water and Maintaining Springs in the Great Artesian Basin* (AWMSGAB) Project identified the 'spring group' as the scale for which effective management of springs can be practically undertaken [19-21].

Spring Typology

The hydrogeological and ecological understanding of the characteristics of GAB springs have been brought together in the development of a spring typology (Figure 3) which also adapts earlier work [8, 16, 22, 23]. Within the spring groups, springs can be classified according to 'type'. This is an effective way to classify them according to common attributes and allows an assessment of vulnerability to be applied to a spring type, rather than an individual spring. If the risk assessment of a particular threat suggests a significant level of risk to the spring type, then an individual site-specific spring risk assessment may be required.

The first tier of the typological classification (wetland type) uses the Australian National Aquatic Ecosystem (ANAE) classification scheme [24], with a further four tiers developed for GAB springs. The four tiers relating to GAB spring typology are defined according to water source, hydraulic environment, structural linkage and surface morphology.

A summary of the classifications of spring typology is provided below. More detailed descriptions are included in the background document prepared to support this Adaptive Management Plan [25].

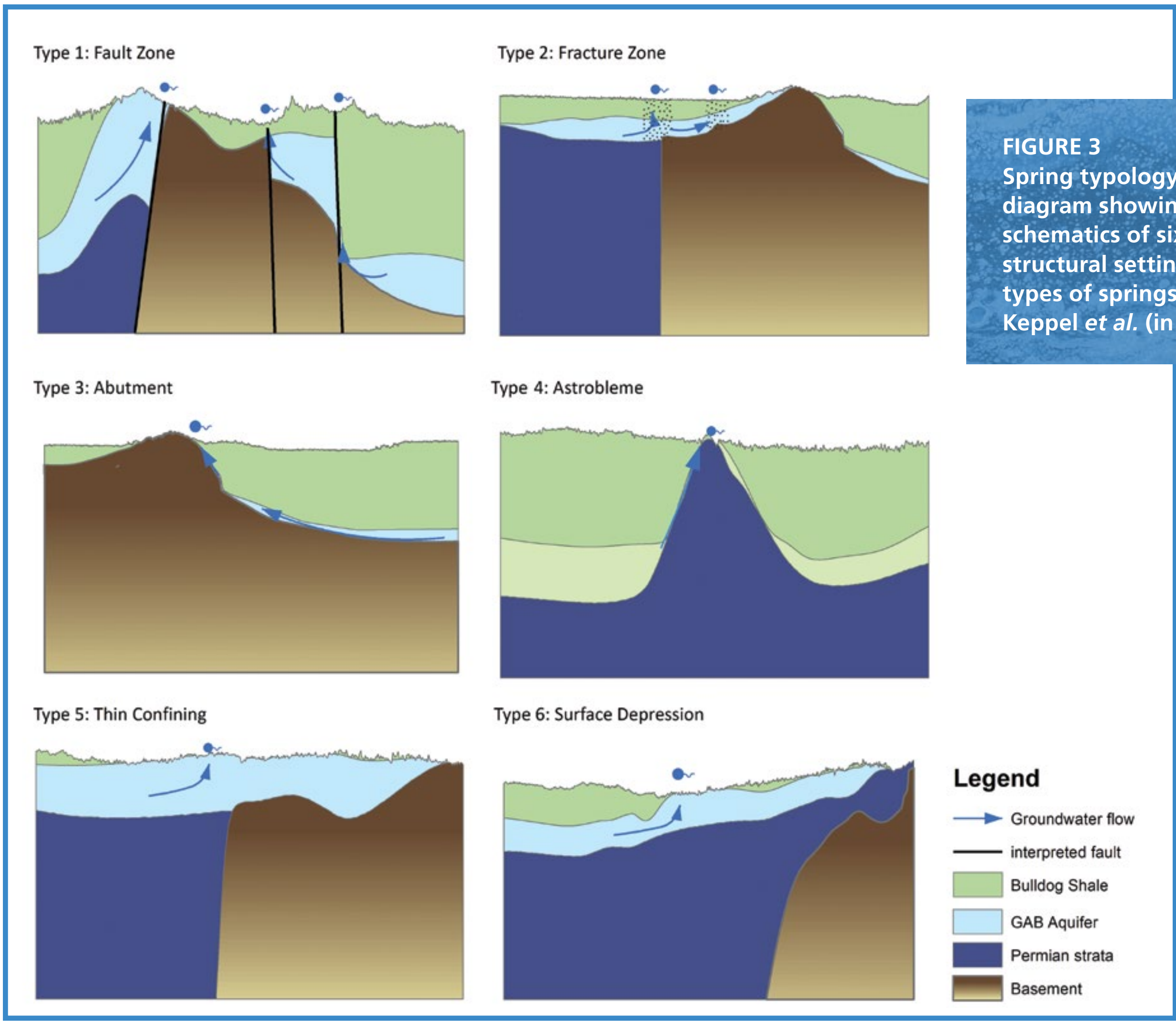


FIGURE 3 Spring typology diagram showing schematics of six structural setting types of springs. (After Keppel *et al.* (in prep.))

Water Source

Wetlands associated with GAB springs are predominantly supplied by groundwater, although if they occur in drainage channels, in low lying areas or in aquifer recharge zones, there may be a surface water contribution to the overall wetland environment. That being said, it is that predominant and persistent contribution of GAB groundwater that is central to these environments' ability to support the unique ecosystems that they do and is therefore the main reason behind their primary typological classification.

Hydraulic Environment

Groundwater-dominant springs are considered to exist in two types of groundwater hydraulic environments:

- Artesian springs are those that result from the upward movement to the surface of water from a confined aquifer via conduits in the confining layer, such as geological structural features (fractures, faults, abutments) or thinner, more porous parts of the confining layer
- Non-artesian springs result when unconfined groundwater either discharges under gravity to the land surface (e.g. water flowing out of an upland fractured rock aquifer), or is exposed by a land surface depression.

The majority of springs in the GAB, particularly in the western GAB, are in the artesian category.

Structural Linkage

The structural features and processes that form conduits through which groundwater is discharged at the surface to form springs in the GAB are summarised below [15, 26]. Additional details are provided in the background supporting document [25].

Type 1 – Fault Zone

Springs occurring near an identifiable fault zone (Figures 3 & 4). Faults may be located near a basin margin or mid-basin.

Type 2 – Fracture Zone

Springs occurring in regions where the depth to the main GAB aquifer is great enough that major structural deformation occurs to form a breach but where there is no major fault structure identified (Figures 3 & 5). The cause of fracture development may vary.

Type 3 – Abutment

Springs occurring when the aquifer comes into contact with an impermeable rock outcrop and the pressurised water is forced along the edge of the outcrop to the surface (Figures 3, 4 & 6).

Type 4 – Astrobleme

Springs associated with a meteorite impact crater (termed "Astrobleme").The impact crater results in localised uplift of basement rocks and removal of surficial rocks within the impact zone, as well as causing localised fracture deformation. The one known example of this type is at Mt Toondina in South Australia [27, 28] (Figures 3 & 7).

Type 5 – Thin Confining

Springs occurring in regions with very thin confining layers (Figures 3 & 8). In some cases, the confining layer has been completely removed through weathering and associated processes to form the spring environment observed.

Type 6 – Surface Depression

Springs occurring where the surface topography intersects the aquifer. This most commonly occurs in creek lines and low-lying areas in conjunction with thin confining aquifers (Figure 3).

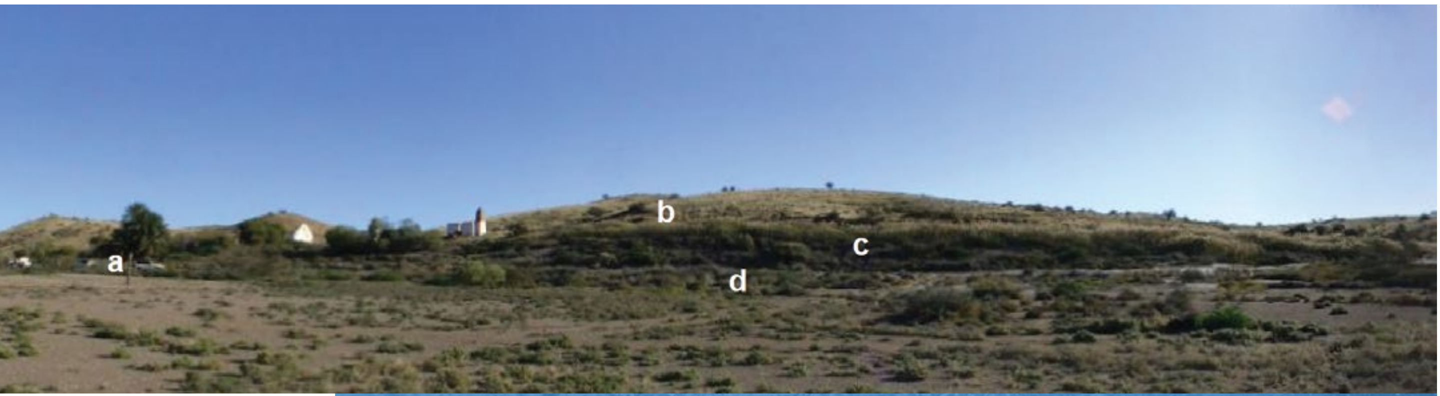


FIGURE 4
Panorama of the Freeling Springs south site, looking west. Freeling Springs is an example of a Type 1 (fault) and Type 3 (abutment) spring complex. The largest spring (a) is located at the far south of the complex. The Peake and Denison Inlier (b) is composed of up-thrown Adelaidean basement rocks. The Kingston Fault is marked by a large stand of *Phragmites australis* supported by discharging groundwater (c). Calcareous spring deposits (d) are present in the foreground. (From Keppel (2013))

FIGURE 5
Micro fault found in outcropping Cadna-owie Formation near Birribirriana Springs. Such small-scale structures may lead to the formation of Type 2 (Fracture zone) springs. (Photo: M Keppel)

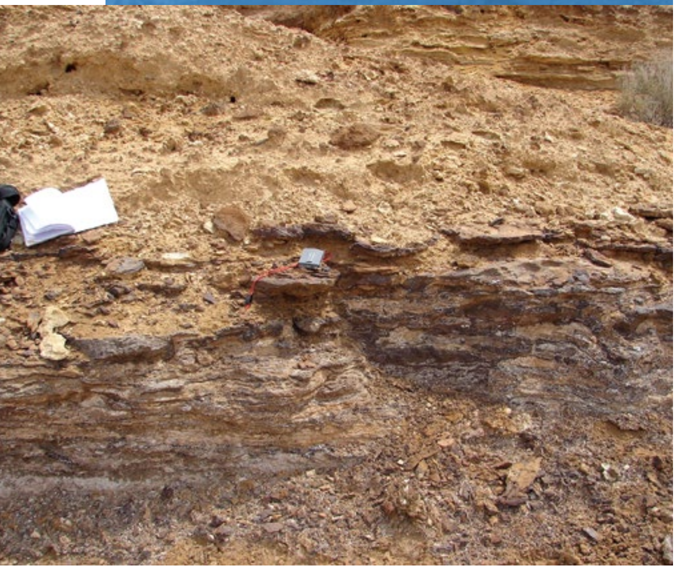


FIGURE 6
North Freeling Springs, a Type 3 spring occurring at an abutment. (Photo: S Lewis)

FIGURE 7
Panorama view of Mt Toondina, which is the only known site of Type 4 (Astrobleme – springs associated with meteoric crater) occurring in the GAB. (Photo: M Keppel)

FIGURE 8
Oogilima Springs, near the shoreline of Lake Cadibarrawirracanna is an example of a Type 5 (Thin confining) spring. (Photo: M Keppel)

Surface Morphology

A number of common surface morphology types related to GAB springs have been described, as listed below. At the spring group and spring complex levels, it is possible to see a combination of the main structural linkage processes and indeed multiple examples of morphological types as well. It is unlikely that all structural and morphological types would be present within one spring complex but at the supergroup level it is possible to find all of the structural linkage processes in operation.

Carbonate Mound

Mounds are characterised by rocky travertine positioned above the surrounding terrain, typically forming a raised vent area that may or may not be accompanied by a tail feature (Figures 3 & 9). The point of spring water emergence is commonly a captured pool at the centre of the mound that is often vegetated.

Carbonate Terrace

Travertine terraces that can be raised above the surrounding landscape but do not form the distinctive mound (Figure 10). The formation of terracing as opposed to mound structures is usually related to underlying topography.

Rocky Seep

Groundwater seeps from rocky cracks and fissures (Figure 3). This morphological type is generally associated with parts of the GAB that abut basement outcrop areas and is distinguished from the carbonate terrace type in that there is a lack of significant travertine deposition.

Peat/Fen/Bog

Spring substrate in these morphologies is largely organic in origin and can form large mounds composed of vegetative mass and entrapped sediment where the underlying topography and flow conditions allow (Figure 3). Where mounds do not form, a traditional swamp or bog will be apparent.

Clay Swelling

Groundwater emerging just below the surface creates a swelling mound of mud/clay with little or no water discharge (Figure 3). The mound is quite plastic and will deform under pressure often releasing more water.

Mud Mound

Mounds formed as groundwater emerges below the surface into unconsolidated soil (Figures 3 & 11). The mound is formed as mud is forced upwards under pressure of the discharging groundwater. Similar to clay swellings, mud mounds may be quite plastic and will deform if disturbed.

Sand/Silt

Mound forms when wind-blown sand is deposited around wet vegetation and then is expanded as more vegetation grows on the substrate. The resulting wetland vegetation may deposit large amounts of organic matter and form a peat/fen bog at the vent (Figure 3 & Cover photo).

