The unique aquatic ecosystem of Talaroo Hot Springs

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Abstract

Spring wetlands are biodiversity hotspots; however, conservation efforts for many spring wetlands are limited by a lack of knowledge. This study provides information on the natural values of the hot spring and associated wetlands at Talaroo Station in north Queensland. The natural features, the aquatic biodiversity and the threats to their ecological functioning are the focus of this investigation.

Talaroo Hot Springs is a unique geothermal natural spring ecosystem characterised by the hot, carbon dioxide rich water discharging from multiple vents and interacting with a community of microorganisms to produce a terraced travertine mound. The microorganisms are the most conspicuous parts of the mound in the form of yellow fans and the black stromatolite barrages of cyanobacteria (*Ewamiania thermalis*). The springs also support other rare and endangered species, such as the Salt Pipewort (*Eriocaulon carsonii*) and an aquatic snail (*Gabbia* sp.), which is likely to be a new species. Ecological understanding of hot springs is lacking from Australia, and Talaroo Hot Springs is amongst the few geothermal sites worldwide where life in extreme environments can be studied and further scientific investigation is likely to identify other new species.

The study was initiated and supported by the Ewamian Aboriginal Corporation representing the traditional owners of Talaroo to provide information for their plan of management. Priority threats to the ecosystem functioning include introduced species, such as Cane Toads and Feral Pigs, and physical disturbance to the mound, which can alter water flow paths that maintain the active microbial processes that build the mound.

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Introduction

Spring wetlands across the globe have been identified as isolated biodiversity hotspots possessing a diverse range of aquatic biota (including vertebrates, invertebrates, vascular plants and algae) that are often rare and restricted (Erman 2002; Fensham *et al*. 2004; Wager & Unmack

2004; Cantonati *et al*. 2012; Bogan *et al*. 2014). Freshwater springs have also been the focus of human civilisations for thousands of years as they provide a consistent and easily accessible source of water. Human tools and artefacts have been discovered during archaeological investigations near other spring wetlands indicating the long association between people and springs (McCarthy *et al*. 2010; Pigati *et al*. 2014; Powell & Fensham 2016). Similarly, spring water use by terrestrial biota has been identified by the fossils of large vertebrates such as camels, horses and mammoths recovered by palaeontological investigations of spring sites (Springer & Stevens 2009; McCarthy *et al*. 2010; Pigati *et al*. 2014).

In Australia, the focus on springs in Indigenous storytelling and mythology provides further evidence to their use and cultural importance (Harris 2002; Powell *et al*. 2015; Moggridge 2020). More recently in history, springs have provided an avenue for the colonial exploration and use of Australia's arid and semi-arid interior (Harris 2002; Powell 2012). The location of Great Artesian Basin (GAB) springs in the landscape guided early Australian pastoralists and geologists to the presence of artesian water and with this knowledge began the widespread development of bores and bore drains for the watering of cattle and sheep in arid areas (Fairfax & Fensham 2003; Powell 2012; Powell *et al*. 2015). Unregulated development of groundwater resources has led to reductions in aquifer head pressures and catastrophic loss of water discharging into spring wetlands across the world (Cantonati *et al*. 2006, 2012; Bergey *et al*. 2008; Unmack & Minckley 2008; Nevill *et al*. 2010; Powell *et al*. 2015; Powell & Fensham 2016). Freshwater ecosystems including springs are subjected to many threats, including habitat destruction, changes in hydrology, climate change, pollution and the spread of invasive species (Dudgeon *et al*. 2006; Marshall & Negus 2019).

The effect of these various threats to spring wetlands may result in them becoming unsustainable, requiring targeted management to conserve their multiple and at times competing values. For example, GAB discharge springs have been significantly affected by numerous anthropogenic threats, especially aquifer drawdown, and as a result many associated species and biological communities are listed as endangered under the *Environmental Protection and Biodiversity Conservation Act 1999* (Fairfax *et al*. 2007; Fensham *et al*. 2010; Fensham *et al.* 2011). GAB recharge springs and those associated with local aquifers are not protected under this conservation listing; however, these wetlands can still have merit for conservation (Fensham *et al*. 2004).

Talaroo Hot Springs are located on Talaroo Station, a 31,500 ha pastoral lease located in the Einasleigh Uplands bioregion near Georgetown in north Queensland (Fig. 1). The springs are characterised by a biologically active mound with several discharging vents emanating from a granite-based aquifer (McGregor & Sendall 2017). The Talaroo site is situated in the geological Georgetown inlier outside the GAB boundary (Radke *et al.* 2012) and the springs are therefore not GAB related and not afforded the conservation status of GAB discharge springs. There are few records of the biodiversity associated with the spring mound and its outflowing wetlands, or information on the anthropogenic threats, that can be used to support the management and conservation planning of the site.

Figure 1. Location of Talaroo Hot Springs near Georgetown in north Queensland.

This study describes some of the natural values of the Talaroo Hot Springs and associated wetlands including aspects of biodiversity of the spring wetland areas. Our survey and investigations were motivated as input to the development of the *Talaroo Indigenous Protected Area Plan of Management* (Ewamian Aboriginal Corporation 2017) by the Ewamian Aboriginal Corporation and so discusses some of the important management issues for the site. Ewamian people are acknowledged as the traditional owners of Talaroo, and elders have described their own cultural values associated with the springs (Buhrich, personal communication).

