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Springs of the Great Artesian Basin – Knowledge Gaps and Future Directions for Research, Management and Conservation

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Abstract

This Special Issue of 19 papers published by The Royal Society of Queensland is especially timely as Aboriginal Peoples, pastoralists, scientists, governments and conservation groups work towards the recovery of groundwater pressure, threat abatement and conservation of spring communities and species throughout Australia's Great Artesian Basin (GAB). Our introductory paper outlined contributions from individuals, sectors and perspectives, weaving a narrative around the major themes of the compendium. Here we summarise, often in the words of the authors, the next steps to fill fundamental knowledge gaps, implement management strategies, enhance mechanisms to conserve endemic species, and develop effective models of governance and stewardship. To conclude this synthesis, we bring to attention a recent "Plea for Improved Global Stewardship of Springs" (Cantonati et al., 2020) – a fitting framing for our summary of actions needed to revere, understand and protect the springs of Australia's GAB. These springs are among the most revered, structurally complex, ecologically diverse, evolutionarily unique and threatened groundwater-dependent ecosystems in Australia. We owe it to the many Aboriginal nations that comprise the GAB, all other life sustained by springs, and future generations of Australians to conserve these precious oases of life in Australia's arid, semi-arid and northern tropical regions.

Keywords: Great Artesian Basin, springs, cultural values, endemic species, groundwater-dependent ecosystems, aquifer drawdown, feral animal disturbance, alien species, governance and stewardship models, conservation and management frameworks, EPBC Act, 1999

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Introduction

Springs of the Great Artesian Basin (GAB) are sites of fascination and wonder as oases of life in arid, semi-arid and northern tropical landscapes of Australia. The majority, and certainly the most well-researched springs, are located in the more arid areas of these landscapes in Queensland, New South Wales and South Australia, and they are the focus of this Special Issue published by The Royal Society of Queensland.

Water springing forth from beneath inland desert plains is revered by Aboriginal Peoples, who have long cherished their inherent connection to the basin and its springs, soaks, shallow aquifers and Country. The chain of springs that extends from Kati Thanda–Lake Eyre to north-eastern

Queensland forms vital points in cultural lore and song-lines, and springs remain important sources of material and spiritual inspiration for traditional custodians (Ah Chee, 1995; Moggridge, 2020). Springs also served as a vital resource during early European exploration and occupation of inland Australia by providing reliable water supplies in essentially dry landscapes. During this time, as with pre-colonial times, springs served as nodes that facilitated exchange and communication across vast distances. They were instrumental in guiding the routes of the Overland Telegraph Line from Darwin to Port Augusta, and the Ghan railway from Darwin to Adelaide.

The discovery in the 1880s that settlers could dig wells and drill bores to exploit the waters of the Great Artesian Basin was pivotal for the emerging pastoral industry (Brake et al., 2020). However, colonial modes of management and exploitation quickly led to severe impacts on springs. Unlimited groundwater extraction through bores, excessive wastage through evaporation and seepage from bore drains, physical disturbance from introduced species and vain efforts to improve flow all contributed to a loss of 20% of springs over a short 200-year period (Fairfax & Fensham, 2002; Powell et al., 2015; Rossini et al., 2018). The loss of GAB springs is of concern because of their extremely high cultural and conservation values, and because their demise or inactivity is a sign of the broader issue of diminished pressure in the aquifer at large (Fensham et al., 2016).

Springs have been recognised worldwide as groundwater-dependent ecosystems of disproportionately high biological diversity (Cantonati et al., 2020). They form evolutionary refugia – permanent or semi-permanent groundwater-dependent habitats supporting rare and endemic species of plants and animals that have adapted and persisted over millennia (Davis et al., 2013; Murphy et al., 2015a). Springs that emerge from the GAB in Australia support a high diversity of endemic aquatic species. However, the majority of these endemic species have a high risk of extinction due to their small geographic ranges, severe habitat loss and ongoing threats to the groundwater-dependent wetlands they occupy.

Despite the unique nature of GAB springs, their many endemic species and the severity of the threats they continue to face, these groundwater-dependent ecosystems have only recently attracted formal conservation attention. The flora and fauna associated with springs came under Commonwealth protection in 2001, via the listing of "the community of native species dependent on natural discharge of groundwater from the GAB" as endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999). A Recovery Plan was published in 2010, with the overall objective to maintain or enhance groundwater supplies to GAB discharge spring wetlands, maintain or increase spring wetland habitat area and ecological health, and increase populations of all endemic organisms (Fensham et al., 2010).

Likewise, two decades have passed since the publication of the original national strategic management plan for the GAB (GABCC, 2000). Importantly, development of the national plan led to the first nationally coordinated basin infrastructure funding program, the Great Artesian Basin Sustainability Initiative (GABSI), commencing in 1999. These two national initiatives are now being renewed with greater vigour and focus on the importance of saving water, a major factor in improving spring health and conservation.

Over time, Australians have achieved a greater awareness of GAB springs as groundwater-dependent ecosystems, their endemic species, the processes that sustain them and the activities that threaten them. Yet there is no recent compendium of papers about the arid and semi-arid GAB springs and the prodigious efforts over decades to guide wise and respectful use of the groundwater resources of the basin. Likewise, the absence from this volume of papers about the springs of tropical northern Australia is a reflection of limited work on these systems, and another gap to be filled in GAB research and management.