FIGURE 9
The Bubbler carbonate mound is an example of a Type 6 (carbonate mound) morphology type. (Photo: M Keppel)

FIGURE 10
Carbonate terracing and spring vents vegetated by common reed (*Phragmites australis*) at Freeling Springs (Keppel *et al.* 2019). (Photo: M Keppel)

FIGURE 11
Mulligan Springs, an example of the Mud Mound morphology type. (Photo: M Keppel)

Spring Types within South Australia

Within the three South Australian spring supergroups, a combination of some or all of the four types of structural linkage processes of spring formation often occurs within one spring group.

The distribution of spring types across the south-western GAB in South Australia is shown in Figure 12. They are described as follows:

- Lake Eyre Supergroup is the most extensive group, situated along a 400 km arc between Marree and Oodnadatta. Many springs in this group are typical carbonate mounds, often forming large carbonate mounds or even small hills. Many are extinct and some large Pleistocene mounds occur, such as Beresford Hill [29]. A significant number of sand mounds and peat and fen bogs are also present here.
- Dalhousie Supergroup is 50 km south of the Northern Territory border and contains the most active springs in the GAB, accounting for 90-95% of the GAB spring discharge in the South Australia [31]. Springs form mounds composed of sand and clay or carbonate, with some Pleistocene mounds having ferruginous and siliceous deposits.
- Lake Frome Supergroup includes low carbonate mounds in Lake Frome and on the edge of Lake Callabonna, and abutment springs on the northern edge of the Flinders Ranges, as well as several large groups of sand and silt mounds [27, 30-34].

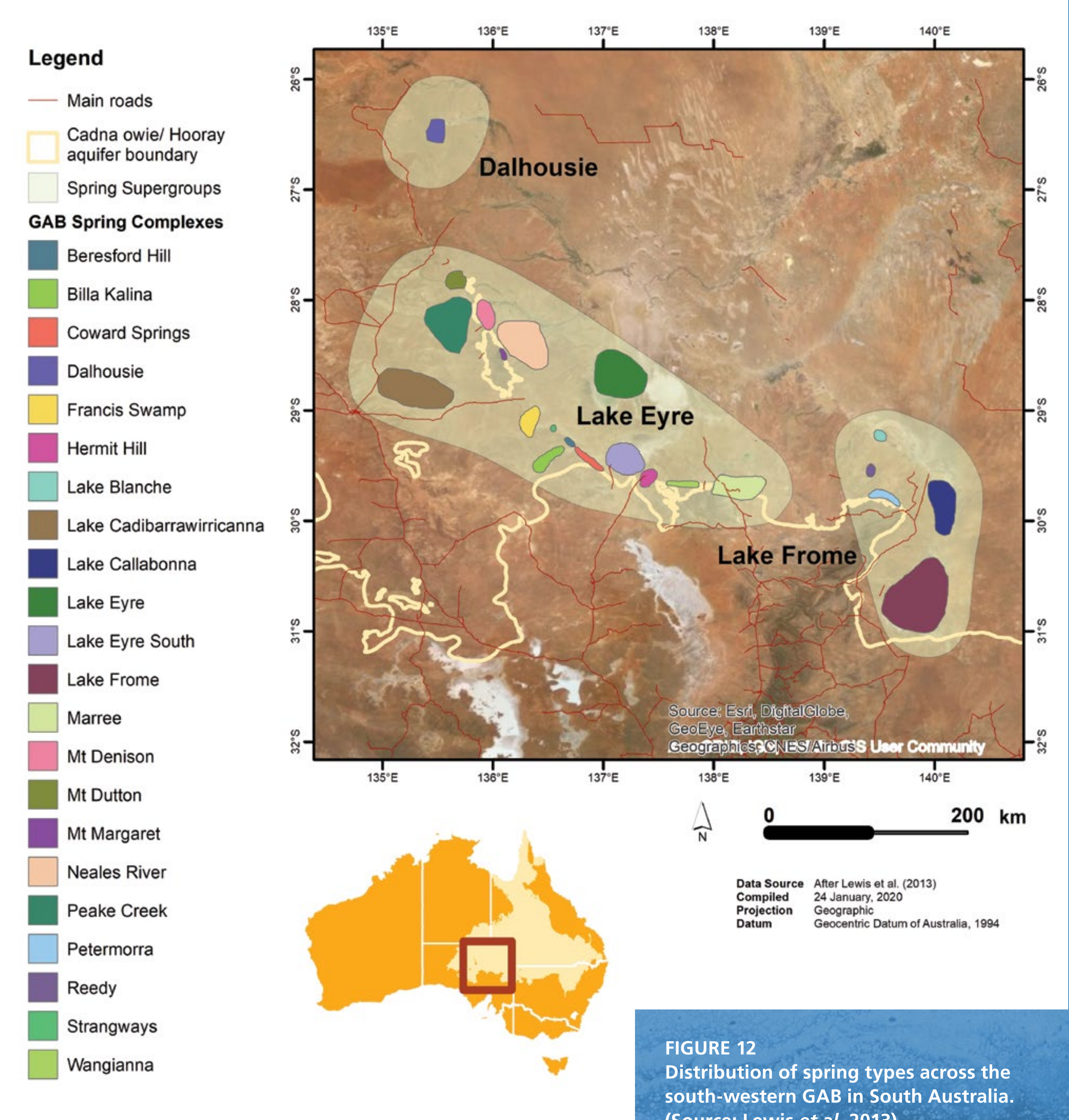


FIGURE 12
Distribution of spring types across the south-western GAB in South Australia. (Source: Lewis *et al.* 2013)

Risks to Specific Spring Types

The typology of springs links with their vulnerability to certain risk factors [28]. For example, springs at the margins of the GAB associated with geological fractures or sediment thinning are at high risk from groundwater pressure reduction. The travertine mound, abutment and rocky seep and terracing types are among the most at risk of sulfation in response to groundwater pressure changes. Rapid changes in pH and conductivity have proven to be lethal for spring endemic flora and fauna. All springs will be vulnerable to the impacts of increased water extraction particularly in the vicinity of large-scale mining developments. Springs with a significant component of surface recharge, such as Dalhousie Springs, are vulnerable to reduced inflows and changes in water temperature inputs. Further detail is provided in the supporting background document [25].

Spring Values

Physical Processes and Structures

Artesian springs in the GAB are features of iconic geological, evolutionary ecological, and biogeographical significance. They have been features in the landscape across the Basin for many thousands of years. The springs provide a record of changes in groundwater discharges, spring deposits and biological history and diversity. [4]

Many springs are highly important from a geological and geomorphological perspective with associated structures derived from precipitation of salts and minerals over thousands of years (Figure 3). There are also important differences in water chemistry. Spring processes and structures that have evolved over millennia support living communities that are limited and controlled by quantity and quality of spring flows and the surface structures and environment in which springs occur [30-35].

Natural Values

The highly variable structures and processes of springs provide insights into the evolution of land systems and the natural communities that they support. The values of physical structures and processes of springs are recognised nationally and internationally. The maintenance of these natural structures and processes is an essential part of protecting spring values [7].

Land systems in the GAB vary from tropical forests around the Gulf of Carpentaria and temperate forests along the Great Dividing Range to vast arid and semi-arid country in the central and western parts of the Basin. The springs play a different role in each of the land systems. In the arid and semi-arid landscapes springs are genuine oases in the desert. GAB springs support plants and animals of immense conservation significance. Springs support genuinely unique flora and fauna that live in and around spring outflows. The importance of the plants and animals of the mound springs is reflected in the fact that they are classified as "endangered" under Commonwealth legislation – the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act) [6].

The physical processes and structural features of springs affect the natural communities that live in and around them. Groundwater dependent ecosystems (GDEs) in and around springs support invertebrate fauna of particular scientific and ecological importance with some species entirely restricted to individual springs or localised groups of springs[35]. Many endemic, rare and relict species are found, including tiny Hydrobiid snails, Ostracods, Amphipods and Isopods. The distribution of the snail species can be separated into regional spring groups. Even within an individual spring, different species can occupy different sections of the aquatic habitat. Recent studies have found 42 newly identified invertebrate species in the South Australian springs, with 25 of these species endemic to spring environments [19].

Seven endemic fish species are restricted by arid landscapes, land use or isolation to very specific spring locations. These include the Mitchellian freshwater hardyhead (*Craterocephalus stercusmuscarum*), Lake Eyre hardyhead (*C. eyresii*), the spangled perch (*Terapon unicolor*), the purple-spotted gudgeon (*Mogurnda mogurnda*) and the desert goby (*Chlamydogobius eremius*) [36]. Queensland has three fish categorised as endangered under the *Nature Conservation Act 1992* associated with Basin springs; these are the Edgbaston goby (*Chlamydogobius squamigenus*), the Elizabeth springs goby (*Chlamydogobius micropterus*) and the red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) [37].

Waterbirds such as ducks are more mobile, moving between springs. Crakes and rails, swamphens, moorhens, and black-tailed native hens have been recorded at springs. Brolgas (*Grus rubicundus*) may be seen on rare occasions. Blue-winged parrots (*Neophema chrysostoma*) are reported to spend winter months in the vicinity of springs and artesian bores in the south-western GAB, migrating back to Tasmania in the summer [36].

Some springs are dominated by tall reeds (*Phragmites australis*), and there is evidence that this has been present in some spring systems for as long as 30,000 years [19]. Bulrush (*Typha domingensis*) also occurs at some sites. Typical wetland vegetation around many springs is a fringe of sedge, *Cyperus laevigatus*, commonly growing to about 30 cm high [36].

Another sedge, *C. gymnocaulos*, is a tough rhizomatous perennial growing to 1 m high and is somewhat resistant to grazing. Cutting grass (*Gahnia trifida*) is also a sedge, found at less disturbed springs, disjunct from other populations hundreds of kilometres to the south. Samphires, chenopods and other salt tolerant species are found on damp, more saline soils around the springs.

A cluster of common reeds (*Phragmites australis*) in the vent of the Little Bubbler in 2013, surrounded by the sedge *Cyperus laevigatus*. (Photo: A Jensen)

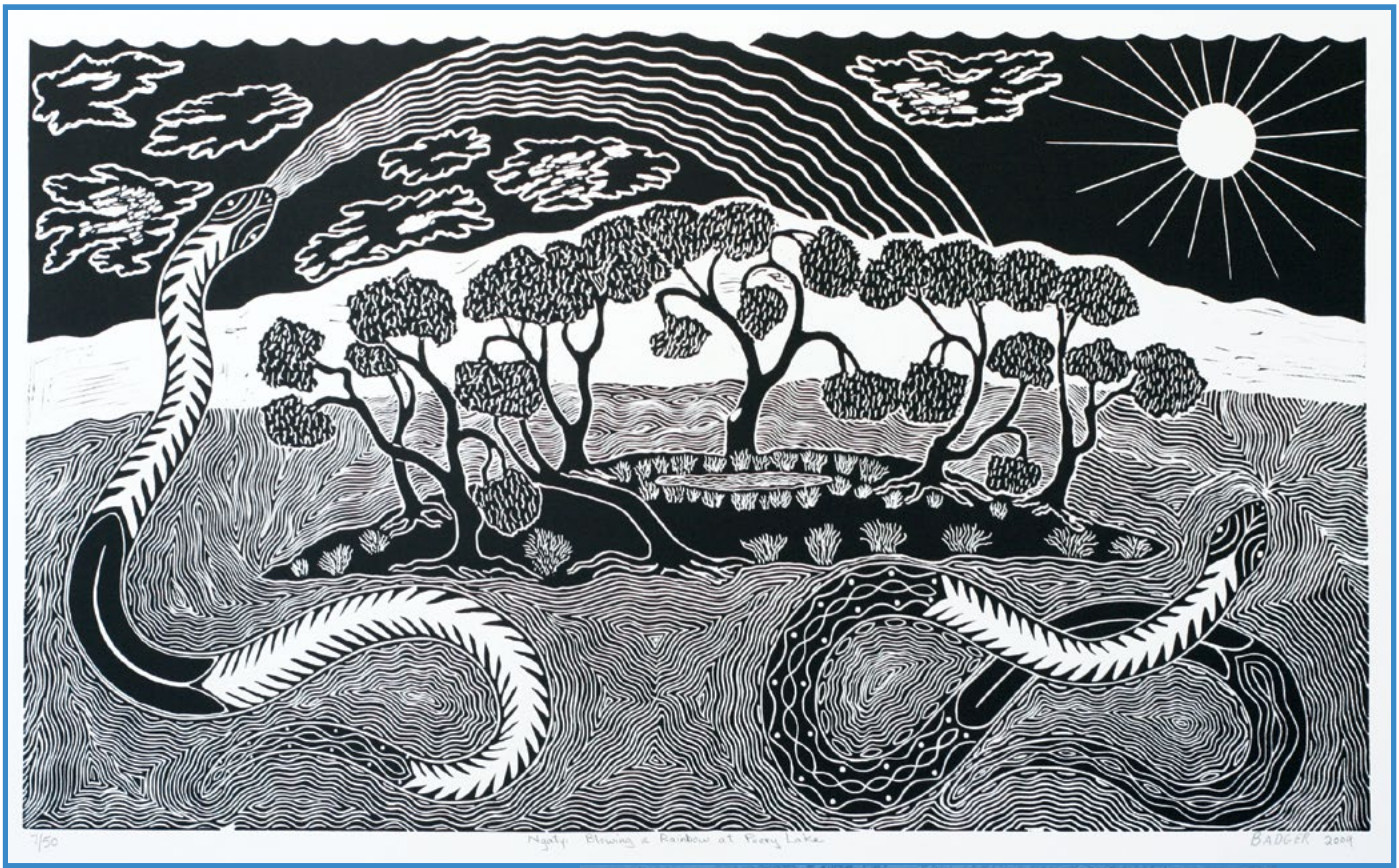


Figure 13
Linoprint of two Ngatji blowing a Rainbow around a mound spring at Peery Lake near White Cliffs, NW NSW. Portrays the traditional cultural significance of GAB mound springs to Barkandji people and other Aboriginal groups in NSW. ©Badger Bates (2009).