Methods

Site description

The mound complex is approximately 5–10 m higher than the surrounding landscape, with an area of approximately 2400 m^2 (McGregor & Sendall 2017). The spring mound is largely devoid of terrestrial vegetation, with patches of grass in places where a small amount of soil has accumulated along the edges of open or flowing water. Six vents of different sizes discharge hot artesian water from the top of the mound surface, with several additional vents at the lower edges of the elevated mound discharging water into the wetland area located around Wallaby Creek (Fig. 2). The spring vents are characterised by pools of water of varying size (the largest being Wallaby Vent, Figs. 3 & 4), where upwelling water is confined by a rim of travertine. Several vents are inactive (i.e. Top Vent and Mid Vent) and do not have outflowing water, while others have discharge of groundwater indicated by movement of fine particles and bubbles. These active vents spill water over the travertine rims onto the mound surface.

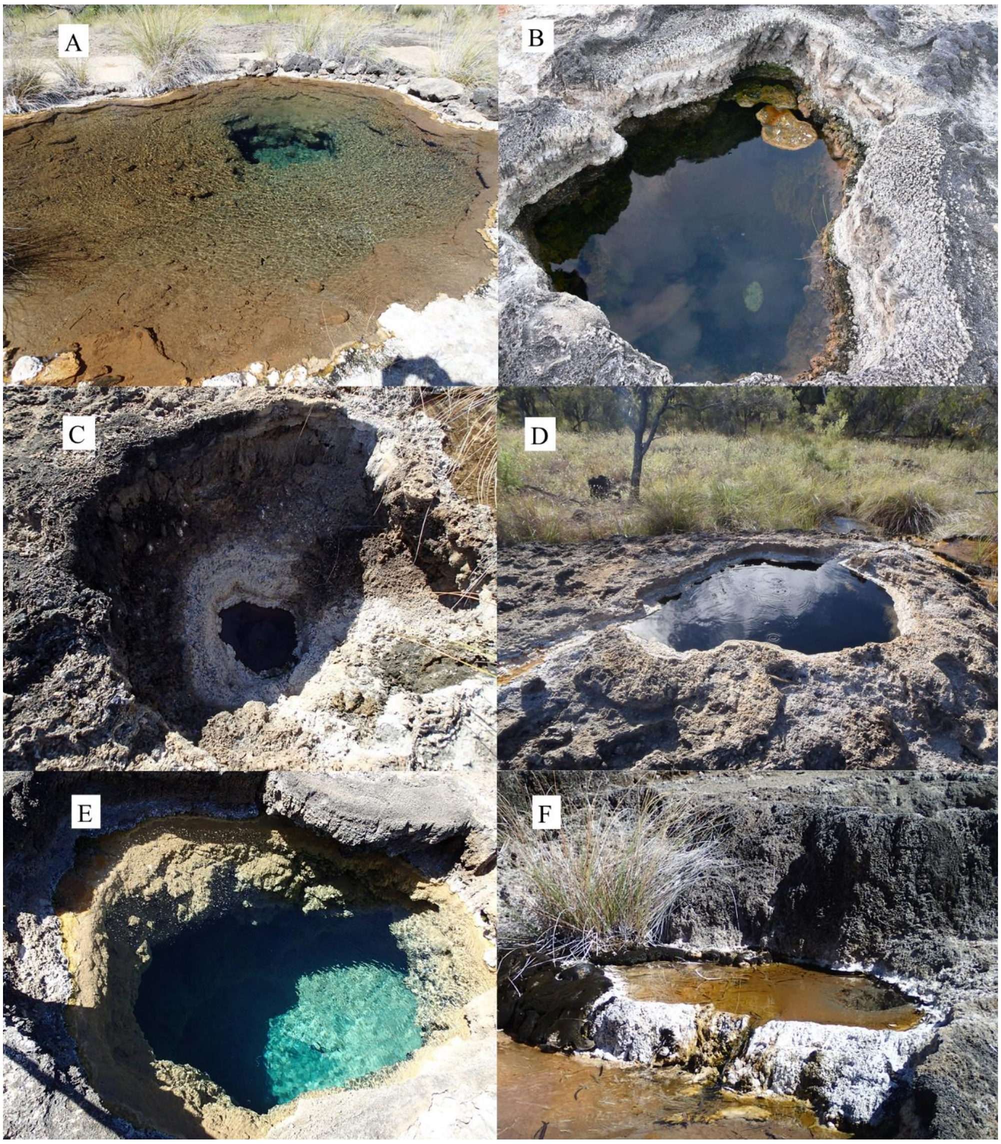

Figure 2. The six active spring vents at Talaroo: A - Wallaby Vent; B - Top Vent; C - Mid Vent; D - Low Vent; E - Hot Vent; F - Small Vent.