This Special Issue of 20 papers published by The Royal Society of Queensland is especially timely as Aboriginal Peoples, pastoralists, scientists, governments and conservation groups work towards the recovery of groundwater pressure, threat abatement and conservation of spring communities and species throughout the GAB. Our introductory paper outlined contributions from individuals, sectors and perspectives, weaving a narrative around the major themes of the compendium (Arthington et al., 2020). Here we draw out the major recommendations from those contributions. We summarise, often in the words of the authors, the next steps to fill fundamental knowledge gaps, implement management strategies, enhance mechanisms to conserve endemic species, and develop effective models of governance and stewardship. To conclude this synthesis, we bring to attention a recent "Plea for Improved Global Stewardship of Springs" (Cantonati et al., 2020) – a fitting framing for our summary of actions needed to revere, understand and protect the springs of Australia's GAB.

The Importance of Groundwater to Australian Aboriginal People

The Special Issue begins with an account of the importance of groundwater to Australian Aboriginal people, based on the research of Bradley Moggridge from the Kamilaroi nation in north-western New South Wales. Moggridge (2020) records the beginnings of his research on the relationships between Australian Aboriginal people and groundwater, with the intention "to inspire other Aboriginal people and researchers to take the subject matter further". Brad's telling of Dreamtime stories and rituals of caring for the land, water and all living beings illuminates our understanding of Aboriginal knowledge and affirms our profound cultural inheritance as new Australians. Unfortunately, the cultural significance of many GAB springs remains poorly documented, as other papers note (e.g. Silcock et al., 2020). This leaves valued artefacts and stories insufficiently recorded and protected (Pointon & Rossini, 2020). Traditions of passing knowledge along generational lines have also been lost, and what remains is under further threat from social changes and physical changes to spring country.

The importance of working with Aboriginal communities and custodians to achieve cultural and social outcomes is a central theme of the GAB springs Recovery Plan (Fensham et al., 2010) and the new Great Artesian Basin Strategic Management Plan (Department of Agriculture, Water and the Environment, 2020). Brad's paper and other contributions herein (e.g. Harris, 2020; Jensen et al., 2020; Silcock et al., 2020) reinforce the imperative to integrate knowledge and wisdom from all sources, including that held by the original custodians of springs country, in spring investigations, management and conservation.

Hydrogeology and Hydrochemistry of GAB Springs

Habermehl (2020) provides an introductory hydrogeological foundation on groundwater flow patterns and ages, discharge from artesian springs and spring deposits, drawing upon the history of extensive hydrogeological investigations and numerous studies that characterise the groundwater sources supplying various GAB spring complexes. The paper illustrates the remarkable variety of spring formations, such as the conical mound springs and travertine terraces in the south-western parts of the basin. Investigations reviewed therein highlight the importance of understanding the relationships between springs and their source aquifers, and the hydrogeological processes that create and maintain springs in the arid environments of the Great Artesian Basin.

Although numerous studies characterise the groundwater sources supplying various GAB spring complexes, uncertainties remain in some areas of the basin. This uncertainty has implications for water allocation, groundwater resource management and the protection of spring wetlands.

Through discussion over the last decade of advancing spring knowledge in the Surat Basin, Flook et al. (2020) describe the application of hydrogeoecological survey data in developing detailed conceptual models of springs and their associated wetlands, and in designing monitoring strategies to better understand spring dynamics and responses to groundwater drawdown. The paper highlights the importance of understanding the drivers of the observed dynamics at springs and their criticality for determining appropriate monitoring strategies and for understanding how changes in groundwater pressure could affect wetland ecosystems. In parallel, the paper highlights how understanding changes in abundance and distribution of associated biota can be more meaningfully achieved through further unpacking of the spring water balance.

Using groundwater hydrochemistry and environmental tracers, Keppel et al. (2020) identifies the likely sources of groundwater supporting the Lake Callabonna and Lake Blanche spring complexes in South Australia for the first time. His identification of the RDGS (Rolling Downs Group Sandstone) aquifer in the region has important ramifications for understanding the hydrogeology of the GAB. The paper recommends hydrochemical modelling, such as a mixing model, as a necessary next step to identify the potential for, and to quantify, mixing between different groundwater sources: "Given the prevalence of ecologically sensitive spring environments, as well as established pastoral and petroleum industries in the region, management and regulation of groundwater affecting development requires a refocus from predominantly a single aquifer to potentially multiple aquifers."

Surveys continue to yield new information in the less well-studied parts of the GAB, such as the Mulligan River springs, the only permanent surface water in this dry region on the edge of the Simpson Desert in far-western Queensland (Silcock et al., 2020). This paper explores the hydrogeology, cultural history and ecology of the Mulligan River springs using historical maps, journals, diaries, letters and newspaper articles from early explorers, pastoralists and travellers, and interviews with the managers of contemporary pastoral stations. Recent surveys document the biota and current condition of these remote springs, and we learn that the Mulligan River springs are different from most GAB springs in the lower diversity of their flora and fauna, and absence of endemic species. Silcock et al. (2020) recommend further work to elucidate spring hydrogeology, particularly with regard to projected water use by extractive industries in the Eromanga Basin, and understanding spring dynamism and apparent recovery of some springs after bore capping. Furthermore: "Detailed archaeological work at the springs would provide further insights into Aboriginal use of the springs, including their place in the broader cultural landscape and potential significance to Aboriginal trade networks in inland eastern Australia."