Aquatic species water ribbon (*Potomogeton pectinatus*) is found within spring pools, along with filamentous algae. A very important plant species is the extremely rare button grass or salt pipewort (*Eriocaulon carsonii*). The *Eriocaulon carsonii* F.Muell. species complex consists of rare perennial mat-forming forbs endemic to mound springs of central and north-eastern Australia. Previously considered to be a single species, it is now treated as five distinct taxa (three species and two sub species) occurring over a highly disjunct range of more than 1500 km. All of the taxa are nationally endangered or critically endangered according to IUCN criteria, except for *E. carsonii* subsp. *orientale* which is vulnerable [38]. It has very It has very specific habitat requirements, growing in a dense mat above and below the spring vent and covered by a thin film of water, in locations with highly organic soils and consistent clean water flow [39]. It is extremely vulnerable to trampling by stock and pugging of its habitat.

Greater understanding of ecological values of springs has resulted from the Allocating Water and Maintaining Springs in the Great Artesian Basin (AWMSGAB) investigations, with investigations into biodiversity, distribution and species richness in spring ecosystems [21]. Springs are much more diverse than previously reported, with a high degree of endemism and little dispersal between springs [40]. The AWMSGAB project confirmed that species richness for focal groups of species is positively associated with springs that have flowing water in their tails and negatively associated with stock impacts on spring structures.

Indigenous Cultural Values

The GAB springs have deep cultural significance for Indigenous Australians. GAB springs have supported pulses of occupation by First Nations people during suitable conditions for more than 40,000 years. Important cultural stories and practices are linked to springs and associated topographical features, reflecting the importance of these permanent water sources in the otherwise dry landscapes. Many springs are sites of important events and stories (Figure 13). Some well-known stories include a Kuyani story about the ancestral Rainbow Serpent Kanmari associated with The Bubbler, Blanche Cup and Hamilton Hill, and an Arabana fish and crane story associated with Mangkapilhinha (Edith Springs). A site *Panki Warrunha* 'White Ribs' is located near Strangways Springs complex [41, 42, 43].

Springs on the western edge of the Basin formed an important trade and communication corridor for Indigenous groups. First Nations and their regional communities maintain cultural, social and spiritual connections with Basin springs and their associated ecological communities and landscapes.

Traditional Custodians for country covering GAB springs locations in South Australia include Arabana, southern Arrernte, Antakarinja, Dhirari, Dieri, Pirlatapa, Yandruwandha, Wangkangurru, Karangura, Ngamini, Kokatha and Kuyani [44]. Dalhousie Springs are on southern Arrernte lands and most of the western arc of springs along the Oodnadatta Track are on Arabana lands.

Historical and Modern Cultural Values

The springs have high cultural and economic value for GAB communities and for the wider Australian population as unique natural assets. European exploration and early settlement relied on the springs for water sources, determining the routes for the Overland Telegraph and transport routes such as the Oodnadatta Track and the Ghan Railway [41].

European explorer Peter Warburton discovered Coward Springs in 1858. Noted explorer John McDouall Stuart led several expeditions through springs country and in 1859 named Elizabeth Springs and Freeling Springs. Stuart completed his trans-continental crossing in 1862 following the springs route around the western edge of Kati Thandi-Lake Eyre, laying the basis for the route of the Overland Telegraph from Adelaide to Darwin, which was completed in 1870-1872.

GAB springs continue to have high cultural and economic value for GAB communities and for the wider Australian population as unique natural assets [2, 3]. The GAB springs and bores have provided the only reliable source of freshwater for humans and pastoral stock, as well as mining and outback towns, influencing the direction and extent of development of the inland following European settlement.

One such settlement was Coward Springs, near Kati Thandi-Lake Eyre South. An artesian bore was sunk there in 1886, to a depth of 400 feet, with water rising 15 feet into the air due to the artesian pressure. The Coward Springs Hotel provided services to road and rail travellers from 1887 to 1953, but was demolished in 1965 [45].

By the 1920s, Coward Springs bore had corroded and millions of gallons of water flowed freely, creating a new wetland in the desert. The bored was redrilled and relined in 1993 to control the discharge rate. However, the artificial wetland created a diverse habitat for a wide variety of biota, and the bore has been permitted to remain with reduced flows under a Heritage Agreement with the state Environment Minister, also including two restored railway buildings [45]. Coward Springs now provides a popular camping ground for tourists travelling on the Oodnadatta Track, adjacent to Wabma Kadarbu Springs Conservation Park.

GAB springs continue to have high cultural and economic value for GAB communities and for the wider Australian population as unique natural assets [2, 3]. Coward Springs is now a popular camping ground for tourists travelling on the Oodnadatta Track.

FIGURE 14
Flow from Beresford Railway Bore 1987, prior to capping. This well is no longer uncontrolled and was decommissioned in 2011 (Photo: C Harris)

Strangways Springs stock fences and Repeater Station ruins (Photo: A Jensen)

Legislation and Regulations

Management of GAB springs falls within State agencies dealing with governance of land use, planning, water use, environmental conservation, soil conservation, agricultural and development activities.

Management and Compliance

Cooperative management of the Basin included the co-funding of the Great Artesian Basin Consultative Committee by Basin governments and the Commonwealth in 1998.

The first GAB Strategic Management Plan (SMP) developed a Basin-wide non-statutory management plan collaboratively between governments and the Great Artesian Basin Consultative Council [46]. The SMP was the first 'whole of-Basin' management plan to be adopted by all governments responsible for the management of the Basin, to address the critical issues and limitations in management identified by Basin stakeholders. The first SMP had a fifteen-year timeframe and detailed a staged Plan for implementing the strategies and objectives, as well as reviewing and reporting progress [47].

The Basin governments, including the Commonwealth with the support of the GABCC, co-funded the Great Artesian Basin Sustainability Initiative (GABSI) to assist landholders to cap and pipe uncontrolled bores [2, 48]. Relationships amongst all Basin stakeholders both within and outside government have proven robust over this time, and this has been assisted by Great Artesian Basin advisory bodies which have been set up in South Australia, Queensland and New South Wales. These bodies have provided a community voice with regard to management activities. Recognising the linkages between other cross-state water Basins, meetings have occurred with Lake Eyre Basin and Murray-Darling Basin Community Advisory Committees to develop joint approaches for coordinated management.

Groups other than government and landholders also contributed to Basin health. In South Australia BHP contributed $2.325 million to the GABSI program in that state as part of its mining conditions and in Queensland several bore rehabilitation projects were sponsored by mining companies.

All four Basin governments have developed statutory water management plans for Basin water resources: in Queensland the Great Artesian Basin Water Resource Plan (2006) [49] is complemented by the Great Artesian Basin and Other Regional Aquifers Water Plan (2017) [50], and in New South Wales it is the Water Supply Plan for the NSW Basin Groundwater Sources (2017) [51]. In the Northern Territory the Great Artesian Basin (NT) Water Allocation Plan (2013-23) is current [52]. In South Australia the Water Allocation Plan for the Far North Wells Prescribed Area (2009) [53] is under review in 2019 [54], and the Regional Natural Resources Management Plan (2017-2027) was completed in 2017 [55].

The water management plans set limits on the amount of water that can be taken, balancing new development with needs of existing water users and the environment [47]. At the national level, the second GAB SMP covering the next fifteen years 2018-2033 was released for consultation in November 2019 [2].

Legal Protection

Springs and related flows to watercourses, lakes and wetlands have been recognised as having important and unique cultural and ecological values. The community of native species dependent on natural discharge of groundwater from the Basin was listed as a threatened ecological community under the EPBC Act in 2001 [6, 56]. However, this listing was limited by the lack of available data for all springs at the time. Given the major expansion in technical investigations and knowledge of springs, the listing needs updating.

These threatened communities were managed under state laws through the *NSW Threatened Species Conservation Act 1995* [57], which was repealed by the *Biodiversity Conservation Act 2016* [58]. Springs in Queensland have some protection under the *Queensland Vegetation Management Act 1999* [59] and the *Environmental Protection Act 1992* [37, 60]. In South Australia, the *Pastoral Land Management and Conservation Act 1989* [61] and *Natural Resources Management Act 2004* [62] contain broad provisions advocating due care in managing natural ecosystems, while the *Native Vegetation Act 1991* [63] has more specific provisions for the protection of native vegetation.

Further community recognition of the importance of the Basin springs is reflected in special conservation areas protected by various State legislation. A number of important spring complexes, spring groups or individual springs are afforded some protection in conservation reserves in South Australia, including The Bubbler and Blanche Cup along the Oodnadatta Track and Dalhousie Springs near the Northern Territory border. Some important key spring groups in Queensland are protected under heritage and other agreements, for example with *Trust For Nature* (Jensen *pers comm.* 2019). However, there is currently some legal uncertainty about declaring Heritage Agreements over springs on long term Crown Land pastoral leases in South Australia. Another potential option for springs management and monitoring may be negotiation of offset payments with mining companies, using the provision for Significant Environmental Benefits (SEB) under the *Native Vegetation Act* [63] and brokered via a non-government organisation (NGO) such as Nature Foundation SA.

FIGURE 15
Edgbaston Springs in Queensland (Photo: B Donaghy)

Edgbaston Reserve in Queensland was purchased in 2008 with assistance from the Australian Government and through private funding directed to the conservation organisation, Bush Heritage Australia (Figure 15). This reserve protects two nationally threatened fish: red-finned blue-eye and Edgbaston goby in the Basin spring-fed pools [64].

Another emerging opportunity is the rapid development of the market in biodiversity credits, where landholders can earn an income from management actions which protect ecosystems. There are potential opportunities to apply these methodologies to protection of GAB springs.

For example, the private company GreenCollar has developed a sophisticated system of reef credits for farmers in catchments connected to the Great Barrier Reef. Farmers must demonstrate that no sediment or nutrients leave their farms. GreenCollar set up the process of analysis and accreditation and enter the credits in the market. Reef credits are being bought by Qantas, the Commonwealth Government, the Queensland Government and green investors. The system is established at no cost to the farmer, and GreenCollar is paid with a cut from the credits generated. A similar system could be developed for application to GAB springs.

State Governance

Each of the state and territory governments manages water extraction from the Basin in line with their own legislation, policy and regulatory frameworks. Such arrangements have progressed groundwater management, particularly where management rules have been developed in consultation with communities, however more progress is required.

The following achievements in improved governance at state level have occurred since the first GAB Strategic Management Plan to 2018.

In **South Australia**, the Water Allocation Plan (WAP) objectives are in line with those of the GAB Strategic Management Plan, the EPBC Act 1999 and the 2004 Intergovernmental Agreement on a National Water Initiative [2, 6, 46, 65]. The Water Allocation Plan (WAP) establishes a framework which includes managing Basin water in South Australia. Almost all Basin water extraction in South Australia requires a water entitlement and allocations through a licensing regime [66]. The new WAP will introduce a new flexible water licensing system [54, 55]. It is designed to be able to adapt to future changes in supply and demand, while protecting property rights and the environment.

The system being introduced consists of a water entitlement to a part of a specified consumptive water resource and an annual water allocation against that entitlement. Works to access the water source require a works approval which indicates how and where water can be taken, in addition to a site use approval indicating how and where water can be used on land.

South Australia included statutory conditions on pastoral water licences, tying water allocation to stocking rates on the property and requiring landholders to deliver water to stock through a well-maintained closed water delivery system. A compliance program was implemented in consultation with landholders.

In South Australia, only groundwater is prescribed in the Far North region. Surface water is managed under the provisions of the *Natural Resources Management Act 2004* [57]. Section 127 of the NRM Act provides for the control of various activities that divert water or alter surface flows from a natural watercourse (e.g. dams, levee banks, creek crossings, excavating or removing rock, sand or soil, and draining or discharging water into a watercourse). Such activities are controlled through Water Affecting Activity (WAA) permits issued by SA Arid Lands NRM staff on behalf of the SA Arid Lands Natural Resources Management Board [66].

All information on South Australian governance provisions is current to December 2019 but should be updated after new arrangements for Natural Resources Management Boards come into effect in 2020.

In **New South Wales** the Water Sharing Plan for the New South Wales Great Artesian Basin Groundwater Sources 2008 commenced on 1 July 2008 and the amended Plan from 2014 is currently in force at November 2019 [47]. This Plan sets limits on extraction and establishes rules for sharing water between the different types of water users and the environment. It sets the volume available to landholders under their basic right to access domestic and stock supplies and the volume available to licensed entitlement holders also sets rules for the location of bores to protect access for other users and impacts on the environment. Schedule 4 High Priority Groundwater Dependent Ecosystems lists 35 geothermal springs [26]). Amendments to the Water Sharing Plan for the NSW Great Artesian Basin Groundwater Sources have been passed in 2011, 2012, 2013 and 2014, with the 2014 version as the current legal instrument [67].

Queensland developed the Great Artesian Basin Water Resource Plan (WRP) 2006 and Great Artesian Basin Resource Operations Plan 2017 [49, 50]. These documents provided the framework for the management of Queensland's Basin groundwater, including providing security of supply for current and future water users and the protection of groundwater flows to springs and watercourses. The plans also broadly defined the areas and circumstances in which water could be taken or made available, as well as requirements for ongoing monitoring and reporting.

A new Water Plan, Great Artesian Basin and Other Regional Aquifers 2017, commenced on 2 September 2017. This plan includes many of the features of the previous plans and it also addresses the changed situation in relation to water demand in Queensland and contemporary planning policies. New elements in the plan include:

- improved water efficiency by mandating all uncontrolled bore and drains be made watertight by 2027
- water allocations for the economic and cultural use of Aboriginal people
- simplified water trading in the Basin (Department of Natural Resources, Mines and Energy 2018).

The *Water Act 2000* (Queensland) requires a licence for stock and domestic take; however, there is no volumetric limit on these licences.