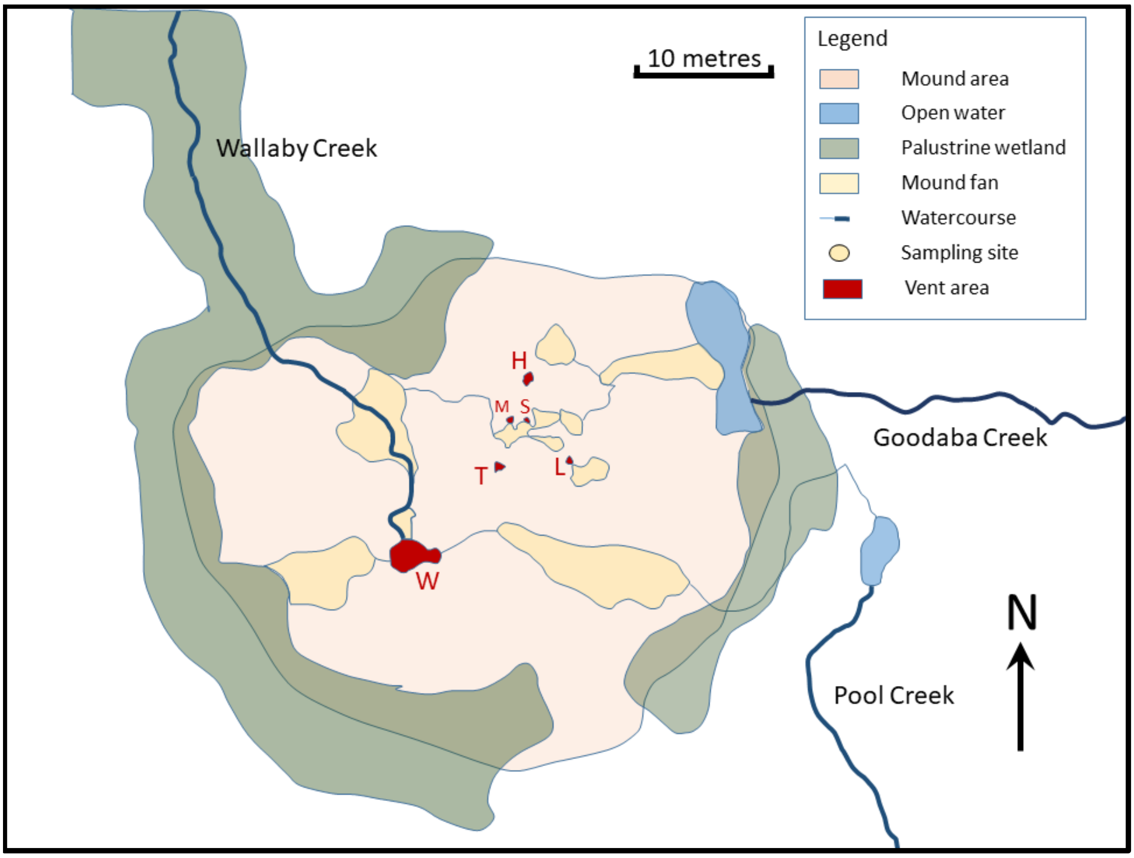

Figure 3. Schematic overlay of Talaroo spring mound area from drone photo (Fig. 4) with details of each feature. W – Wallaby Vent; T – Top Vent; M – Mid Vent; H – Hot Vent; S – Small Vent; L – Low Vent.

Figure 4. Drone photograph of the spring mound area. Note the distinctive yellow sulphur bacterial mats.

Field survey

The vents within the Talaroo Hot Springs complex and the drainage streams originating from the springs were sampled during May 2013 and further sampling in Wallaby Creek was undertaken during May 2015. Sampling included physical measures of the mound, water chemistry and biota.

Physical features

The dimensions and depth of the vents were recorded using a weighted tape measure and locations recorded with a Garmin GPS (model GPSMAP 60; Olathe, KS, USA). The authors visually surveyed the mound area and surrounding landscape and noted morphological characteristics of the travertine.

Water quality

Water temperature, pH, conductivity and total dissolved solids were measured in situ with a Hanna hand-held multiparameter meter (HI98129) in each of the spring vents. Water samples were collected from two of the vents; from Wallaby Creek and from the Einasleigh River upstream of the spring discharge streams, for laboratory analysis as per standard Queensland Government collection procedures (Department of Environment and Science 2018).

Algae and bacteria

Algae and bacteria were collected by hand and preserved in 1% buffered formaldehyde. These samples were analysed and taxonomically identified in the laboratory using a compound light microscope. Results of analyses on the terrace barrages of dark cyanobacteria have been reported separately in McGregor and Sendall (2017). Separate samples were collected for a benthic diatom survey.

Benthic diatoms were collected as a composite sample of scrapings from submerged surfaces (e.g. woody debris, rocky substrate and aquatic vegetation) and pipetted soft surface sediments. These samples collected were preserved in small vials with 100% ethanol. Diatoms were identified by the University of Adelaide. The process followed is described in Negus *et al*. (2019a), but includes samples being prepared initially by removing carbonates and organic matter and mounting the samples on microscope slides using a mounting medium (Naphrax®). The diatom community was identified using a minimum of 300 valves or ten transects. Observations of the diatom community's responses to changing water temperature along the outflowing water courses were reported in Negus *et al*. (2020).

Aquatic invertebrates

Aquatic invertebrates were sampled from the spring vents, pools and vent discharges where they aggregate into the outflowing streams. Biota from the spring outflows were collected by direct picking using forceps and pipettes to minimise damage to the delicate habitat in this area. Other samples were collected using a 5 m kick sample taken with a 250 µm mesh net and specimens were live picked from white plastic trays.

Invertebrate specimens were placed into labelled plastic vials and preserved in 100% ethanol for transportation. These were processed using a stereo-microscope. Specimens were identified to the taxonomic level of family, except for Chironomidae (identified to subfamily), Acarina and Oligochaeta (identified to subclass) and Ostracoda (identified to class). Specimens were then identified further where possible. Observations of the invertebrate community's responses to changing water temperature along the outflowing water courses are reported on in Negus *et al*. (2020).