Ecology and Conservation of Spring Biota

Springs of the GAB are renowned for the richness and endemicity of the native aquatic species that occupy their wetland habitats. Despite their high conservation value, many of these species are at risk of extinction due to their small geographic ranges, severe habitat loss and ongoing threats (Rossini et al., 2018; Rossini, 2020). As small geographic range appears to be the norm, it is probable that severe biodiversity losses accompanied the broad-scale loss of springs that occurred post 1890 (Fensham et al., 2010). Habitat loss that has not led to extinction is still associated with the loss of genetic diversity (Faulks et al., 2017) and the potential loss of cryptic species or clades before they are discovered or described (Mudd, 2000). Our ability to conserve these species depends on knowledge of their distributions and environmental needs, yet we lack such information for the vast majority of species (Rossini, 2020). In this volume, five papers advance our knowledge and enrich our understanding of the patchy distribution patterns, special habitat requirements and conservation status of some of these unique spring species (Choy, 2020; Clifford et al., 2020; Kerezsy, 2020a,b; Rossini, 2020).

Core to understanding and conserving springs is sound knowledge of their biota. The unique evolutionary histories created by disjunct distributions across the basin's springs create complex evolutionary quandaries. Many researchers who dive into these questions find complexes of cryptic species (Murphy et al., 2009; Murphy et al., 2015b), surprising patterns of population structure (Wilmer et al., 2008; Worthington-Wilmer et al., 2011) and, more often than not, new species. Species new to GAB springs are being described at a rate of two per year, at present, with many invertebrate species known as putative endemics but still awaiting formal description. Choy (2020) presents a case study of one of these. The "enigmatic" freshwater shrimp – *Caridina thermophila* – is found in GAB springs at only four locations within the Barcaldine supergroup. Choy concludes that "… very little is known of the exact taxonomic status, distribution, demography (population size, structure, natality and mortality rates) and ecology of this species". This is not unique, as detailed by Rossini (2020), and has major consequences for how effectively we can conserve species in GAB springs (Pointon & Rossini, 2020).

In some cases, spring species are taxonomically well defined, and their distributions are relatively well known. To understand how threatening processes may impact them, we need autecological summaries, which for many species are woefully inadequate or absent altogether (Rossini, 2020). Kerezsy (2020a) shows how an ecological account of a particular species, its distribution and its environmental requirements can be achieved. He builds on a legacy of field ecology concerning spring species (e.g. Ponder et al., 1989; Rossini et al., 2018; Rossini, 2020). Taxonomy is the first step on a long journey towards understanding spring species, but without data on how these unique organisms associate with, and rely on, their distinctive habitats we cannot communicate or predict how threatening processes may impact them. We are also missing the unique stories each of them can tell about changes in our continent's environment, and how life finds a way to persist in new ways. As summarised by Kereszy (2002b): "Persisting as they do in such unique and specialised habitats, the study of these GAB fish species – and all GAB springs endemics – can reveal much about evolution, speciation and resilience. It is therefore imperative that we respect and conserve them and their unusual habitats."

Kerezsy (2020b) and Rossini (2020) present syntheses of the conservation status of two large groups of spring taxa that present very different conservation challenges. The fishes endemic to springs, as summarised by Kerezsy, are relatively well studied, and whilst the ecological knowledge of some species is limited, he has been able to present an overview of the present conservation status of this group. In contrast, the invertebrates represent the most diverse but least taxonomically resolved and least protected group of spring inhabitants. Rossini (2020) documents risks, fundamental data deficiencies and inconsistencies in the process of listing invertebrates under EPBC Act criteria (the most speciose group of endemics). Using gastropods endemic to the Pelican Creek Springs complex as exemplars, she illustrates challenging issues around accurate estimation of two vital metrics: geographic range (EoO – extent of occurrence) and the habitable or inhabited area (AoO – area of occupancy). The analyses of her paper provide support for all species of gastropods and crustaceans to be listed and hence protected individually under the EPBC Act. Further discussion of the efficacy of the EPBC Act to conserve and protect springs and their endemic biota comes later in this synthesis (Pointon & Rossini, 2020).

These ecological papers present an overview of how knowledge of the biological values of GAB springs has, and can continue, to grow. They stand as important baseline references for other contributions to the Special Issue regarding threats, adaptive management plans and mechanisms to ensure protection. It is impossible to understand the potential impacts of threatening processes – historical, contemporary or predicted – without knowledge of how GAB species respond to and rely on elements of a spring's environment. Adaptive management plans cannot monitor nor correlate changes in a spring's community with changes in the environment without this baseline data. Furthermore, legal protective mechanisms cannot function effectively without up-to-date understanding of conservation risk or the potential impact of proposed project activities. Through these contributions we hope that the power of ecological enquiries into GAB spring ecosystems and their biota is recognised, emphasised and further studies are supported.

Threats to GAB Springs and Their Biota

Threats identified in the GAB springs Recovery Plan include: aquifer drawdown; excavation of springs; stock and feral animal disturbance; alien (introduced exotic) species of plants and animals; tourist visitation; and development of impoundments (Fensham et al., 2010). This Special Issue stands as an opportunity to review some of these threatening processes, and to provide examples of how activities and research over the past decade have sought to understand and reduce their impacts on springs. Here we summarise the findings and recommendations of papers that address three major threats given emphasis in the springs Recovery Plan: aquifer drawdown, feral animal disturbance and alien species.

Aquifer Drawdown

Scientific exploration and development of the GAB commenced following the construction of the first artesian bore in 1878. A vast system of open artificial channels, known as bore drains, was constructed to distribute flowing water to individual or groups of pastoral properties, often over significant distances. The benefits for settlements and the growing pastoral industry were enormous, but gradually gave way to concerns about declining bore pressure, water losses to evaporation, and adverse effects on spring ecosystems.