In the **Northern Territory** the Great Artesian Basin (NT) Water Allocation Plan (2012-2033) was completed in 2013 [52]. The plan is being prepared in accordance with the Water Act, and will assist the Northern Territory in meeting its obligations under the Basin SMP (2010, 2018) [2, 14]. This Plan will regulate water resource management of all water extraction required to be licensed under the Act for the whole of the GAB Water Control District in the NT.

The principal objectives of the Plan are to:

- maintain public water supply
- protect the environment
- support indigenous culture and communities, and
- ensure sustainable development.

The Plan applies to the declared District in the south-east corner of the Northern Territory, which is equivalent to about six per cent of the Northern Territory. This area of approximately 86 500 km², is based upon the sediments and outcropping of the Eromanga Basin within the Northern Territory. It applies to all surface water and groundwater, including but not limited to water in the GAB aquifer, within the District. There is currently no significant or licensed surface water extraction within the District. Surface water is important because of its environmental and cultural significance and as a source of recharge to the relevant groundwater resources.

Groundwater is the important consumptive water resource within the District and the majority of water extracted from the Basin Northern Territory is used for a licensed public water supply to the community of Finke/Apatula supply, and for unlicensed stock and domestic purposes.

The most likely future use for water in the District is associated with the current wave of oil, coal and gas mining exploration. Water use associated with mining activities is currently exempt from water licensing requirements under the Act and therefore cannot be regulated by the Plan. Nevertheless, any water allocations permitted under the Plan will need to be considered in the context of any water extraction made for mining purposes.

Land Tenure

Indigenous people have strong cultural ties to springs located on land used for pastoral and other productive purposes. In South Australia, advice on production is provided by the Department of Primary Industries (PIRSA) in the North West Indigenous Pastoral Project (NWIPP), in partnership with the Indigenous Land Corporation (ILC). Cultural and environmental values are being included in property plans, as well as weed and feral animal management. Kokatha Pastoral Pty Ltd hold Andamooka, Purple Downs and Roxby Downs Stations. Bungala Aboriginal Corporation hold Emeroo Station.

Much of this work is being reinforced through funding from the BHP Foundation *Ten Deserts Project*, with multiple partners investing in coordinated projects to support and empower traditional owners to look after country [68]. The Ten Deserts of Australia span 2.7 million km² across five state and territory boundaries, encompassing cultural and environmental linkages that ignore those boundaries. A core component of the project is ranger training and empowerment, with a focus on practical land management skills. The aim is to secure future long-term funding and revenue streams.

In the South Australian portion of the GAB, a limited number of important springs are protected within State reserves or protected through private initiatives and localised, targeted Government programs. However, the vast majority of GAB springs occur on privately managed pastoral lands or land used for other activities. Several Pastoral leases are now owned by mining or petroleum companies, but are also subject to lease provisions set down by the Pastoral Act (1989) and overseen by the Pastoral Board [61]. The Act is currently under review, and in the early stages of public consultation.

The Arabana Aboriginal Corporation, whose tribal name is *Ngurabanna*, the land of the mound springs, is the prescribed body to administer Arabana interests over 69,000 km² of Arabana Native Title Land to the south-west, west and north-west of Kati Thandi-Lake Eyre, an area including hundreds of GAB springs [69].

Threats to Spring Condition

A threat is defined as any action or influence that may lead to or cause an unacceptable change. The risk is the probability that human actions will trigger a threatening process.

There are two primary threats to the values of GAB springs:

- the artesian pressure in the GAB which sustains the springs is being measurably reduced by the many thousands of bores sunk to reach the groundwater resource;
- spring environments are being disturbed through physical destruction of geological features, loss of spring vegetation through grazing by stock and pest animals, increased nutrients from animal excretions, weed invasion and, in some isolated cases, through excavation.

Threats from Water Extraction

The extraction of GAB water through bores results in a cone of pressure depression around the bore. The amount of pressure reduction and the extent of the depression cone depends on the rate of water extracted and the characteristics in the aquifer from which the water is removed. The reduction in pressure gradually stabilises as long as the extraction rate from the bore remains constant. Pressure will slowly recover once extraction is reduced or the bore is decommissioned (plugged and abandoned). Cones of pressure reduction overlap when water is extracted from sources in close proximity. This results in regional pressure reduction that can reduce or stop artesian flows from springs and bores [2].

Flows from the springs are estimated to have decreased by at least 30% from flow rates at the time of European settlement due to development and extraction impacts, leading to pressure decline [14, 47]. It has been reported that more than 1000 springs have dried up as a result of GAB water extraction through artesian bores [54] (Figure 16).

Regional Water Extraction

Water extraction from the GAB is effectively mining the water resource, given the natural and on-going pressure decline and much lower recharge rates than previously believed. Over the past century the natural decline in potentiometric surface pressure has been accelerated by human extraction of water through bores and changing land-use in recharge areas [2]. The identification of significant surface water sources of recharge via shallow aquifers in the western GAB means that climate change could be a potential further threat to water availability for springs, particularly for Dalhousie Springs. The effects of climate change on water availability should be included in risk assessments for the springs, especially in the Western region [30].

Programs to repair uncontrolled flowing bores commenced in 1977 and continued through the 1980s and 1990s, with cooperative programs between South Australia and Queensland. Efforts to install controls on uncontrolled flowing bores were substantially increased from the beginning of the 21st Century, as a result of a Basin-wide initiative supported by State and Commonwealth Governments and water users. This led to a GAB Strategic Management Plan and the GAB Sustainability Initiative (GABSI) [2, 14, 46]. GABSI was a joint funding program between the Australian, New South Wales, Queensland, South Australian and Northern Territory governments and Basin landholders. It was initiated in 1999, to be implemented over three five-year funding rounds.

The GABSI cooperative funding arrangements enabled the installation of 'closed water delivery systems', consisting of bore rehabilitation and replacement as well as the design and installation of pipe valves tanks and troughs required to replace bore drains (Figure 17). This investment of more than $300 million by governments and landholders was a key driver changing management of artesian bores and springs in the Pastoral industry. In addition, sustained research, consultation, monitoring, education, and policy development proved invaluable and essential components in the transition to efficient stock water management since 2000 [48].

FIGURE 16 Uncontrolled open bore drain (left) and capped system (right). (Photos: L Brake & A Smith)

FIGURE 17
Closed water delivery systems ensure that water for stock is captured and delivered to stock through piped systems with tanks, float valves and troughs. (Photos: L Brake)

There are more than 50,000 bores in the GAB and much of the water delivery infrastructure is leaking and wasteful. Substantial progress has been made in managing the primary threat of pressure reduction leading to reduced spring flows. GABSI and prior cooperative programs since the 1980s have successfully rehabilitated 759 flowing bores and converted 31,553 km of bore drain with piped systems, saving an estimated 235,640 ML of water every year and reducing the rate of pressure loss. However, the job is not complete; work needs to continue in order to sustain pressure at a Basin scale. More bores need to be capped. Capped bores will continue to fail because of corrosion and delivery infrastructure will require continuous maintenance. More than 535 uncontrolled bores and 6,700 km of open bore drains are yet to be replaced by closed delivery systems. Ongoing maintenance of bores and water delivery systems is required to prevent a return to historical conditions. [2, 14, 44] (Figure 17).

Local Water Extraction

The major consumers of GAB water are mining and petroleum operations, including co-produced water, and pastoral use to supply water for stock. Towns and other users account for a minor volume.

Mining and Co-produced Water for Mining, Gas and Petroleum

In South Australia, mining operations in and near the Basin have been extracting GAB water since the 1980s, in particular from the Olympic Dam bore-fields. Mines in north-western Queensland and north-eastern New South Wales were extracting water long before that. The extraction of co-produced water, a bi-product of the petroleum and gas industries, has significant impacts on pressure in and around wellfields in the Basin. The volume extracted by these industries is very significant. Unless carefully managed, this pressure reduction can affect flows from springs. Any additional water extraction for oil and gas, mineral mining, coal seam gas and geothermal developments may generate risks to flows from GAB water bores and springs [2, 4, 14].

The majority of groundwater water abstraction from the GAB for the minerals industry is by the Olympic Dam mine, for mining operations as well as water supply to the town of Roxby Downs. Groundwater abstraction is governed by the *Roxby Downs (Indenture Ratification) Act 1982*, which provides for a special water licence (Keppel *pers comm.* 2019) [53, 54]. The operators of Olympic Dam (BHP) are required to undertake groundwater and environmental monitoring and provide the Government of South Australia with an annual environmental monitoring report, detailing mine performance against a list of environmental outcomes, compliance criteria and leading indicators as well as targets for continuous improvement.

Other mining operations abstract water under normal water licensing provisions under the NRM Act (2004) [62], with such water being used in all aspects of mining, dewatering, drilling, plant operation and camp supply. Mining operations have compliance reporting obligations under the conditions of their mining lease, with such reporting describing relevant groundwater and other environmental monitoring activities undertaken.

Extractions from the GAB by the petroleum industry are in the form of co-produced water which comes to the surface during the production of liquid petroleum and gas. After separating out the hydrocarbon component, co-produced water is generally disposed of in evaporation ponds. Additionally, a small volume of groundwater may be used for drilling, road maintenance or processing operations.

Groundwater abstracted by the petroleum industry is done so under a common licence held by the South Australian Government Minister for Energy and Mining. Petroleum companies report detailed monthly groundwater and petroleum hydrocarbon abstraction totals to the Government of South Australia as part of their Petroleum Licence conditions.

The regional impact on pressure from the extraction of co-produced water can generate risks to spring flows. The effect of extracting co-produced water must be considered when analysing the likelihood of risks to spring flows. Robust modelling information is required that can accurately predict the drawdown and ensure that pressure changes do not adversely affect spring flows. Management of the risks must include on-ground actions to maintain the impact of both regional and local water extraction within acceptable limits.

The impact of the petroleum sector is expected to increase as new operations come on line, with increased demands for water. Within the SA GAB, the petroleum sector currently holds a cumulative licence for 60 ML/day, due to increase to 80 ML/day in 2021. The SA DEW is developing a groundwater model to provide an evidence-based baseline and predictions for monitoring the impact of these extractions, including identification of groundwater sources. Monitoring of water extractions by mining and petroleum operations is facilitated by the fact that these industries are required to report use volumes regularly.

FIGURE 18
Emerald Spring on Stuart Creek Pastoral Lease has been used as a source of stock water by pastoralists since the mid-1800s. (Photo: S Lewis)

Water for Stock

In the early days of pastoralism in the mid to late 19th century, GAB springs provided often the only reliable water supplies for stock. The first artesian bore was drilled into the Basin near Bourke in 1878 for stock water. The benefits that accrued from access to artesian water from bores quickly revealed the true value of Australia's largest freshwater resource, so by 1915 more than 1,500 bores had been drilled into the Basin.

In order to maintain a clean water supply, the early pastoralists often fenced springs and piped spring water to an external trough. However, with the sinking of artesian bores from the late 1870s, bore water became the primary water resource and the fencing around the springs was not maintained, eventually allowing direct stock access to previously protected springs. Remnants of the early fencing can still be seen at many springs: Some of the original fencing still exists around the first mound spring discovered by European explorers, Emerald Spring on the Stuart Creek Pastoral Lease (Figure 18).

Pastoral use is not as easily reported, since bores and springs are not easily metered and some pastoral users utilise groundwater in shallow aquifers overlying the GAB. Pastoral volumes are largely estimated from flow measurements on uncontrolled bores and conservative estimates on controlled bores. A further calculation can be added based on the number of stock, to estimate the minimum requirement to meet stock needs in drought conditions.

The Pastoral Industry is a significant water user in the Basin, but the transition to closed water delivery systems on pastoral properties is far from complete. Regulations concerning the judicious use of water for stock, including the installation and maintenance of closed water delivery systems, are associated with statutory plans in each State (*see State Governance above*). However, the installation and maintenance of efficient water delivery infrastructure is still problematic for some landholders in terms of cost and labour.

Oversight and Monitoring of Water Extraction

Technical investigations are continuing to improve understanding of groundwater sources and connections and the rates of extraction by different sectors. In the South Australian section of the GAB, the draft Water Allocation Plan (WAP) – a revision of the 2009 WAP – includes licensing provisions for the Far North Prescribed Wells Area (FNPWA), covering all GAB and non-GAB groundwater resources. Most of the water used in this area is extracted from the GAB. The draft WAP, currently out for consultation, includes modelled estimates of annual allocations to various sectors, confirming mining and petroleum as the major water user in the region at around 50,000 ML/year, including the Prominent Hill mine. Modelled annual water take for stock use is modelled to be around 10,000 ML/year [54]. These numbers are included in the WAP as the basis for determining volumes for future water licensing, and will be confirmed once public consultation concludes in March 2020.

However, the picture is complicated by the fact that, while most of the groundwater is from the GAB, there are other groundwater sources included. The draft WAP covers the management and allocation of water from all groundwater resources across Far North South Australia, including the Arckaringa Basin, the Cooper Basin, the Hamilton Basin, the Officer Basin, Lake Eyre Basin and Paleo-drainage channels.

The development of the WAP for the FNPWA and the supporting modelling being developed by DEW will establish a more detailed baseline for monitoring and adaptive management feedback loops for future management of groundwater resources in the Far North region. The models and methodologies would have application for adaptation to other regions of the GAB, as needed.

Town Water Supplies and Tourism Water Use

More than 120 towns and settlements in the Basin rely on access to a reliable source of GAB water for town water, taking 8% of water extracted [2]. Some Basin towns use water sustainably and have water saving policies while others are less judicious and have less efficient water management practices. Domestic water supplies, water to improve the amenity of the town environment and water for local businesses are essential to the viability of regional towns. Tourist attractions in the Basin are based on features such as historical flowing bores and wetlands or 'Hot Spring Baths' that extract water from the GAB. A range of activities in the Basin rely on harvesting artesian pressure and heat as well as water.