Terrestrial invertebrates

Ground-dwelling terrestrial invertebrates (such as ants) were sampled on the spring mound in and around the spring vents and the mound outflow characterised by the yellow biofilm. Collecting was undertaken using six pitfall traps, set for approximately 24 hours. The traps consisted of 250 mL plastic jars, 77 mm high and 67 mm in diameter, filled with 70% ethanol as per Steward *et al*. (2011). The ethanol acted as a killing agent and preservative, and a drop of detergent was added to break the surface tension, preventing captured invertebrates from escaping. This method collected invertebrates that were potentially attracted to ethanol, or at least were not repelled by it, although ants have not been found to be attracted or repelled by ethanol (Greenslade & Greenslade 1971). A cover, made from a 15 cm diameter plastic plate, was positioned approximately 100 mm over each pitfall trap to prevent rain, leaf litter and other debris from blocking the trap and reducing its efficiency (Williams 1959). A label was placed inside each jar on retrieval, and the lids were screwed back on for transportation to the laboratory. Terrestrial invertebrates were identified in the laboratory with a stereomicroscope and counted. Ants (Formicidae) were identified to genus, and aphids (Aphididae), Coccoidea, and thrips (Thysanoptera) were not identified further.

Results

The pattern of water flow across the surface of the spring mound is quite complex and water also flows within the mound. Most obvious are the yellow fans where water provides habitat for a biofilm of bacteria and algae which form the distinctive colour. The biofilm creates an impervious porcelain-type coating on the travertine allowing water to flow over the surface and into the small watercourses that lead away from the mound or into surrounding palustrine wetlands. Where the biofilm has been disturbed or has not yet formed completely, the surface water flows have been observed to reduce and completely disappear, due to seepage losses into the porous travertine (i.e. sub-surface flows).

Another striking feature associated with directing water flow are the ridges (or barrages). The tops of many of these barrages are alive and form erect thick black felt-like mats of cyanobacteria which grow above the water surface. The barrages act as mini dams, creating shallow pools and ponds where other microflora and macroinvertebrates can exist. When flows are redirected, and the barrages become dry and devoid of life, they remain as hard travertine. Many travertine terraces and ridges (barrages) along the outer and lower areas of the mound are dry and are significantly larger (up to 50 cm) than those on the higher and currently active areas.

Paths of flow have changed over time, both through human intervention and natural changes in discharge patterns, including flow directions straight from the edge of the vents. This flow change was evident by the presence of the dry terraces and barrages (where water had clearly flowed previously) and remnant pools, notches grooved into vent rims and holes drilled through the side of vents. Recently filled wet terraces and pools were also seen with dead grass and no bacteria yet growing. Water flow has also been altered by previous landholders to feed the constructed swimming pool situated adjacent to the travertine mound and potentially the grooved notches in the vent rims. As such, all three streams flowing from the springs show signs of being physically altered in the recent past.

The chemical processes and various bacterial and algal species create the range of travertine microstructures. Some of these form miniature stromatolites, while others are complex and fine branching or reticulated rock formations (Fig. 5). Dead insects, reptiles and even mammals can be seen in the travertine (Figs. 6 & 7). These animals presumably died as a result of the water temperature exceeding their tolerances. Their bodies appear to be either sites of calcite nucleation or are coated by bacteria and mineralised, leading to fossilisation within the travertine rock; a potential lagerstätte (Allison 2018). The fossilisation of insects in the mound discharges indicate that the deposition of new carbonates on the mound is rapid. However, there is little to no deposition occurring in the outflowing watercourses which in contrast have slower, deeper and cooler water, which is not likely to be supersaturated or conducive to carbonate formation.

Outflowing creeks and surrounding wetlands

Several shallow pools of different sizes have formed around the edges of the mound and receive water from flow coming off the mound or from seepage within the travertine. Three discharge streams have formed by the outflowing water from the vents and historically these streams connected the springs complex with the Einasleigh River.

The vegetation community around the spring reflects the constant water supply. Five plant species have been recorded that are regionally uncommon (specifically associated with the springs) including the endangered Salt Pipewort (*Eriocaulon carsonii*) that is associated with GAB springs (Fensham *et al.* 2011) (Fig. 8). Salt Pipewort was observed around the eastern edge of the mound where moisture accumulates, and the larger shallow pools are situated. This area is also where Goodaba and Pool Creeks originate. Larger stands of Salt Pipewort were observed in the wetland surrounding Wallaby Creek and associated wetlands.

Some of the water that historically flowed through Pool Creek has been redirected into Goodaba Creek, which appears from air photos to have been