Brake (2020) describes the effects of water extraction and use on artesian pressures and bore flow rates, and the history of efforts to control flowing artesian bores and reduce wastage of the GAB water resource via GABSI and other programs. The Great Artesian Basin Sustainability Initiative (GABSI) was centred on artesian pressure recovery, sustaining GAB spring flows and assisting landholders in the rehabilitation of bores and water delivery infrastructure. Brake (2020) concludes that although GABSI achieved its major objectives over nearly two decades, and has been very successful in supporting the transition to closed water delivery systems, it is not complete. There are now more than 50,000 bores in the GAB, of which 6600 are artesian bores, and at least 430 of these bores remain uncontrolled. He notes that if the true return on the investment is to be understood, "reliable information on the broader inputs and outcomes of GABSI beyond just dollar cost of water saved needs to be investigated".

In a 2010 benefit-transfer study, Rolfe (2010) estimated the off-farm benefits of improving the management of the GAB to be at least as high as $17.8 million per year, outweighing the annual program costs of $15.5 million per year from the Australian and state governments in Stage 2 of GABSI. Off-farm benefits accrue to different societal groups and interests, including recreation, tourism, biodiversity assets and cultural heritage, options for future use and conservation, and reductions in greenhouse gases. Information on these benefits will provide "key evidence needed to guide future management and investment decisions concerning the taking of water from the valuable GAB resource in the future" (Brake, 2020).

Effects of Exclusion Fences Around Springs

Grazing by native species is a natural feature of spring ecology and can be essential for maintaining microhabitat and species diversity (Unmack & Minckley, 2008). However, springs can be seriously affected by over-grazing and habitat disturbance caused by livestock and feral species (pigs, camels) as well as native animals (Fensham et al., 2010). De-stocking, and fencing around GAB springs to exclude stock and feral animals, are well-established management approaches for protecting springs of high conservation value, especially in situations where baiting, shooting and mustering fail to provide sustainable outcomes (Negus et al., 2019).

Unlike the GABSI initiative designed to tackle groundwater drawdown, efforts to fence springs have been local and strongly dependent on strong support of land managers or community groups. Two contributions included here present excellent documentation of the impacts of fencing springs to alleviate the threat of disturbance by stock and introduced species. The Eulo Springs supergroup is one of the most taxonomically rich but least understood spring complexes in the GAB (Rossini et al., 2018). Peck (2020) documents a program where feral animal activity was managed effectively through appropriately designed exclusion fences. Through qualitative condition assessment he shows that when feral animal activity is well managed, artesian spring wetland communities have a considerable capacity for recovery. Peck amply demonstrates that qualitative assessment methods have proved useful for local management staff to gather, collate and interpret data about spring condition on a routine basis.

In a data depauperate system, where on-country managers are often the people with best access to such remote locations, simple yet effective monitoring tools are essential for tracking how the system responds to threat mitigation. Peck (2020) suggests that these scoring techniques have potential to provide early-warning signals of changes in spring condition that should be assessed using quantitative ecological surveys and further research. Many springs in the GAB are located on private property (Harris, 2020), and numerous springs we need to protect to ensure the persistence of the majority of endemic taxa are managed by people who live on productive landscapes. Fencing, therefore, can be a useful tool for protecting high-value springs where the acquisition of an entire property under a conservation arrangement is not possible. Monitoring of these remote but valuable springs can provide vital data (Rossini et al., 2016), and Peck (2020) has demonstrated how simple monitoring frameworks can allow on-country managers to document how a threat mitigation practice is creating positive outcomes for their springs.

Threat mitigation like fencing does not always result in a predictable or ecologically positive outcome. Increases in the abundance and biomass of particular plant species following stock exclusion by fencing can result in competition with other native vegetation, alterations to microhabitats, increased transpiration and loss of areas of open water habitat. Lewis & Packer (2020) present 35 years of observational data on the response of the common reed (*Phragmites australis*) and other spring vegetation, following exclusion of stock. This study highlights a unique situation, where efforts to mitigate a threat arising from past land-use change has created another threat through changed dynamics of a native plant.

Phragmites australis is a tall perennial grass native to Australia but with a cosmopolitan distribution; it forms monodominant stands in many wetlands throughout temperate and dryland regions of the world (Packer et al., 2017). The GAB study is remarkable for its longevity. It has shown that the dominance of *P. australis* waned in some springs after 30+ years of stock exclusion and, in another case, has not colonised a spring free of *P. australis* at the time of de-stocking, despite the presence of source populations in a neighbouring spring. These authors document how shifts in the abundance of *P. australis* have inevitably had impacts on another spring plant of conservation concern, *Eriocaulon carsonii*. This listed endemic GAB springs plant appears to have been reduced in distribution and abundance where *P. australis* has become monodominant. This long-term study highlights the necessity to commit to post-intervention monitoring like that presented by Peck (2020). Without it, such subtle impacts and emerging unpredicted threats with decades of latency may be overlooked, creating new threatening processes for more vulnerable spring taxa.

In their discussion, Lewis & Packer (2020) recommend experimental fencing of a landscape mosaic of springs with and without *Phragmites*, and monitoring of nutrient levels (elevated over time by stock excreta) to test predictions of their influence on the performance of *Phragmites*. Admirable efforts to control *P. australis* in the Irrawanyere (Dalhousie) springs have also demonstrated how First Nations management with fire can help return the balance in favour of endemic species and their habitat. Both Peck's and Lewis & Packer's contributions emphasise how the monitoring of threat abatement actions is essential and can be a relatively simple and accessible task.