There is no clear Basin-wide policy concerning town water supplies or water for tourist attractions and small businesses. Work is needed to establish standards for town water and water requirements for special amenity features. Governments and local residents could then develop water management practices that ensure water is being extracted within resource limits and used efficiently to return appropriate benefits to the community. Judicious use by local governments and town residents needs to be encouraged and water saving programs implemented.

By the 1920s, Coward Springs bore had corroded and millions of gallons of water flowed freely, creating a new wetland in the desert. The bored was redrilled and relined in 1993 to control the discharge rate. However, the artificial wetland created a diverse habitat for a wide variety of biota, and the bore has been permitted to remain with reduced flows under a Heritage Agreement with the state Environment Minister, also including two restored railway buildings [45].

The Peake Repeater Station ruins, with the date palm to the left indicating the location of the springs (Photo: A Jensen)

Impacts from Restricted Spring Vents

While decline in pressure is the primary cause of decline in spring flows, it has also been found that the conductivity of spring vents can be a contributing factor. As vents become restricted through various impacts, flow rates decrease. If flow rate increases again, surface structures may develop differently or spring vents may change location. This can change the rate of growth of the spring mounds or the shape and size of the wetted area within spring groups. There is a unique interplay between hydraulics, hydrochemistry and the environment which is responsible for mound structure formation and the maintenance of spring flow after a mound structure has formed [70].

Spring flow rate is not a reliable indicator of aquifer pressure variations, due to the effect of the vent conductance; the elevation of potentiometric head above the discharge point is recommended as the primary measure to monitor the vulnerability of springs to aquifer drawdown [71].

Reduced flows have a direct impact on aquatic and riparian ecosystems, with lowered water availability and reduced habitat area. The springs along the south-western edge of the GAB form a linked migration path between habitats for birds and other animals. The loss of springs at critical points in that linked route could disrupt connectivity between springs and within and between spring groups.

Apart from loss of aquatic habitat in surrounding wetlands supported by spring tails, decreases in flow may result in the development of acid sulfate soils due to the exposure and oxidation of highly sulfidic soils in the discharge zone, releasing sulfuric acid and lowering pH of water in pools and wetlands to toxic levels.

Acidification may be a recent phenomenon responding to changes in aquifer pressure and consequent flow reductions, although there is evidence that acidification occurred at Strangways Springs thousands of years ago. Springs at particular risk of acidification in the western GAB have been identified [71].

Desert goby Endemic fish species at Elizabeth Springs (Photo: S Lewis)

Threats from Land Use

Land management in and around springs and the maintenance of pressure affect spring structures and ecosystem functions. The land-use effects which may need to be addressed to maintain spring values include:

- physical excavation of spring vents
- loss of habitat for threatened species, particularly endemic species
- impacts of stock grazing on native vegetation and spring fauna (fish and invertebrates)
- changes in water chemistry in response to stock access
- impacts of increased nutrient loading from stock manure
- *Phragmites* expansion and impacts on habitat diversity
- invasive weed species, eg annual beard grass (*Polypogon monspeliensis*)
- management of visitor impacts.

Grazing by Stock and Feral Animals

The vast majority of springs in the GAB occur on land managed under private tenure for pastoralism, other agricultural activities and are therefore open to grazing impacts and other forms of physical disturbance. Most of the natural springs of the GAB have been subject to grazing and other related impacts for a century or more, with actions to provide lasting protection for some springs not getting under way until the 1980s. Since that time key springs have been protected within reserves – such as *Witjira National Park* (Dalhousie Springs) and *Wabma Kadarbu Mound Springs Conservation Park* in South Australia (Figure 19) and *Edgbaston Reserve* in Queensland (Figure 15). Some springs and spring groups on pastoral land have been protected through the efforts of pastoralists themselves and South Australia's Environment agency. Nevertheless, the majority of GAB springs remain open to impacts associated with stock grazing, other agricultural activities and pest animals [72].

FIGURE 19
Elizabeth Springs in Wabma Kadarbu Mound Springs Conservation Park near Lake Eyre South. (Photo: S Lewis)

As a natural water source, springs provide watering points for stock on pastoral properties, and water for other land-use activities. The severity of impacts of feral animals including horses, donkeys, camels, rabbits, and pigs is regionally significant in particular areas of the Basin. Springs subject to high grazing pressure from cattle and feral animals often receive high nutrient loading. Grazing animals can disturb or destroy geological structures associated with the springs, affecting or possibly blocking spring vents.

Other deleterious impacts upon GAB springs include destruction of vegetation, impacts on fish and spring invertebrates, and changes to water chemistry. Physical damage, such as trampling and pugging in spring pools, can be severe, destroying plants, disturbing the soil surface and creating multiple small pools with concentrated manure. Typical damage is illustrated at one spring in the Levi Springs complex, showing poor spring condition under stock impacts, followed by rapid recovery after fencing around several springs and retention of an alternative water point for stock (Figure 22). Springs that have increased nutrient loads to pools and riparian fringes show changes in spring characteristics and biodiversity, with an imbalance in native vegetation species, growth of invasive species and algal blooms.

Excavation and Artificial Wetlands

There is a long history of excavation of springs to provide ready access to water for humans and stock, particularly in Queensland. There is evidence that early Aboriginal groups excavated springs near campsites [43]. Following European settlement, homesteads and towns that relied on springs for drinking or irrigating gardens often modified surface structures to increase water storage and to access and distribute flows more easily. Excavation provided stock with readily accessible to water but generated risks associated with surface disturbance (Figure 20). The practice of spring excavation continued in some areas until recently [2].

Flows from uncontrolled and leaking bores create artificial wetland habitats in an arid environment which encourage the spread of invasive weeds and animal pests.

Invasive Weed Species

Weeds have been introduced to GAB springs through a range of mechanisms [72]. Some introduced plants were deliberately planted in the springs environs – such as date palms at Dalhousie and other springs such as Nilpinna and Big Perry. Other weed species have been brought in by stock, feral animals or on the clothing or vehicles of visitors. Apart from palms, other weeds in springs include the grasses, annual beard grass and bamboo, and forbs such as *Spergularia*. Weeds can out-compete native vegetation and have impacts upon spring flora and fauna. Some weeds, such as palms and bamboo, can also use large volumes of spring water, thus affecting spring flows.

Fire

Palaeo-ecological analysis of spring deposits indicates that fire has been an influence on spring landscapes for 30,000 years or more [19]. Before European settlement, fire may have been associated with traditional land management practices or lightning strikes. The use of fire in springs management is a topic of ongoing research but it is apparent that the inappropriate use of fire can have significant impact upon spring fauna, particularly in springs with reduced flows.

Management of Visitor Impacts

Early inhabitants, explorers and modern travellers have been attracted to springs, resulting in impacts initially from horses and camels, and now from 4WD traffic, campers and feral animals.

Increasing numbers of visitors with 4WD vehicles are travelling the Oodnadatta Track and crossing the Simpson Desert, with GAB springs seen as desirable attractions en route. A visitor management plan has been prepared for Dalhousie Springs to control impacts of increasing numbers of visitors staying overnight and swimming in the pools. Measures can include defined access routes, controlled parking, boardwalks over sensitive areas and fencing to exclude rabbits.

FIGURE 20 Herrgott Springs near Marree, seen here in 1985, were an early source of water for the town. Subsequently used for stock water, they have been heavily modified by excavation and ongoing water extraction for many decades (Photo: C Harris)

Improved Evidence Base

Scientific knowledge of the Basin resource and its connectivity to other surface and groundwater systems has significantly increased, and the most important connections are in the recharge zones of the Basin [1]. New knowledge has been collated of the structure, hydrogeology and water chemistry in the Basin, culminating in the Great Artesian Basin Water Resource Assessment and the subsequent new information generated for the Hydrogeological Atlas of the Great Artesian Basin [1, 2, 73, 74].

Substantial evidence on the cultural importance of springs to Aboriginal and Torres Strait Islander people and to other stakeholders has also been collected and reported [74-78].

In the South Australian section of the GAB, more than $14 million has been invested in research projects into the physical, hydrological and biological characteristics and processes of mound springs.

The *Allocating Water and Maintaining Springs in the Great Artesian Basin* (AWMSGAB) project completed in 2013 for the National Water Commission investigated complex surface and groundwater interactions and GAB springs characteristics on the western margins of the GAB [19, 22, 30-32, 71, 76]. This $6.25 million project substantially updated understanding of GAB's geology, ecology and hydrology.

All springs on the western margin of the GAB were mapped and recorded, and baseline condition assessments undertaken to provide an essential baseline for assessing the effect of current and future management actions.

The water balance for the region was refined using a number of methods to estimate various types of recharge and discharge processes, challenging long-held assumptions that the GAB is in a steady state. The study found instead that potentiometric pressure has been declining over millenia and that recharge rates are far exceeded by modern discharge and extraction rates.

The biodiversity value of the GAB springs was reinforced through identification of 25 new endemic invertebrate species out of 42 new species identified, in addition to known rare and endangered communities. A palaeo-ecological profile was developed over 30,000 years for Warburton Springs, including evidence that common reeds have been present throughout that period [19].

New cost-effective techniques to monitor spring flow rates and ecosystem responses were developed. The project also developed a risk assessment framework to assess the response of GAB springs and their unique ecosystems to reductions in aquifer pressure, either from long-term natural decline or human impacts.

The findings of the AWMSGAB project have been published in six volumes, with a detailed summary of all the findings in Volume VII [26].

The *Lake Eyre Basin Springs Assessment* (LEBSA) project was one of three water knowledge projects undertaken by the then South Australian Department of Environment, Water and Natural Resources (DEWNR; since re-named the Department for Environment and Water (DEW)) to inform the Bioregional Assessment Programme in the Lake Eyre Basin (LEB) [78].

A key aim of the LEBSA project was to improve data knowledge through field investigations to inform future decision making and management for the South Australian portion of the LEB and areas overlying the Arckaringa and Pedirka (coal) Basins (the LEBSA project area). It collated general survey data and photo points, hydrological, birds, vegetation, fish, geological, and water chemistry. The project described eight specific spring types cross-matched with evidence-based tables to summarise the current understanding of GAB spring complexes [28, 29, 34, 78, 80-82].

Field surveys at Dalhousie, Billa Kalina, Mt Denison, Allandale, Peake Creek and Lake Cadibarrawirracanna provided a much-needed expansion on baseline information held for spring complexes and captured data in three broad categories: morphological, biodiversity and hydrogeological (including hydrogeochemical) [27, 28] (Figure 21).

Monitoring methods were developed synthesising existing and new remotely sensed mapping techniques for long term monitoring of spring wetland extent as an indicator of trends in flow rates. A method was also developed for mapping areas of diffuse discharge.

The LEBSA project outcomes will inform the storage of spring data, leading to consistent data capture and management across South Australia and Queensland, with the database managed by the Queensland Herbarium. LEBSA data was the basis for a Basin-wide evaluation of biodiversity, conservation values and risk assessment in 2018 [76].

FIGURE 21
Fretted travertine rims are a feature of a number of outlets at Strangways Springs. (Photo: C Harris)

Springs Evaluation Process

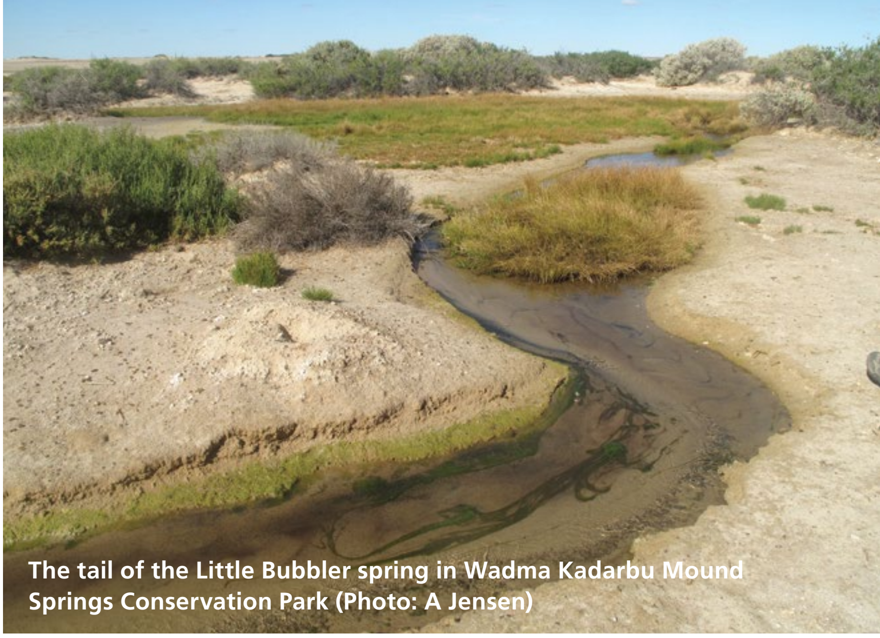
A comprehensive study has spatially analysed the threats and risks for all springs in the GAB with reliable data [76]. It included a spatial assessment of biodiversity patterns and conservation values of discharge springs across the GAB and assessed the degree of conservation protection afforded to spring complexes and endemic species. The study identified 6308 springs in 326 spring complexes across 13 supergroups in the GAB and found that 5412 springs remain active, with the rest dormant. Springs were assigned a conservation rank [79] based on status of endemic taxa and risk.

A re-evaluation of taxa found 98 taxa with sufficient information to be confident of taxonomy and present-day distributions, with sufficient evidence to suggest they are found only in, or would perish without, GAB discharge springs [76]. Seventy-six of 326 complexes contained one or more endemic taxa, the majority of which are invertebrates. Some environmental characteristics of spring complexes (e.g. spring surface water persistence; relative spatial proximity and hydrologic connectivity) were good predictors of the likelihood of spring complexes containing any endemic taxa. However, serious information gaps were identified. Literature regarding the basic ecology of >50% of taxa is completely absent and the vast majority of species have little information available regarding how they respond to threatening processes.