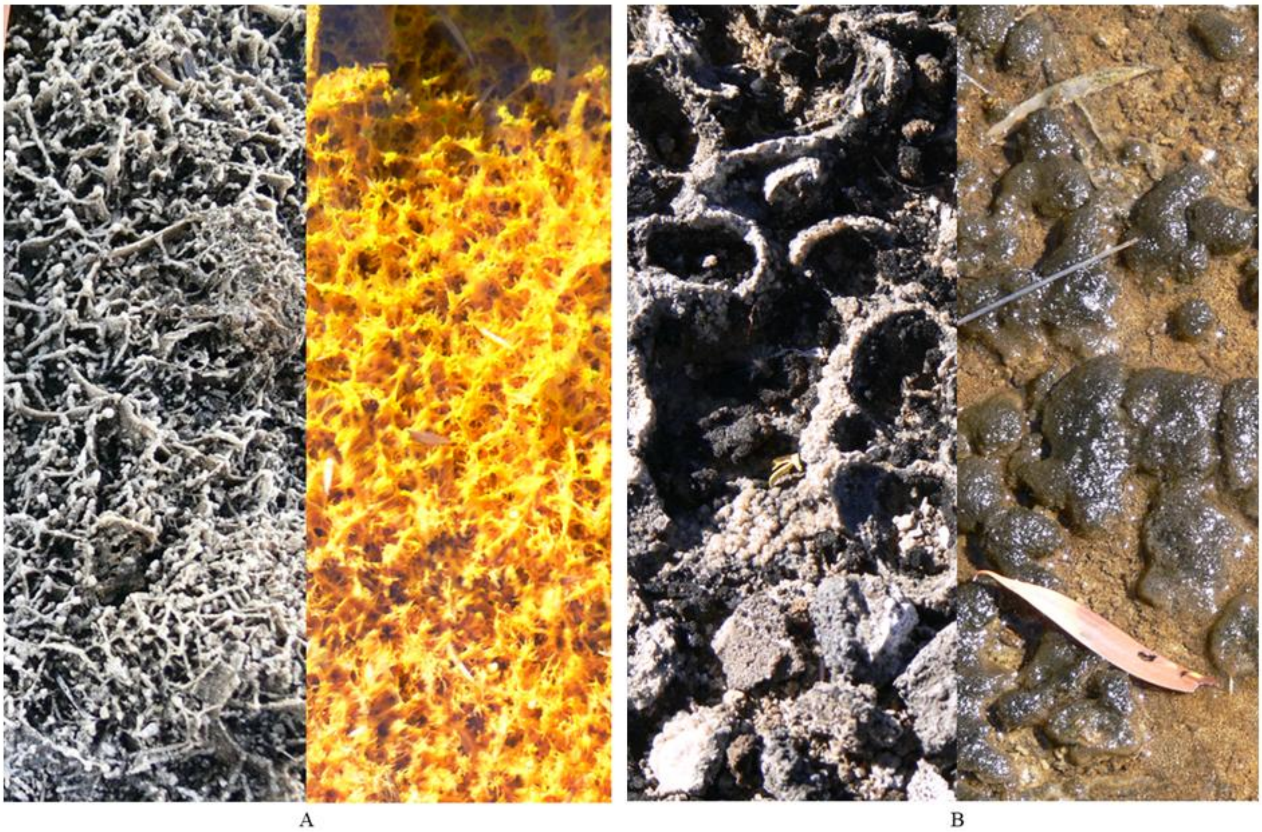

Figure 5. Two examples of fine travertine formations and the A - bacteria, and B - cyanobacteria that may have produced them by biomineralization.

Figure 6. An adult dragonfly being fossilised in the spring water.

Figure 7. A fossilised carnivorous mammal skull embedded in travertine.

Figure 8. A patch of Salt Pipewort (*Eriocaulon carsonii*) near one of the spring creeks.

a minor overflow gully in the past, probably operating only after rainfall. Goodaba Creek now receives most of the discharge and this may explain how it has become very deeply incised into a narrow gorge (>2 m deep, but only 30 cm wide) as it flows down the hill to the Einasleigh River. The deep incision of Goodaba Creek has created at least one small "waterfall" which would restrict movement of fish and other migratory species from the Einasleigh River.

Wallaby Creek originates from the largest vent (Wallaby Vent) after it has flowed down a large, terraced section and fans dominated by sulphur bacteria (Fig. 9). Vents along the western edge of the mound also flow into the wetlands associated with Wallaby Creek. Wallaby Creek has previously been redirected into a pipe near the spring's exclusion fence and the flow re-emerged in the adjacent paddock where it has created a small shallow *Typha* (bulrush) wetland. The high water velocity in the pipe prevented passage of biota. Wallaby Creek at this stage did not provide a connection between the spring complex and surrounding wetlands and the Einasleigh River.

The water flow has since been redirected from the pipe and reconnected with its former flow path which was still evident from the dark green line of vegetation to the Einasleigh River. Pool Creek appears to have been the major discharge stream in the past, but now receives very little flow. The water it currently receives has passed through the swimming pool prior to discharge.

Physical measures and water quality

Water chemistry from several vents has been summarised in McGregor and Sendall (2017) and from other locations within the watercourses in Negus *et al*. (2020). Water temperature in the vents ranged from 48.5–62.7°C (Table 1). The in-situ measures of the chemical characteristics of the vents were relatively consistent and the physical sizes of the vents ranged from the 1.1 m wide "Mid Vent" to the 8.6 m "Wallaby Vent" which also had the highest discharge (Table 1). The spring water was also notably high in fluoride and sulphate, which is very different from the water in the nearby Einasleigh River into which it discharges (Table 2). These results indicate that the river and the spring waters are from different sources.

Figure 9. A distinctive and colourful fan (composed of bacterial biofilm) that drains into Wallaby Creek. Note the black colonies of the cyanobacteria, *Ewamiania thermalis*.

Table 1. In-situ water quality and physical characteristics of the Talaroo spring vents. N/A = not available. Latitude and Longitude are in decimal degrees.

Vent	Latitude	Longitude	Depth (m)	Widest point (m)	Water temperature (°C)	Conductivity (µS/cm)	pH	Comments
Top	-18.11904	143.96136	1.10	1.55	48.5	1415	7.98	1 outflow; highest
Low	-18.11904	143.96143	2.10	1.35	61.0	1438	7.74	2 outflows
Mid	-18.11898	143.96135	N/A	1.1	62.7	N/A	N/A	No outflow; small and shallow
Hot	-18.11893	143.96138	2.10	2.35	61.0	N/A	N/A	1 outflow
Small	-18.11895	143.96144	0.30	0.6	58.9	1423	7.69	1 outflow; swirling particles in discharge
Wallaby	-18.1192	143.96123	2.00	8.6	62.6	1444	7.84	3 outflows; bubbles

Table 2. Water chemistry of the laboratory tested water samples collected at Talaroo and in the nearby Einasleigh River as a comparison.