Ecology and Control of Alien Aquatic Species

Aquatic species introduced to Australia from other continents have colonised many freshwater habitats, including GAB springs and bore drains. One of these has received significant focus in spring research as its impacts are of major concern (Pyke, 2008). The alien eastern gambusia (*Gambusia holbrooki*) is a small, aggressive live-bearing fish that was first introduced to Australia for control of larval mosquitoes. It has spread widely in Australia, feeds opportunistically across aquatic food chains, and now threatens the persistence of the critically endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) in Edgbaston (*Byarri*) Springs (Kerezsy & Fensham, 2013). This conservation reserve was purchased by not-for profit conservation group Bush Heritage Australia in 2008 to protect its springs and biota. Efforts to reduce *Gambusia* populations using Rotenone, a plant-based toxin, and removal of the red-finned blue-eye to predator-free habitat, have had measurable success at Edgbaston (Kerezsy, 2020a,b; Kerezsy & Fensham, 2013). However, gastropods and crustaceans may be susceptible to rotenone.

Edgbaston (*Byarri*) Springs is home to a second endangered fish, the goby (*Chlamydogobius squamigenus*). Surveys to establish its wider distribution in and around Edgbaston Reserve produced a surprising discovery – gobies are living in bore drains at Ravenswood, approximately 20 km from their natural spring habitat at Edgbaston (Kerezsy, 2020a). Kerezsy suggests that management of such an endangered species could involve a suite of unconventional methods, e.g. "retaining populations in artificial environments that utilise GAB water but otherwise are physically different from GAB springs". This option for conservation of a spring-dependent species has prompted an important policy question. Should some bore drains be left open (unpiped) to provide 'insurance' habitat for endemic species faced with threats in their natural spring habitat? In this instance, relying on bore drains as insurance habitat for the endangered goby is risky because all bore drains sampled by Kerezsy (and the great majority of bore drains in central-western Queensland) have been colonised by eastern gambusia. Tracking competitive interactions and responses of red-finned blue-eye and Edgbaston goby to *Gambusia*, and further experimental studies to control this alien species, should be a priority. More broadly though, should artificial habitats that have developed a new aquatic ecosystem over time be protected when they help conserve endangered or other high-priority species? “This survey demonstrates that endangered species, despite being disadvantaged by small populations, limited suitable habitats and the imposition of invasive species, are sometimes capable of persisting in less-than-perfect circumstances. To enable such species to endure, and to improve these circumstances as much as possible, should therefore be the aim of all endangered species programs and recovery plans.”

Another alien pest that has received less attention is the cane toad (*Rhinella marina*). This species also threatens the conservation of GAB spring ecosystems at Edgbaston (Clifford et al., 2020). Cane toads are opportunistic feeders, taking aquatic as well as terrestrial invertebrates. At Edgbaston Springs their gut contents were dominated by aquatic invertebrates, especially Coleoptera and endemic species of Gastropoda, with small intakes of Acarina, Amphipoda, Diptera, Epiprocta, Hemiptera, Hirudinea and Oligochaeta. Clifford et al. (2020) recommend further dietary analyses to determine seasonal patterns of cane toad foraging behaviour and the ongoing impact of these amphibians on spring ecosystems.

The occurrence of two vertebrate pests with opportunistic feeding behaviours and a preference for aquatic invertebrates (including endangered species) in this precious conservation reserve is particularly worrying. The case presented by Clifford et al. (2020) reiterates the importance of ecological studies to aid understanding of the mechanism by which a threatening process can act. The Edgbaston Springs complex is one of the most data rich in the GAB – and an exemplar of how research informs management and conservation. Publications concerning the impact of *G. holbrookii* on the critically endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis)* have drawn serious conservation attention to this species’ plight, leading to direct and innovative conservation interventions. However, like cane toads, *G. holbrookii* also consume other elements of the endangered GAB-dependent community, especially invertebrates. As outlined by Rossini (2020), invertebrate taxa are poorly documented, often their taxonomy is unresolved, and they are inconsistently protected by conservation listings. Clifford et al. (2020) highlight another emerging and poorly understood threatening process that will be difficult to manage.

Recovering Springs

Although many discussions of conservation action in this Special Issue focus heavily on the role of policy and basin-scale initiatives, two papers remind us of the powerful role of citizens in understanding threats and protecting springs. These efforts can be overlooked by academic science or high-level policy initiatives. Impacts and histories are best documented as stories – in some cases decade-long stories. These stories emphasise the critical role of the human connection to springs in ensuring their conservation. Springs across the Great Artesian Basin hold stories of unsung heroes, from First Nations Peoples since time immemorial, through long-term commitments of dedicated individuals and groups, to emerging partnerships.

Harris (2020) describes five decades of ‘watching mound springs’ through professional activities and engagement with many key scientists and Aboriginal custodians of South Australia’s mound springs. He recalls the interest and controversy surrounding the Olympic Dam Mine project developed to mine world-ranking quantities of copper, uranium, silver, gold and rare earth elements. Later in life he formed the community group Friends of Mound Springs (FOMS). As Founding President, Harris (2020) guided many activities focused between Marree and Oodnadatta in South Australia. A sister group, Friends of Simpson Desert Parks (FOS), supports spring protection at Dalhousie Springs.