The degree of conservation protection is varied, with significant gaps [76]. Many taxa have not been assessed, especially those with narrow ranges. Plants and fish are relatively well assessed and represented in conservation listings. All have some populations within protected areas.

A major finding of the study is the lack of data on invertebrates, which make up the majority of springs taxa [76]. Invertebrates are poorly represented in listings and no recorded populations occur within a protected area. However, protected areas may have invertebrates present but lack taxonomic and distribution data of sufficient confidence to have been included in the analysis. No invertebrates are listed as threatened species and thus are not included in legal protection measures.

Following on from the AWMSGAB and LEBSA investigations [21, 78], the improved evidence is the basis of a risk assessment framework which has been developed [77] to assess the values of GAB springs and the need for a response to manage the risks to springs and their unique ecosystems from reductions in aquifer pressure and surface disturbance.
The assessment process can also be applied to remediating impacts from structural risk factors.



The tail of the Little Bubbler spring in Wadma Kadarbu Mound Springs Conservation Park (Photo: A Jensen)

The framework is designed to enable risk assessment of such complex environmental assets, through a multi-stage Plan that facilitates:

- classification of springs and spring groups according to their morphological types (*see earlier section on Typology of Springs*)
- identification of the degree of threats presented by proposed groundwater developments and the likely impacts on spring flow rates
- identification of the degree of threats presented by surface disturbance factors and the likely impacts on dependent ecosystems
- assessment of the vulnerabilities of springs and spring groups to identified threats according to their typology and degree of exposure to the threat
- assessment of the specific ecological values of springs and spring groups
- a system of ratings for the likelihood of impacts arising, the specific vulnerabilities of springs and specific ecological values of their ecosystems
- a simple visual summary of the overall assessment outcomes and the ratings applied
- acknowledgement of uncertainties in the risk evaluation Plan and recommendations for further information required to reduce uncertainties
- assessment of the controls, either existing or necessary, to mitigate assessed risks.

The risk assessment framework developed for the south-western GAB is one of several regional frameworks which have been developed across the GAB [76].

Evidence-based Management Tools

There are many examples of management tools which have been applied at individual spring sites to address particular risks and the local situation. The threats and risks are described below, with some examples of management options.

Closed Water Delivery Systems

Installation of closed water delivery systems remains a high priority. Valuable lessons concerning drilling standards, planning and improved design and technology for water delivery infrastructure, as well as the necessity for cooperation and willing compliance, have been learned during the past century of GAB management.

On-going work is required on cooperation, compliance and a coordinated policy between governments and landholders to ensure that bores are controlled and closed water delivery systems are maintained for stock watering infrastructure worth more than $3.5 billion across the Basin [83].

Excavation of Spring Vents

The excavation of springs represents a severe form of disturbance. In many cases, restoration of excavated springs will not be a feasible option, although this may be considered on a case-by-case basis, particularly where some of the core structural or ecological spring features are still present. It is important that adequate regulatory provisions are in place to control any future spring excavations and to minimise disturbance of spring vents.

Stock and Pest Animal Exclusion

Healthy GAB springs require cessation of uncontrolled access by stock and pest animals. Two general approaches can be considered [84].

The first is reservation for conservation purposes, either as public conservation areas through State national parks and wildlife legislation, or through private conservation initiatives.

The second option for stock and feral animal exclusion on lands under private tenure is protection of selected spring areas while retaining them under private tenure. This could involve taking entire paddocks out of production but is more likely to involve fencing of selected springs or spring groups (Figure 22).

Based on monitoring of fencing programs undertaken on pastoral areas in the past 30 to 40 years [71, 87], the following relevant observations can be made:

- Fencing individual springs is generally not a preferred option, particularly if the fencing is tight around the spring with the wetland tail extending through the fence. It is a small conservation return for effort and leaves fencing vulnerable to pressure from stock.
- Fencing of groups of springs is far preferable, with fencing well removed from spring wetland areas. However, fencing of groups of springs is likely to incur high initial capital costs and needs a clear commitment to the costs and effort associated with monitoring and maintenance.
- Fencing, particularly in remote areas, is expensive – estimated at up to $5,000/ km. Maintenance of fencing can also be relatively expensive and clearly requires ongoing commitment.
- Land management needs in terms of stock-water also need to be taken into account. In some areas, land managers have relied on springs for stock-watering. However, there are many situations where stock have had an impact on groups of springs whereas just one or possibly two water-points would suffice. Restricting water-points in a particular area can also have benefits for stock management, particularly in terms of mustering.

Where springs have a history of being used for stock watering the following options for fencing of GAB springs is proposed [72, 84]:

- Where fencing of a group of springs is proposed, it may be possible to exclude one or two of the outer springs, to be used for stock watering.
- Where an entire group is to be fenced it may be possible to pipe water from one of the outer springs to an external trough / water-point.
- If an individual spring that has been an important water-point is to be fenced, piping water to an external watering-point may be an option.

FIGURE 22
Stock grazing at Levi Springs in the south-western GAB (above). In 2019, the same spring (below) showed rapid recovery only six weeks after stock-proof fencing was completed in cooperation with the pastoral lessees. (Photos: C Harris)

Control of Weeds

The control of weeds requires a spring by spring approach or spring group by spring group approach. Within South Australia, weed infestations are generally not severe in springs in the Lake Eyre or Lake Frome supergroups, whereas palms have been a significant issue at Dalhousie and have been subject to extensive control programs. In the Lake Eyre supergroup there are isolated instances of bamboo (*Bambusa* sp) (e.g. Nilpinna, Birribirriana springs) [84].

Monitoring, Evaluation and Reporting

The Adaptive Management Plan and Template propose a range of on-ground options to protect spring values by modifying spring access and surface impacts while causing minimum disruption to landholder operations. In so far as practical, stock and other animals will continue to have access to spring water while managing unacceptable impacts of grazing, and surface disturbance. An appropriate management response will be negotiated between landholders and regulators based on an evidence-based spring monitoring and evaluation process.

The best evidence available needs to be utilised to design and apply spring classification systems based on location, hydrogeological structures, geochemistry, natural and cultural values as well as current condition. Such an information base is required as a basis for identifying and managing the risks to springs. The evidence base needs to be interactive and flexible to accommodate new findings and changes in spring conditions.

The interactive spring classification data can then be used as an information base for an effective efficient monitoring system to identify changes to spring flows, geochemistry and ecosystems that may pose risks to spring values.

Monitoring changes in spring flows and surface condition is problematic due to natural changes in flows from individual vents and sporadic patchy data on spring surface condition (Figure 23). Monitoring has been sparse, intermittent and variable, insufficient to provide timely, objective evidence for on-ground responses. A review in 2010 of the state of current and historical water monitoring data for the Far North region of South Australia found that a serious lack of adequate data on the condition of regional water resources had been a major impediment to sound decision-making on water resources management in that region [85].

Timely robust data and long-term monitoring data are key elements in understanding and responding to changes that risk spring health. A coordinated and funded national GAB springs monitoring program is required to provide the necessary data for sound decision-making on springs management andto collate all relevant springs data across the GAB region. Data sources should be sought from three time periods [85]:

- pre-measurement phase (1850-1940)
- early measurement phase (1940 to 1980)
- late measurement phase (1980 to present).

A Monitoring Coordinating Committee should be nominated, supported by a monitoring team ideally consisting of a hydrologist, an historian/archivist, an ecologist and a hydrogeologist. A primary recommendation is that all projects involved in water-related activities in the GAB should be required to collect appropriate data and forward it to a central collection point linked to the GABCC and the implementation of the SMP. An agency should be nominated to set up an integrated water database to manage regional hydrology and related environments, building on the work already commenced by SA and Queensland agencies and research groups [21, 74, 75, 76, 78].

The late measurement phase should investigate the uses of remote sensing to identify spatial variation of hydrologic parameters such as radar measurement of spatial rainfall variation, surface wetness, vegetation growth and decline. Any models constructed and calibrated using the later data should be used to fill in possible outcomes for earlier phases and checked for compatibility with earlier non-quantitative records.

Average rainfall for the Far North region is predicted to decline by 2-5% and transpiration rates will increase by 2-4%, thus causing greater stress on water in storages and biota dependent on this water. The variability will increase, causing deeper and longer droughts and less frequent but more severe major events such as floods [85].

Critically, in the BOM national water resources and flows forecasting system there are no rainfall gauges over a large area of the south-western GAB, including the desert/ Lake Eyre regions and the arc between the Strzelecki Track and Lake Frome, apart from gauges at Birdsville and Innamincka. The only flow monitoring stations are on Cooper Creek and the Diamantina River to the north-east, with some past project-based monitoring stations on the Neales River. Current daily rainfall and flows data from the Bureau of Meteorology (BOM) are based on averaged radar data from Alice Springs and Woomera, which are only accurate for a range of 200 km, so of limited use for GAB springs in the south-western sector.

It is critical to ensure that sufficient data monitoring points are included in the national grid to provide better climate and flow data for the whole GAB region.

Monitoring of Trends in Spring Condition

Monitoring the condition of springs serves two important functions in the Adaptive Management process. Firstly, in many instances it may provide evidence of declining condition of springs to identify where management interventions are needed. Monitoring at this stage may also indicate the nature of impacts and processes that dominate at particular spring locations (eg surface disturbance by grazing or reduction in flow). Secondly, after changes to spring management have been implemented, continued monitoring is essential to assess their effectiveness. In addition, some spring protection mechanisms may require objective evidence of outcomes: monitoring data are needed to provide this.

It is difficult to design a monitoring system that can serve all these purposes for all GAB springs. The main challenges are the broad geographic dispersion and scale of the spring communities, the wide variation in spring typology and surface morphology, short and long term natural variations in flow and wetland communities, and the variety of disturbances to be monitored.

Spring flow has often been used a key indicator of spring status and condition, but it is highly variable on a diurnal, seasonal and annual basis, and very difficult to measure *in situ* in complex wetland environments. However, for hydro-geological interests, measurement of hydrostatic pressure is important as an indicator of pressure trends and *in situ* flow monitoring should be included in future monitoring programs.

For ecological interests which focus on the spring-dependent ecosystems, the area of wetland communities supported by spring flow is the preferred ecologically-relevant indicator of spring condition that is currently being used for monitoring some GAB springs. Considerable recent research has demonstrated the effectiveness of remote sensing approaches in objective, continued monitoring of some spring groups on the south-western margin of the GAB (Figure 24).

FIGURE 23
The Blanche Cup and The Bubbler complex, one of the best-known mound springs sites in the south-western GAB, has long been subject to monitoring and investigation but has not had a consistent long-term monitoring program. This view shows the pool at the top of Blanche Cup mound spring (foreground), with the extinct Pleistocene mound spring Hamilton Hill rising 40 m in the background. The spring complex is in Wabma Kadarbu Mound Springs Conservation Park near Lake Eyre South. (Photo: A Jensen)

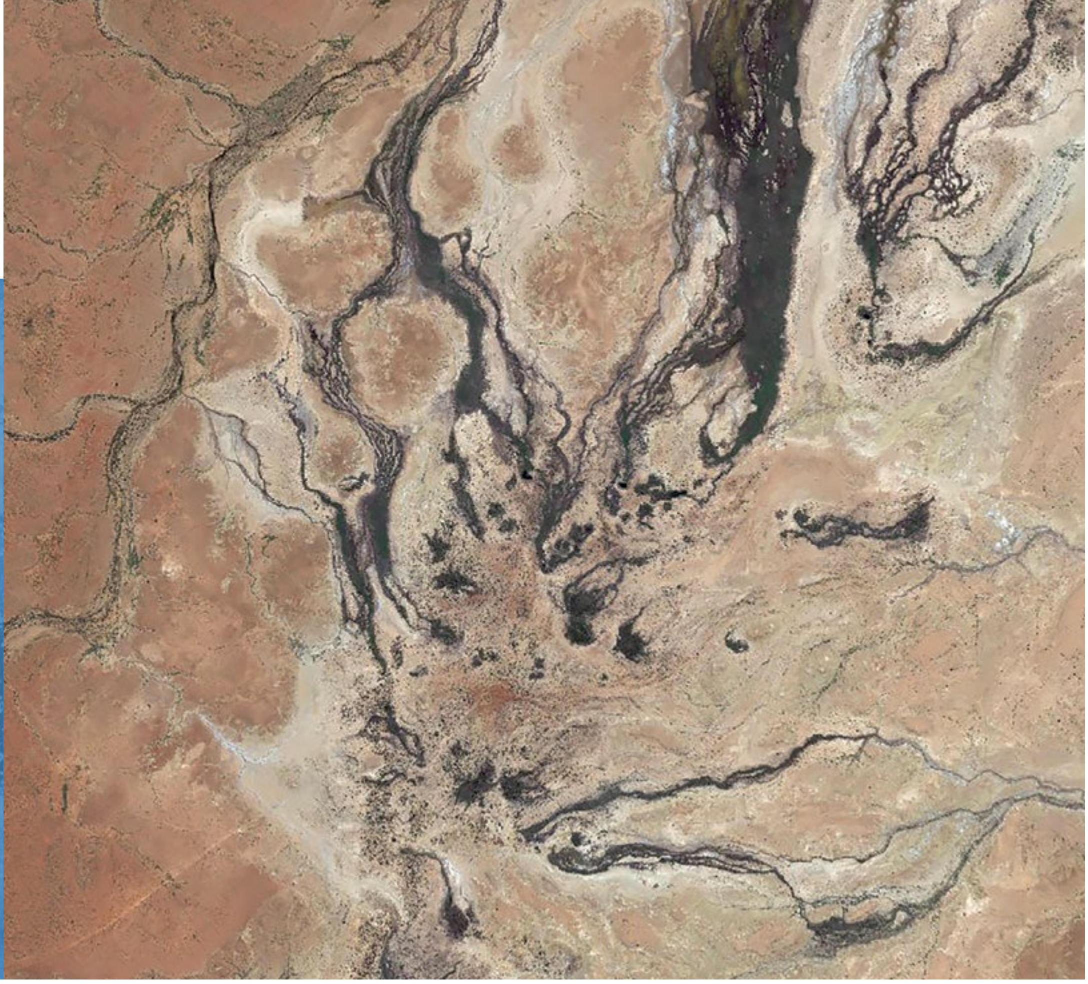


FIGURE 24
Remote sensing image of Dalhousie Springs demonstrating the fine visual detail available for measuring and comparing the wetted areas in and around springs at selected time intervals to determine trends in condition of springs and their dependent ecosystems. (Image: World View II)