		Site			
Component	**Units**	**Einasleigh River Loudon Bridge**	**Low Vent**	**Hot Vent**	**Wallaby Creek**
pH at 25°C		8.9	7.9	8	7.9
Conductivity at 25°C	µS/cm	295	1270	1270	1270
Total dissolved ions	mg/L	227	827	837	854
Total alkalinity as $CaCO_3$	mg/L	143	157	155	158
Total hardness as $CaCO_3$	mg/L	96	50	50	50
Sodium adsorption ratio		1.3	15.9	15.7	16.2
Residual alkalinity	meq/L	1	2.1	2.1	2.2
Calcium	mg/L	15.5	18.9	19.2	19.1
Magnesium	mg/L	13.8	0.5	0.5	0.6
Sodium	mg/L	28	257	256	262
Potassium	mg/L	4	6	6	6
Hydroxide as OH	mg/L	<2	<2	<2	<2
Carbonate as CO_3	mg/L	26	<3	<3	<3
Bicarbonate as HCO_3	mg/L	122	191	188	192
Sulphate as SO_4	mg/L	<1.00	91.1	93.8	97.5
Chloride as Cl	mg/L	16.7	255	262	267
Fluoride as F	mg/L	0.31	8.64	10.2	9
Phosphate phosphorus	mg/L	<0.05	<0.05	<0.05	<0.05
Nitrate nitrogen as N	mg/L	<0.50	<0.50	<0.50	<0.50
Bromide as Br	mg/L	<0.05	<0.05	<0.05	<0.05
Sum Cations	meq/L	3.2	12.3	12.3	12.6
Sum Anions	meq/L	3.4	12.7	13	13.2
Sum (Cation-Anion)	meq/L	-0.147	-0.388	-0.719	-0.646
Ion Balance	%	-2.2	-1.6	-2.8	-2.5

Algae and bacteria

The barrages formed by the cyanobacteria are present as circular to elongated dark blue-green to black tufted and pinnacle colonies. This species has been recently described as a new genus, *Ewamiania thermalis* (McGregor & Sendall, 2017) (Fig. 10). Sulphur bacteria are characteristic orange-yellow in colour and are a dominant feature along the vent discharges and fans of water flow across the mound (Fig. 9).

A total of 88 diatom species were recorded from across the mound complex (Appendix 1), and the community assemblage was significantly related to water temperature, with the hotter water temperatures closer to the vents associated with reduced richness and abundances (Negus *et al*. 2020). No diatom species were collected from the vents and this was attributed to the high temperatures likely being outside their thermal tolerances (Negus *et al*. 2020). The species *Rhopalodia musculus* was collected across most sites and was the only diatom species readily collected in the locations with hotter temperatures (i.e. > 40°C; Negus *et al*. 2020).

Aquatic invertebrates

A total of 56 taxa of aquatic invertebrates were recorded (Appendix 2) within the mound complex between the vents and the locations on the spring-fed creeks where water temperatures reached ambient conditions (Negus *et al*. 2020). Several taxa were identified at locations with high temperatures on the upper area of the mound fan, including three insects: a Libellulidae nymph (dragonfly); a Gerridae (water strider); Hydrophilidae adult (water scavenger beetle); and also Acarina (water mite); and Ostracoda (seed shrimp) (Negus *et al*. 2020).

Four families of the class Gastropoda were identified and three were identified to species. The specimens not identified further are from the family of Lymnaeidae. The specimens of the family Planorbidae were identified as *Gyraulus hesperus* and specimens of the family Bithyniidae (Fig. 11) were identified as *Gabbia affinis*. The specimens from the family Thiaridae were initially identified as the introduced species *Melanoides tuberculata*; however, instead these are now believed to be *Stenomelania denisoniensis* (a native species),

Figure 10. Shallow pools formed by cyanobacterial barrages.

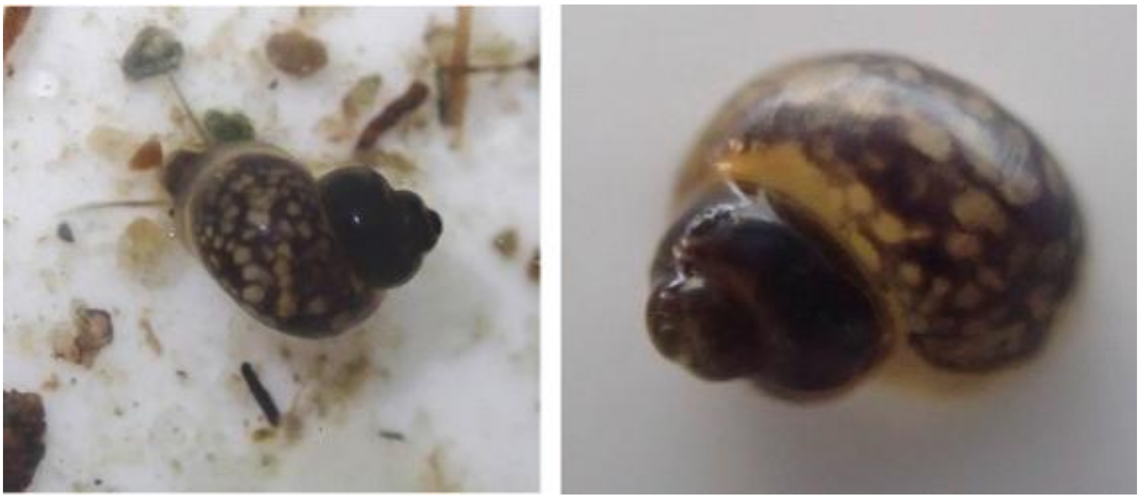

Figure 11. Aquatic snails identified as *Gabbia affinis* from the family Bithyniidae collected from outflow creeks.

which is virtually indistinguishable based on shell morphology (Glaubrecht *et al.* 2009).