FOMS has won many awards for biological and heritage conservation work at GAB springs. Travelling with Harris (2020) on his journey through five decades of involvement with mound springs in South Australia reveals a fascinating history of discoveries and yields many wise insights. He concludes that to consolidate the gains of the past and do things better into the future, we will “certainly need to involve regional stakeholders far more than has been the case hitherto, the pastoral lessees especially, as it is on their stations that most of the unprotected springs occur. And we will certainly need to use the knowledge and connections to the land of its traditional owners more effectively. The legal niceties of Native Title aside, Indigenous people hold moral title to the land, and it is incumbent that we all work together to conserve these remarkable features of our inland landscape."

Edgbaston (*Byarri*) Springs and the ongoing conservation programs are shining examples of how the FOMS legacy is growing and expanding. To protect the springs and endangered fish species, Bush Heritage has installed fish barrier fences to either contain *Gambusia* populations or protect red-finned blue-eye populations from invasion. Red-finned blue-eye have been relocated to other springs to expand their range and the number of springs they occupy. Another strategy has been to establish 'insurance' populations onsite by diverting the outflow of an existing bore into artificial springs. Much of this effort has been supported by volunteers from diverse sources brought together to work with a shared passion to save endangered species and conserve the spring wetlands on which they depend. Engaging volunteers in conservation works at Edgbaston (*Byarri*) Springs has been hugely beneficial, not least because not-for-profit conservation projects need human resources for labour-intensive projects. Volunteers gain fieldwork skills and experience, and the whole enterprise fosters a sense of community and belonging by engaging universities, agencies and the general public in conservation works (P. Kern & L. Hale, pers. comm., 2020).

Spring Regulation and Policy

Legal Protection

The "community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" is protected under Australia's main environmental law, the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999), and the 2013 EPBC Act amendment (the "Water Trigger") establishes water resources as a "matter of national environmental significance" (MNES) in relation to coal seam gas and large coal mining development. Whilst the advantages of these legal umbrella instruments are clear, the level of protection they offer to individual spring species bears scrutiny (Pointon & Rossini, 2020). Only a few species are individually listed (e.g. as endangered) under conservation legislation even though their vulnerability to threatening processes is well known from taxonomic studies, field collections and risk assessments (Ponder, 1995; Fensham & Price, 2004; Kennard et al., 2016). Pointon & Rossini (2020) review the strengths and limitations of the EPBC Act as it applies to the conservation of GAB spring species and the particular features of their biological communities. The paper highlights four complexities associated with the application of the EPBC Act to the management and conservation of GAB springs: the high level of discretion in decision making; data deficiencies that make it difficult to determine whether impacts are sufficiently "significant" to trigger assessment via an environmental impact statement (EIS); the flaws in offset management and mitigation measures; and the fact that community listings may not adequately protect individual species.

Although not GAB springs, a recent case study of Doongmabulla Springs illustrates how these legislative complexities have been addressed under the requirements of the EPBC Act in relation to development of a major coal mine in their vicinity. The Adani Carmichael Coal Mine Project (the project) has been approved at a site approximately 11 km from Doongmabulla Springs, north-west of Emerald in Central Queensland. Protecting these springs from activities associated with this mining development is an important requirement of the project approval. Doongmabulla Springs is a sacred site of the Wangan and Jagalingou Peoples, where the *Mundunjudra* (Rainbow Serpent) travelled to shape the land, rivers and springs. Furthermore, the springs are known to harbour species native to the endangered community dependent on GAB groundwater flows, yet there remains some uncertainty around the source aquifer for Doongmabulla Springs (Currell, 2016). Predictions of drawdown have been challenged, and there is grave concern for the future of these springs (Currell et al., 2017). The paper articulates the challenge of protecting the unique cultural and biodiversity values of springs alongside the ongoing demand for mineral resource development.

Pointon & Rossini (2020) conclude their paper with recommendations to enhance environmental impact assessment, project approvals, and the conditioning, monitoring and reporting of the regulatory processes designed to protect the threatened springs and groundwater-dependent ecosystems of the GAB. They end on a cautionary note: "While scientific effort is slowly building an understanding of GAB ecosystems, failure to strengthen the regulation of impacts on springs and their communities may mean that these efforts merely document the decline of springs and the extinction of species reliant on spring habitats and resources."

Local Management Initiatives

Listing of the GAB springs community as endangered under the EPBC Act has the potential to protect a large, complex and fragmented system of wetland habitats and species that would be difficult to protect solely by elements of the Australian protected area network, such as national parks and other elements of the national estate. Some high-value springs and endemic species are afforded protection as part of large national parks or conservation areas (Rossini, 2020), but the majority are located within large properties under pastoral lease for cattle production. Threats to these springs persist in spite of numerous studies and risk assessments, the bore capping programs, management activities (e.g. fencing springs, pest control) and mechanisms under jurisdictional governance (water allocation plans). Yet a decade on from the release of the GAB Springs Recovery Plan in 2010, critical issues associated with the conservation and management of GAB springs persist, especially on pastoral lands.

Lewis & Harris (2020) review these critical issues in South Australia, where GAB springs located on pastoral lands are subject to vegetation destruction, pugging and pollution by stock and pest animals, leading to habitat degradation and loss. They propose a collaborative GAB springs conservation program involving state government agencies, pastoral lessees and others through application of management agreements under the South Australian *Native Vegetation Act 1991* or *Natural Resources Management Act 2004*, supported by financial backing through the NRM Water Levy for the region. While not directly transferable to other jurisdictions, this program sets out important framing elements based around robust data systems, identification of priorities for conservation, incentives for landholders, initial protection works, ongoing maintenance of protective measures, and a regulatory framework that underpins the incentives program, manages monitoring and compliance, and also provides security for the protective measures by means of a covenant or similar mechanism. Importantly, the authors recommend that the desired management targets for GAB springs should be:

- Springs functioning with the maximum diversity of native flora and fauna present, with species of particular significance conserved, geomorphological features protected, and with natural ecological processes occurring.
- Rationalising stock access to water in areas where springs have historically been an integral stock-watering resource in property management.