Studies have demonstrated that:

- Low resolution MODIS satellite imagery with high frequency (16-days) and a long archive (since 2000) is ideally suited to determining seasonal and longer term changes in spring wetland vegetation at large spring complexes [71]. The resultant time series of wetland area highlight the importance of consistency in season and timing of monitoring in relation to climatic cycles, and show the extreme variation against which long-term trends in condition are often sought.
- Moderate resolution Landsat (30 m resolution) time series (since 1987) provide a strong basis for monitoring wetland area intra and inter-annual wetland area changes at the scale of spring groups and complexes [86].
- Landsat time series also form the basis of the Water Observations from Space produced by GeoScience Australia which can provide monitoring of frequency and extent of inundation [87].
- Commercially acquired very high resolution multispectral satellite imagery (e.g. World View and Planet with resolution below 3 m) provides the fine detail necessary to map and quantify wetland vegetation extent to relate to spring flow rates [71, 80, 81, 86, 87]. Several studies have established spring flow-wetland area relationships, providing confidence in the imagery as a cost-effective, objective monitoring tool.
- This very high resolution satellite imagery also provides fine visual detail suitable for interpreting physical disturbance in and around springs (Figure 24).
- Historic aerial photography is a resource that may provide limited information about past conditions of springs. State government aerial survey programs vary, but most have acquired black and white and colour photography over the remote environments hosting springs at barely decadal intervals, and at small scales (typically 1:80,000) that provide insufficient spatial or temporal resolution to adequately monitor springs. Some more intensive monitoring programs have commissioned digital aerial imagery of specific springs and groups, but often this is being replaced by high-resolution satellite imagery.
- Drones mounted with a variety of sensors are being used increasingly for environmental assessment and monitoring. While they have potential to acquire very high-resolution imagery of small targeted areas at chosen times, their applicability and feasibility for spring monitoring remains to be assessed. Current limitations include the need for experienced on-ground operators in these remote locations and the logistics of imaging large or dispersed spring ecosystems.
- Very high resolution satellite imagery is potentially suitable for documenting spring surface conditions; some is available at high temporal frequencies suitable for monitoring changes over time.

The recommended approach is for phased implementation, starting with trials and demonstrations to further assess the feasibility and applicability of monitoring methods to particular spring contexts. The trials would draw on the most promising methods that have been demonstrated in studies across the GAB to date. It is unlikely that one method will be suitable for the wide variety of spring types and ecosystems across the Basin.

Many of the proposed monitoring approaches (e.g. satellite image-based monitoring) are best implemented for spring groups or complexes, and undertaken by government, NRM or regional land management bodies, in collaboration with land managers. These may be supplemented by on-ground methods such as photopoints or *in situ* flow monitoring that is best undertaken by land managers with responsibilities for particular springs.

In situ monitoring is currently carried out by BHP in the spring fields affected by their water extraction in the south-western GAB. The monitoring program includes both remote sensing and on-site flow measurements to assess spring flows and maintenance of the full area of spring-dependent ecosystems. A current project funded by the South Australian Government and BHP is evaluating more comprehensive satellite-based monitoring of wetland areas. The Department for Environment and Water previously conducted annual *in situ* monitoring of flows at Dalhousie Springs using block weirs at four sites [85]; however, none are currently operational and all sites are in need of infrastructure and instrument upgrades (Mangeruca, *pers comm.* 2019). DEW is in the process of refurbishing two of the weir sites and re-establishing satellite communication with the weather station, with the works planned for 2020 (Figure 25). Future monitoring programs should evaluate the need to continue *in situ* monitoring as appropriate to individual sites.

Classification and monitoring data can then be used to make decisions about appropriate management actions for a spring complex or group. An adaptive approach to spring management is necessary because spring characteristics, surface conditions, GDEs and impacts of land-use are highly variable. Simply recommending fencing as a barrier to animals using springs as a watering source is not the complete answer and may not be feasible for a number of practical reasons.

New techniques to monitor spring flow rates and ecosystem responses include remote sensing to allow larger scale regular monitoring, which is more cost-effective than resource-intensive ground surveys [70, 86, 87]. A strong linear relationship was established between spring-fed wetland extent and spring flow rates at both Dalhousie and Mt Denison Springs complexes.

A comprehensive, coordinated, long-term monitoring program with committed funding will be needed to underpin the Adaptive Management Template and ensure sustainable management of GAB springs into the future (see ***Monitoring, Evaluation and Reporting*** above).

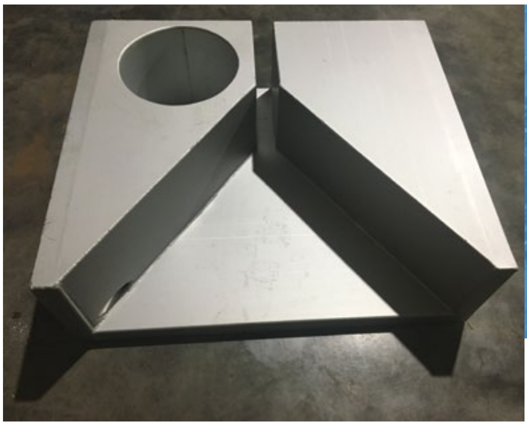


FIGURE 25 Flume to be installed in 2020 at one of the flow monitoring weirs at Dalhousie Springs (Photo: F Mangeruca)

Sunset over the main vent of Big Spring in Edgbaston spring complex, part of the Barcaldine supergroup in the Queensland GAB region (Photo: R Rossini)

Review and Adaptive Management Actions

Adaptive Management Loop

Adaptive management requires a review loop to assess the effectiveness of management actions and to check the need for any modification or changes. To complete the Adaptive Management loop, the final step is to review on-ground outcomes and evaluate them against the desired outcomes, with an assessment of the effectiveness of the management actions taken. This information needs to be reviewed regularly and fed back to managers to make any required adjustments and adaptations to the on-ground actions in order to ensure that the desired management outcomes are being achieved.

Review Monitoring Results

The remote and highly diverse nature of the springs present very significant logistical and technical challenges for effective long-term monitoring of trends in spring condition. New methodologies for cost-efficient, effective monitoring have been developed and tested, with promising potential for application Basin-wide to monitor outcomes and provide feedback on any adjustments needed to the risk management program (*see Monitoring section above*).

Regular reviews at five-yearly intervals are recommended, but these should include evidence-based criteria which take account of lag times in ecological responses. An important factor in surface management actions will be regional rainfall events and drought conditions, as well as the influence of spring flow rates. The GAB SMP has a requirement for 5-yearly reviews and site management plans should be linked into this process, which involves production of a Progress Report to the GAB Coordinating Committee [2].

Develop Fit-for-Purpose Strategies and Tools

Monitoring and management actions need to include measurement of more than just changes in groundwater pressure. A holistic management approach is required that addresses the cumulative risks generated by changes in pressure and surface conditions. Fit-for-purpose risk management methodology should be developed for spring groups likely to be impacted by human land-use, to ensure the springs are properly managed and impacts remain within acceptable limits. Risk management strategies need to be fit-for-purpose and inclusive of the management of all identified impacts to a spring site and tailored to a level appropriate to the risks and vulnerabilities of the particular spring type. An objective, rigorous and cost-effective monitoring program is essential for future sustainable management of GAB springs, to assess the condition of assets and the effectiveness of management actions [88].

Build Basin Database

A robust, comprehensive and interactive Basin-wide database is critical to the successful implementation of an evidence-based Adaptive Management Plan for GAB springs. The database needs to combine all available information on spring characteristics, condition, trends, values, groundwater-dependent ecosystems, risk factors and their impacts. It also needs to create a basis for progressive monitoring and evaluation as management interventions are put in place.

A baseline of current condition of GAB springs is being established, maximising use of existing data sets and knowledge. This will need to be regularly evaluated and updated to assess spring status, values and trends in condition. In the future, a portal is proposed to be developed for the whole GAB to collate all available information on every spring and spring group, to make that knowledge accessible to managers to make decisions about appropriate actions to manage threats to springs.

Fill Identified Information Gaps

Notwithstanding very significant advances in GAB springs information since 2000, building on the pioneering research commenced in the 1980s, important gaps remain. Endemic GAB spring taxa have restricted distributions, have very few populations within protected areas and may have high exposure to threats, meaning they may be at substantial risk from the cumulative impacts of a range of threats [76, 77]. Lack of data is a major issue, undermining efforts to manage threats to springs. Data collection should be focussed on biodiversity 'hot-spots'.

Specific data gaps which have been highlighted [21] include:

- evaluation of scientific studies in all GAB states to enable standardised classification
- identification of work needed to reach consistent information across all zones
- investigatigation and test of adjustments to method for satellite imagery monitoring for wetter environments in Queensland and NSW (Qld has more vegetation cover and wetter environments, confusing relationship between vegetation and spring flows, also greater disturbance impacts)
- evaluation of whether spring classifications can be applied across the whole Basin with adjustment for environmental settings and local topography
- investigation of the responses of *Phragmites* and bulrush response to exclusion of grazing over 30-40 years, given the finding that *Phragmites* has been present in springs for up to 30,000 years and is unlikely to be transferred between springs
- further work characterising the hydrochemistry and determining the extent of any connectivity between the GAB and Arckaringa Basin within the south-western GAB region
- evaluation of the effects of stock and other grazing animals upon spring chemistry (eg nutrient levels) and aquatic invertebrates
- assessment of the comparative effects of stock and other introduced animals on concentrated groups of springs (eg Hawker Springs – comparison of impacts on outer and inner springs)
- evaluation of the effects of *Phragmites* proliferation in protected springs on spring fish and invertebrates
- evaluation of the effects of *Phragmites* proliferation on spring vegetation of particular conservation significance (eg *Eriocaulon carsonii*).

GAB Springs Stewardship Initiative – The Way Forward

The GAB Springs Adaptive Management Plan and Template is complete in this document. However, application of the Template, along with the very best research and planning, will not generate the change in culture needed to effectively manage risks, change practices or solve problems. The science and risk management must be incorporated as an integral part of ongoing springs management on a long-term Basin-wide scale. Success in this challenge depends on raising the profile of springs to ensure that ongoing spring management becomes just as much an integral part of GAB management for landholders, water users and governments as the rehabilitation and maintenance of bores and water infrastructure.

A well-designed and presented web-based digital platform, the *GAB Springs Stewardship Initiative* is proposed as the best method to help ensure that the desired outcomes for the springs are achieved. The purpose of the *GAB Springs Stewardship Initiative* (GABSSI) is to provide ready access to attractive, interesting and compelling information about GAB springs, why they need to be cared for and the best way to care for them, through portals titled on *Legislation and Governance, Hydrology of Springs, Classification of Springs, Natural Values of Springs, Cultural Values of Springs, Threats and Risks to Springs, Caring for Springs* and *Monitoring Change*.

An interactive GAB springs website has already been developed by the Department of Environment and Science in Queensland with input from the Department for Environment and Water in SA and support from NSW. Queensland has developed a very attractive functional digital format for telling the story of wetland management (*see the Herbert River template* [1]). The Queensland Department of Environment Policy and Planning, staff from the SA Department for Environment and Water, the GAB Springs Adaptive Management Plan and Template Project Team and other specialists have agreed to work cooperatively to develop a suitable digital platform for GABSSI going forward.

GABSSI is designed to ensure that on-going adaptive spring management is welded-in as a key strategy in future governance arrangements and management priorities for the GAB. This, with a Basin-wide coordinated database, is the next priority for securing the future of the GAB springs.

The current priority initiative at Basin-scale is the *Improving Great Artesian Basin Drought Resilience program* (IGABDR) to support GAB activities such as infrastructure repairs, science, monitoring, extension and compliance (Smith *pers comm.* 2019). The IGABDR program follows on from previous programs GABSI and the Interim Great Artesian Basin Infrastructure Investment Program (IGABIIP) to provide funding support, typically to repair uncontrolled wells. The IGABDR program has been expanded and includes education and communication programs, as well as scientific studies that assist state agencies implement GAB management arrangements. The States and the Commonwealth are working collaboratively to finalise the IGABDR program with focus on improving on-ground project delivery.

The Australian Government has made a total of $27.6m funding available for the IGABDR program. The funding has been made available for projects addressing both improvements to infrastructure and non-infrastructure projects, including initiatives aimed at improving understanding of the GAB through education and access to information. The development of the digital platform to support GABSSI fits the established funding criteria and may be funded through the IGABDR program. The IGABDR program concludes 30 June 2024.

[1] terrainnrm.maps.arcgis.com/apps/MapSeries/index.html?appid=f10d789f31e245fc8fb5c634f27e8bac

Gosse Springs, on Stuart Creek Pastoral Lease near Lake Eyre South, with a dense cover of bore-drain sedge (*Cyperus laevigatus*) (Photo: S Lewis)

GAB SPRINGS ADAPTIVE MANAGEMENT TEMPLATE

This Adaptive Management Template sets out a structured, evidence-based approach for management of the springs of the Great Artesian Basin (GAB). It uses evidence-based methodologies for identifying spring values and making informed decisions about the need to change the management practices to protect particular spring complexes.

Although progress is being made in the management of water extraction and land-uses in and around springs, changes in management practices and investment of resources is required to address the continued deterioration of many important springs. With so many springs across the GAB, the major challenge for this Template is a robust method to identify the values of spring complexes, evaluate spring condition and determine the risks to spring values that need to be managed.