Several species of Ostracoda were collected across the complex, including a species in the hotter temperatures of the mound fan and the outflow from Wallaby Vent. Based on morphology, this specimen was different to other specimens of Ostracoda collected in the cooler waters lower on the mound or in the small creeks (Negus *et al*. 2020). Another Ostracod species collected in Wallaby Creek had an interesting physical morphology and more detailed identification determined it to be *Cyprinotus cingalensis* (Fig. 12).

The species *Cyprinotus cingalensis* is distinct morphologically having overlapping valves with the outlying valve well developed dorsally into a flange (Karanovic 2012), which resembles a shark fin.

Terrestrial invertebrates

Eight terrestrial invertebrate taxa were collected from the area within 1 m of the vents or the warm creek water (Table 3). Five of these taxa were ants, including ants from the genus *Iridomyrmex*, which is recognised as Australia's most ecologically important ant genus, because of their strong interactions with other biota (Andersen 2000).

Figure 12. *Cyprinotus cingalensis* (Ostracoda) with large "finned" flanges collected in Wallaby Creek.

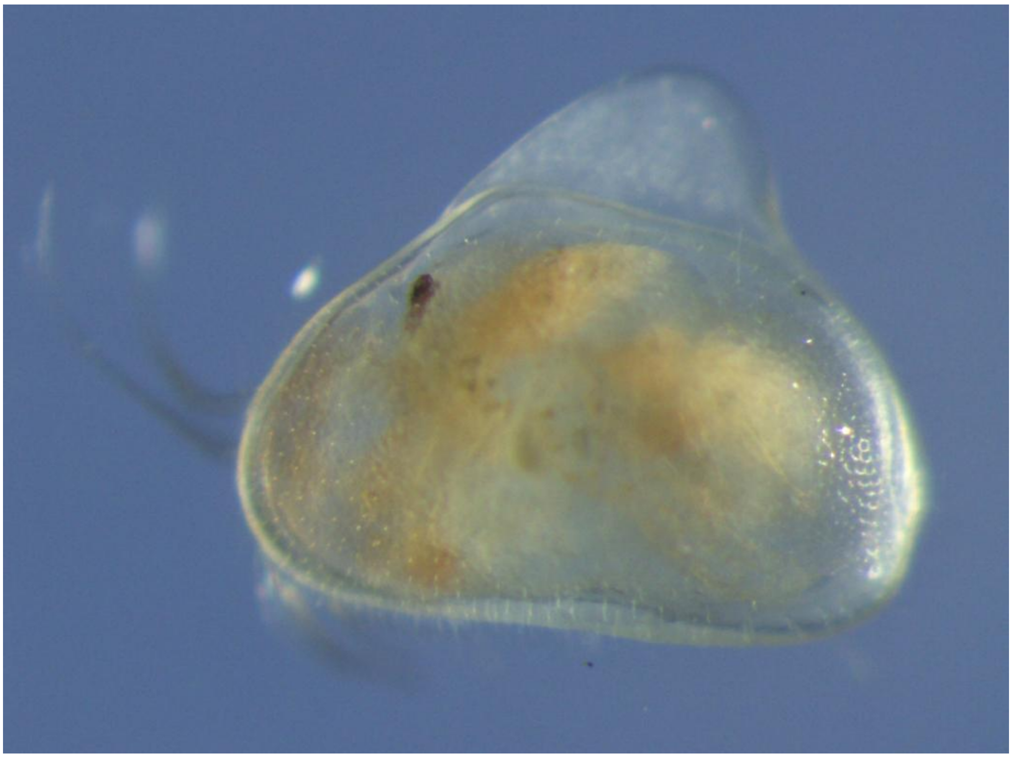

Table 3. List of terrestrial invertebrate taxa found at each sampling location.

Taxonomic group	Superfamily / Family / Subfamily	Taxon	*Wallaby Vent – trap 1*	*Wallaby Vent – trap 2*	*Wallaby outflow fan – trap 1 (Yellowbrick Road)*	*Wallaby outflow fan – trap 2 (Yellowbrick Road)*	*Top Vent – trap 1*	*Top Vent – trap 2*
Formicidae	Dolichoderinae	*Iridomyrmex* sp. (*anceps* group)	X	X	X	X	X	X
	Formicinae	*Paratrechina* sp.		X	X			X
	Myrmicinae	*Cardiocondyla* sp.					X	
	Myrmicinae	*Pheidole* sp.	X					
	Ponerinae	*Rhytidoponera* sp.		X	X			
Hemiptera	Aphididae		X					
	Coccoidea		X	X	X			X
Thysanoptera			X		X			X

Discussion

Development of the mound

The Talaroo Hot Spring mound is primarily composed of travertine (McGregor & Sendall 2017), which is a porous limestone (carbonate) that is chemically and biologically deposited by supersaturated waters such as mineral springs (Drysdale & Gillieson 1997; Pentecost 2005), especially thermal or hot springs such as these at Talaroo Station. The simple chemical process in the formation of travertine is that of carbonate deposition resulting from the reduction in pressure and de-gassing of carbon dioxide from solution into the atmosphere that occurs as the groundwater reaches the surface (Pentecost 2005). This loss of carbon dioxide and associated carbonate deposition can be rapid and is dependent on the concentration of CO_2 in the water, the water temperature (higher temperatures increase the rate of phase change), the amount of water, depth and turbulence (Pentecost 2005). In addition, nucleation of calcites and formation of calcium carbonate crystals are likely to occur in the boundary layers of the flow (where supersaturation is highest). It will also occur on organic material such as the biofilm and dead invertebrates such as the dragonflies at Talaroo, which provide advantageous conditions for this to occur (Drysdale & Gillieson 1997; Pentecost 2005). The highest rates of carbonate deposition occur in travertine hot springs (Pentecost 2005), and while the rate of carbonate deposition at Talaroo is currently unknown, it is likely to be high.