Great Artesian Basin Adaptive Management Plan

Most of the recent management efforts in the Australian natural resources sector have sought to bring stakeholders, research groups and management agencies together under an integrating and inter-governmental framework. The GAB Adaptive Management Plan and Template described by Jensen et al. (2020) follows this model. This plan was the final outcome of extensive collaboration between the (then) Australian Government Department of Agriculture, and sector agencies from South Australia, New South Wales, Queensland and the Northern Territory. It was developed during 2019 by an experienced project team driven with enormous energy and dedication by Lynn Brake, who brought to reality his vision of securing long-term and well-funded future care for GAB springs (Brake et al., 2020). His leadership of the project and the energy he dedicated to the task, all the while battling serious health issues, were inspirational to the project team. This team, managed by Natural Resources SA Arid Lands, brought many of the authors of papers in this volume together to forge a master plan for springs management and conservation.

The GAB Adaptive Management Plan and Template presents evidence-based methodologies to assess and manage risks to spring groups across the GAB while minimising disruption to current users of basin water resources (Jensen et al., 2020). The principles underlying the Template are considered applicable to all spring types in all states across the GAB (Brake et al., 2020). A GAB Springs Stewardship Initiative (GABSSI) was developed in parallel, with the aim of providing 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 a range of interlinked information portals: "This, together with a GAB-wide coordinated database, is the next priority for securing the future of the GAB springs." Jensen et al. (2020) recommended that the Plan and Template be adopted as part of the Implementation Plan for the updated national Great Artesian Basin Strategic Management Plan (2018–2033).

Concluding Recommendations

As this synthesis paper for the Springs Special Issue was about to go to press, *Conservation Biology* published a paper entitled "Plea for Improved Global Stewardship of Springs" (Cantonati et al., 2020). It concludes with this powerful message:

> At a global scale, public awareness and active conservation are needed to reverse the conservation crisis facing springs and associated groundwater as human population pressure increases. Given their significance as biodiversity havens for many rare and endemic species, their keystone ecological functionality within landscapes, their extraordinary cultural and socio-economic values, and the relatively low cost of appropriate management (Knight, 2015), improving the stewardship of spring ecosystems and their supporting aquifers will yield substantial environmental advantages and societal benefits.

To conclude this synthesis of the springs Special Issue, we offer the following summary of actions needed to revere, understand and protect springs of the GAB, including the poorly studied springs of the northern basin, and likewise, springs with different groundwater dependencies and ecological communities throughout Australia. Our summary is framed around the plea's four key objectives and associated action items, and shaped by the recommendations of the Special Issue authors:

1. Recognise GAB springs as a distinctive group of groundwater-dependent ecosystems that warrant special conservation and public attention:
   - Reinforce and amplify basic understanding of springs, the water sources that sustain them, and their unique biodiversity as pivotally important Australian conservation targets.
   - Increase public and political awareness of springs as crucially important groundwater-dependent ecosystems and environmental indicators of the cultural and environmental health of the GAB.
   - Expand and support mechanisms to enhance understanding and documentation of GAB Aboriginal history, Dreamtime stories, sacred sites, language, cultural wisdom, and ecological and hydrological knowledge.
   - Institute models of co-management that empower Aboriginal Peoples to share in the documentation, management and restoration of springs.
   - Expand engagement, communication, outreach and informed debate about springs among all stakeholders.
2. Develop cultural and scientific guidelines and collaborative efforts to improve aquifer and spring stewardship across the GAB:
   - Reinvigorate and support social and biophysical research to develop conservation criteria that emphasise identification and protection of specific cultural sites, spring groups, and spring-dependent species of highest conservation value and risk.
   - Enhance and support spring and aquifer information management resources, e.g. the GAB Springs Stewardship Initiative (GABSSI) and a GAB-wide coordinated database.
   - Develop GAB-wide networks of reference locations with diverse spring types, threats and restoration initiatives, preferably within the framework of Australia's Long Term Ecological Research Network – LTERN (https://www.ltern.org.au).
   - Use LTERN sites as research and educational sentinel sites to monitor and test spring restoration strategies, and

to elucidate spring responses to human impacts, including climate change.

3. Identify, promote and fund culturally and scientifically proven methods for aquifer, spring and biodiversity management, conservation and restoration:
   - Ensure that spring GDEs are included in environmental flow assessments, procedures and regulatory frameworks.
   - Increase research and understanding of the physical and ecological impacts of resource development activities.
   - Expand and support experiments to test alien pest management strategies, conservation plans to recover endemic species, and spring ecosystem recovery programs.
   - Evaluate options for protecting endemic species in non-natural spring environments, bore drains and artificial habitats, or through translocation.
   - Expand and support cultural traditions, educational activities, research degrees, volunteer engagement and training, and NGO support networks.
4. Explicitly include springs in regional, national and international management directives, including enhancement and implementation of existing agreements:
   - Strengthen actions to protect springs via the Recovery Plan for the GAB springs endangered community, by means of the following: jurisdictional conservation legislation and water management plans; Commonwealth conservation legislation (MNES under the EPBC Act and the "Water Trigger"); the Ramsar Convention; and the IUCN Red List of Threatened Species.
   - Apply and test the GAB Adaptive Management Plan and Template and its evidence-based methodologies to assess and manage risks to springs across the basin.
   - Encourage and support Indigenous, scientific and public communities to lobby decision-making political entities for action towards enhanced legislation and management protocols for the protection of GAB groundwater resources, springs and individual threatened endemic species.