The Template must be 'Adaptive' because it is based on emerging evidence from scientific research, landholders' management practices, Indigenous cultural knowledge and government legislation and commitment. The Plan is designed to adjust for differences in spring conditions, land tenures and regulations across the Basin. This means that on-ground actions and outcomes must be flexible, adaptable and robust in order to meet variable management environments and to adjust management actions as monitoring feedback loops provide new evidence for change.

Adaptive Management Process

The first part of the Adaptive Management Template is the Springs Situation Analysis component, an approach which gathers evidence for decision-making (Table 1). The Springs Situation Analysis component assesses the current values of springs, evaluates what is happening to springs and determines their current status, providing a robust evaluation process to determine the need for a management response.

The second component of the Template is the Adaptive Management Response (Table 2), which is a decision-making framework that identifies aspects of spring management to be considered in determining the need for intervention in the management of particular spring groups. This process is negotiated amongst water users, landholders, governments and other interests, and uses the evaluation of the spring situation analysis to identify the risks that may compromise spring values in particular spring groups. It provides a suite of management tools that may be applied to spring complexes and leads to the selection of the appropriate management response.

Determining the Need for a Management Response: Situational Analysis

The Springs Situation Analysis component assesses the current status of springs (Table 1), taking in the following:

- Location and land systems
- Land tenure and use
- Features and values: geological, hydrological, ecological and cultural
- Condition
- Threatening processes, existing and potential
- Regulatory framework relevant to springs management.

A combined appraisal of these factors is undertaken to provide a risk assessment – in effect an assessment of the probability of threatening processes having significant impacts upon spring values. Where the risk assessment demonstrates that significant / unacceptable impacts are likely, this triggers the second component of the Adaptive Management process, the management response.

Addressing Significant Threatening Processes: Adaptive Management Response

The development of an adaptive management response involves a number of steps (Table 2):

- Formulation of strategies to address the threatening processes and manage risks
- Development of actions (eg on-ground activities in accordance with the strategies)
- Funding and implementation of actions and subsequent maintenance
- Monitoring and evaluating the effects of the actions and reporting
- Reviewing the effects of the actions and adapting the management response in line with that review and any relevant new information that may have become available.

Each of these steps is likely to involve a range of stakeholders. The relevant land manager is likely to be a common factor throughout but, depending on the nature and scale of the issue under consideration, other stakeholders are likely to include Commonwealth and State agencies, Indigenous groups, regional natural resource management bodies, research bodies, other non-government organisations and volunteer groups. An important overriding objective is the development of what may be termed a culture of willing compliance, based on information sharing, cooperation and recognition of successes and best practice.

Linking the GAB Springs Adaptive Management Template and the Adaptive Management Plan

This GAB Adaptive Management Template needs to be considered in conjunction with the GAB Springs Adaptive Management Plan (*see first section*). While this Template itemises the steps to be taken in developing, assessing and reviewing actions to address risks to GAB springs, it is the GAB Adaptive Management Plan that includes more detailed information relating to each step in the process.

Key information from the Adaptive Management Plan is summarised in the steps cited in this Template. Table 2 provides a decision framework summarising some of the main management issues for GAB springs and options for management actions.

Definitions of Key Terms

Values
Natural, Indigenous and other Cultural values based on springs operating in their natural state

Impacts on springs
Changes to springs that occur as a result of human use of the GAB or land-use in and around springs

Threats to springs
Any action or influence that may lead to or cause unacceptable changes in spring condition that affect spring values and/or reduce spring benefits

Risks to springs
Probability that human actions will trigger threatening processes which have a negative impact on spring condition

Risk Assessment
Plan of evaluating the likelihood of unacceptable impacts from human actions

Risk Management
Implementation of on-ground actions that mitigate unacceptable impacts to within acceptable limits to sustain spring values

Adaptive Management
Flexible actions and on-ground activities to address identified threats, linked to monitoring to measure outcomes and adjustment of actions over time as required to reduce risks and achieve desired outcomes in spring health

Judicious Water Use
Responsible, productive and efficient use of Basin water that minimises the impacts of extraction on groundwater flows and water pressures while meeting requirements for existing users, water-dependent ecosystems, and for development where appropriate.

Groundwater Dependent Ecosystem (GDEs)
Biological communities dependent on springs

The Bubbler and its boardwalk, with circular patterns in the sand created by the spring bubbling up to the surface. Water flowing into the tail supports an extended wetland area. The extinct mound spring Hamilton Hill is seen in the background (Photo: A Jensen)

TABLE 1: GAB Springs Adaptive Management Template: Evidence-based Methodologies for Managing Risks to Spring Values

SPRINGS SITUATION ANALYSIS

Assessment of Current Status of Spring comples

1 Spring Complex Characteristics

- Location and Land systems
- Physical Processes and Structures
- Natural Values
- First Nations' Cultural Values
- Historical and Modern Cultural Values
- Typology and Scale of Springs

2 Legislation and Regulation

- Land Tenure
- Water and land management regs
- Current Management and Compliance

3 Current Condition and Possible Threatening Processes

- Management and proposed changes
- Threats from Water Extraction
- Threats from Current Land Uses

4 Evidence Base for decision making

- Assessment of current spring evaluation
- Trends under current management
- Evaluation to determine need for management response
- Development of management approach
- Proposal for negotiating on-ground actions and support

ADAPTIVE MANAGEMENT RESPONSE

Negotiated response based on Situation Analysis and Coordinated Strategies and Options

5 Engagement for negotiating response

- Landholders
- Industries
- Government Managers
- Indigenous Groups

6 Risk Assessment – Pressure Loss

- Risk from current and proposed extractions
- Regional water extraction
- Local water extraction

7 Risk Assessment – Land Uses Causing Surface Disturbance

- Mechanical disturbance
- Grazing and pugging
- Water Quality

8 Create a culture of willing compliance

- Ensure shared knowledge of springs and threats
- Consider industry and landholder needs
- Share positive trends

9 Risk Management Strategies to Maintain Spring Flows

- Buffers and water extraction around springs
- Regional extraction policy to maintain pressure
- Maintained closed delivery systems
- Ensure judicious use of GAB water

10 Risk Management Strategies to Protect Surface Structures, GDEs and Cultural Values

- Control of grazing impacts
- Management & monitoring agreements
- Site management plans
- Monitoring with reporting on change
- Management trials

11 On-ground Actions agreed between Landholders, Industries, Indigenous Groups & Governments

- Formal Agreements
- Incentives, rewards and offset options
- Shared funding arrangements
- Compliance

12 Implementation, Funding and Maintenance Strategy

- Long-term funding agreements
- Framework for site agreements
- Regular Review of Springs Status

13 Monitoring Evaluation and Reporting

- Standardised Flow Monitoring
- Surface Condition trends
- Re-evaluation and adjustment

14 Review and Adapt Management Actions

- Adaptive Management Loop
- Review Monitoring Results
- Build Basin Database
- Fill Information Gaps

TABLE 2: GAB Springs Adaptive Management Template: Adaptive Management Response

Template Categories	Location and Land Use	Spring Characteristics	Current Condition	Threatening Processes	Current Regulatory Framework
	Situational Analysis				
Comments and Options	Land use will normally comprise one or more of the following: • Grazing • Other agricultural • Conservation • Eco-tourism	Spring types • Travertine mounds • Astrobleme • Sand mounds • Flat depressions • Abutment springs • Thermal mounds • Rocky seeps and terraces • Diffuse discharge (scald). Values to be considered: • Geological / structural • Cultural (Indigenous and non-Indigenous) • Natural (fauna & flora)	Indicative Categories **Very good**: geological structures intact, no obvious disturbance of wetland vegetation or aquatic fauna. Steady flow: no apparent changes in wetland area. **Good**: geological structures generally intact, minor disturbance of wetland vegetation (eg peripheral grazing by rabbits or minor stock grazing effects). Apparently steady flow. **Poor**: geological structures may be disturbed; moderate ground and vegetation disturbance; and/or aquatic fauna affected by disturbance or by introduced species. Flow may be reduced: wetland tail and/ or wetland area reduced **Very poor**: severe disturbance of geological structures and/ or wetland vegetation and or aquatic fauna. Flow may be significantly reduced, indicated by marked reduction in wetland area.	Loss of pressure – resulting from local or regional water extraction – leading to flow reduction. Acidification – associated with flow reduction at springs with acid sulphate soils	Some controls on artesian water extraction to protect spring flows. Environmental assessment for proposed new extractions. General protection under EPBC Act.
				Excavation: severe disruption of geological, cultural and natural values	Potential control of Water Affecting Activities and clearance controls. General duty of care provisions. EPBC Act.
				Stock and other introduced animals: grazing, pugging, water contamination	General duty of care provisions (eg under Pastoral and NRM legislation). Potential controls under native vegetation legislation re increases or changes in grazing pressure.
				Weeds and pest animals	Regulatory controls generally relate to proclaimed pest species.
				Phragmites proliferation in protected springs	No relevant regulatory framework
				Tourism impacts: soil compaction, water contamination, impacts on vegetation and aquatic fauna	Limited regulatory framework. Site specific constraints within public reserves.
				Water user and landholder support and compliance	State-dependent – eg Water Allocation Plan and regional board support and administration in SA

Decision Point: Risk Assessment: Is action necessary based upon values, condition and threats?

Strategies to manage risks	Options for on-ground actions	Implementation, Funding and Maintenance	Monitoring, evaluation and reporting process	Process for review and revision of actions
Response if Action considered necessary				
Management of regional & local water extraction to maintain pressure & spring flows. Rehabilitation of artesian bores, and maintenance of closed delivery systems	Management of local water and regional water extraction Bore and water infrastructure rehabilitation with initial focus on bores in vicinity of affected springs.	Clearly defined rights and responsibilities to protect spring values. Negotiated funding for installation, maintenance: governments, water users, and landholders. Land manager role in monitoring infrastructure and maintenance	National, State and regional bodies to coordinate. Land managers and local groups may assist in routine monitoring	National, State and regional bodies to coordinate in consultation with land managers and relevant local groups.
Control any further excavation; rehabilitation of excavated sites where feasible	Most excavated springs may be too disturbed to warrant priority. Focus on preventing further excavation.	Governments / regional bodies to work with landholders to eliminate spring excavation.	State and regional bodies to monitor compliance, evaluate and report.	State and regional bodies to have lead role in review in consultation with land managers
Exclusion of stock & introduced animals; provision of alternative water sources where needed.	Fencing of springs (preferably spring groups) or destocking of spring paddocks. Site specific provision of alternative water where needed.	Collaboration between Governments / regional bodies, land managers & third parties. Management agreements to be developed. Primary funding through Governments / regional bodies / other third parties. Land manager role in maintenance	Regional NRM Board (or equivalent) to have lead role in collaboration with State pastoral and environment agencies. NGOs, land managers and volunteer groups may assist.	Regional NRM Board (or equivalent) to have lead role in collaboration with State pastoral and environment agencies. Land managers, relevant NGOs and volunteer groups also involved.
Targeted control programs	Site specific weed control. Site specific programs to eliminate pest animals & prevent spread	Collaborative approach with Governments, regional bodies, third parties and land managers.	Regional NRM body lead role with state agency input. NGOs, land managers and volunteer groups may contribute.	Regional NRM body lead role with state agency input. NGOs, land managers and volunteer groups may contribute.
Generally no action but management trials may be considered.	Generally monitor but consider trials involving fire or physical biomass removal	Specialist work: input from Governments, regional bodies, third parties and land managers	State Env't agency and regional NRM Board (or equiv.). Land managers and volunteer groups may contribute.	State Environment agency and regional bodies to review in collaboration with relevant NGOs, land managers & volunteers.
Targeted consultation for agreed risk management programs	Targeted programs involving extension, infrastructure to guide behaviour; possible controls.	Generally responsibility of Governments and any NGOs involved in springs subject to public visitation.	Reserve / area managers to monitor, reporting to State agencies & regional bodies.	Land manager to review; collaboration with State & regional environment and tourism bodies.
Develop culture of willing compliance. Enforceable regulations for recalcitrants	Ensure shared knowledge of spring values, threats Consider industry and landholder needs Identify incentives, rewards & recognition	Ensure spring values and spring management becomes an integral part of water and land management in local cultures.	State & regional bodies in collaboration with industry groups	State & regional bodies in collaboration with industry groups

Grey kangaroo at Edgbaston Big Spring in the Barcaldine Supergroup (Photo: R Rossini)

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- **Colin Harris** – President, Friends of Mound Springs (FOMS); retired Public Servant with a background in springs research and more than 30 years' experience in spring management
- **Simon Lewis** – Secretary, FOMS; retired Public Servant with more than 30 years' experience in springs monitoring and management
- **Travis Gotch** – Chief Researcher in NWC study *'Allocating Water and Managing Springs in the GAB'*; Vice-President, FOMS; more than 20 years' experience in springs research
- **Megan Lewis** – Professor, University of Adelaide; Chief Researcher in NWC Study *'Allocating Water and Managing Springs in the GAB'*; more than 30 years' experience in remote sensing techniques, including monitoring of GAB springs
- **Andy Love** – Associate Professor, Flinders University Centre for Groundwater Studies; Chief Researcher in NWC Study *'Allocating Water and Managing Springs in the GAB'*; hydro-geologist with more than 30 years' experience in groundwater hydrology in the GAB
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Publication, layout and design were completed by Karen English of elevenacross.

1 Sadly, Lynn Brake passed away on 22 December 2019. On 19 December he was advised of the creation of the Lynn Brake PhD scholarship for research on mound springs. On 20 December he was presented with his own personal print copy of the completed GAB Management Plan and Template, which will be a key tool to continue his campaign to care for mound springs. His legacy will live on.

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Elizabeth Springs, Wabma Kadarbu Mound Springs Conservation Park (Photo: L Brake)

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