Springs of the GAB are among the most revered, structurally complex, ecologically diverse, evolutionarily unique and threatened groundwater-dependent ecosystems in Australia. In the spirit of reconciliation, we owe it to the many Aboriginal nations that comprise the GAB, and all other life sustained by springs, to conserve these precious oases of life in Australia's arid, semi-arid and northern tropical regions. A similar commitment is owed to future generations of all Australians.

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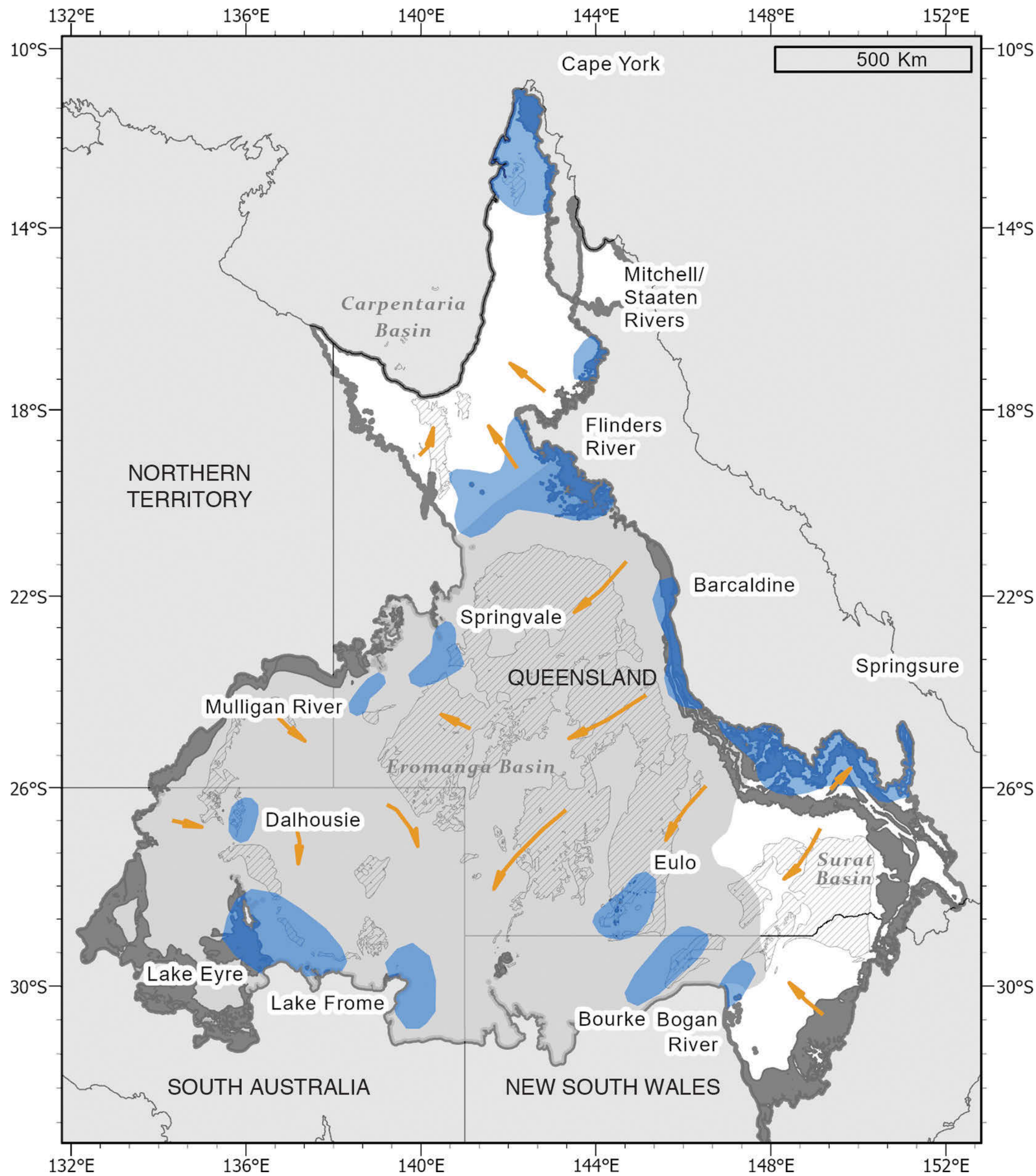
The GAB with sub-basins, major regional clusters of springs (spring supergroups, shown in blue) (Fensham & Fairfax, 2003), local (hatch) and regional recharge areas (dark grey around the GAB periphery), regional flow directions (orange arrows) (Ransley et al., 2015). Source: Flook et al. (2020).



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Craig Walton is a senior policy officer in the Queensland Department of Natural Resources, Mines and Energy. His role is focused on water policy in the Great Artesian Basin; and with a background in plant ecology, Craig is pleased to be overseeing policies and programs targeted at making the basin in Queensland watertight, because of the important ecological and social outcomes that will result from this work.

Steven Flook is Director of Management Strategies and Implementation, Office of Groundwater Impact Assessment, DNRME, Queensland. He is a passionate water resource professional with experience in water planning, cumulative impact assessment, groundwater-dependent ecosystems, science communication, design and implementation of research programs and inter-jurisdictional policy development. His experience relates predominately to investigations in the Great Artesian Basin and the Condamine Alluvium for the Queensland Government.