Cyanobacteria and sulphur bacteria have the resources they need to flourish in the Talaroo Hot Springs and contribute significantly to the carbonate precipitation. The processes that dominate biologically deposited carbonate are still contentious, with one argument being an active process such as those related to photosynthesis by algae and bacteria as a dominant factor, and the other a passive process with the trapping or capture of particles and provision of sites for calcite nucleation being dominant (Guidry & Chafetz 2003; Pentecost 2005). The processes involved with photosynthesis have been proposed as the cause of daily laminations produced in some travertines, but others have proposed that diurnal changes in environmental conditions are the cause (Takashima

& Kano 2008). Regardless of the processes involved, there are many types of depositional structures and facies that are produced by hot springs (Guidry & Chafetz 2003).

The causes of natural changes in the paths taken by flowing water remains unclear; however, it is likely that the accumulation of travertine, including the formation and growth of the stromatolite barrages and fluctuations in groundwater discharge, combine to slowly and imperceptibly adjust flow (Hammer *et al*. 2010). The large relict travertine barrages on the lower skirts of the mound are likely to have grown when the mound was lower in elevation or potentially when the discharge of water was higher and flow paths reached these areas. These larger barrages would have had stable flow for long periods of time to achieve these sizes. Flow paths naturally change but changes have greatly increased since the early colonial explorers, as bathing in deeper terraces which had different temperatures has been noted by early explorers of the springs (Onlooker 1921), although there is no mention of the barrages being alive or dead.

Water quality

Fluoride concentration of the spring waters is five times higher than the *Australian Drinking Water Guidelines* (i.e. 1.5 mg/L) (National Health and Medical Research Council 2011), but comparable to other hot springs in the region such as Innot Hot Springs (Lottermoser & Cleverley 2007; McGregor & Rasmussen 2008; McGregor & Sendall 2017). Fluoride is a natural element in water and is often added to water with naturally low levels to aid in dental health (National Health and Medical Research Council 2011); however, groundwaters can have naturally high levels outside of these drinking water guidelines, such as here at Talaroo. These levels can be detrimental to human health (i.e. causing dental and skeletal fluorosis) when at concentrations > 4 mg/ L (National Health and Medical Research Council 2011). The levels at Innot Hot Springs are attributed to source water from granite aquifers, which are heated and associated with volcanic activity (Lottermoser & Cleverley 2007; McGregor & Rasmussen 2008). Given the high fluoride concentrations and similar water temperatures to Innot Hot Springs, all indications are that the source water at Talaroo originates from the same heated granitic aquifer (McGregor & Sendall 2017).

Aquatic biota

Cyanobacteria and sulphur bacteria have been in existence for over three billion years and are the oldest photosynthetic organisms on earth (Sciuto & Moro 2015). These bacteria are common in thermal spring waters (Valeriani *et al*. 2018). The dominant cyanobacteria present in the spring complex are adapted to living in hot water and are typical of thermal springs worldwide. These include the genera *Scytonema*, *Synechococcus*, *Mastigiocladus* and *Haloleptolyngbya*. In addition, the black sponge-like cyanobacteria that form the barrages (*Ewamiania thermalis)* belongs to the family Scytonemataceae (McGregor & Sendall 2017). The cyanobacteria deposit the minerals dissolved in the water around their cells, creating the porous rock-like travertine formation using a similar process to formation of coral reefs by coral polyps.

Sulphur bacteria metabolism utilises a primitive form of photosynthesis, or alternatively they use chemosynthesis whereby the available sulphur or other chemical compounds are used as an energy source (Colman *et al*. 2016). The available chemical compounds will determine the presence of different microbial species (Colman *et al.* 2016). Bacteria that are involved in the reduction or oxidisation of sulphur dominate the microbial communities of hot springs (Colman *et al*. 2016). However, identifying what specific chemosynthetic processes that occur in any spring is difficult as the diversity of microbial communities in hot springs can be high and multiple species belonging to a range of process groups are likely to exist (e.g. Valeriani *et al*. 2018; Colman *et al*. 2019). Sulphur bacteria also occur in cave ecosystems and deep-sea hydrothermal vents, where photosynthesis may not occur due to the lack of sunlight (Hose *et al*. 2000; Zierenberg *et al*. 2000). Sulphur bacteria in cave ecosystems contribute to the development of the hard surfaces (Hose *et al*. 2000) and similarly are likely to contribute to the formation of the mound at Talaroo.

High water temperatures in and near the vents were likely above the upper thermal limit for multicellular (complex) life. As a result, no aquatic invertebrates or diatoms were collected from the hottest areas sampled in the spring vents (Negus *et al*. 2020). Insects also usually avoid sites with rapid travertine deposition, and although some have been found in hot springs elsewhere, they are not considered specialists to these habitats (Pentecost

2005). Most invertebrate specimens collected from the hotter areas of the mound were likely to be there temporarily and accessing these areas for food (Negus *et al*. 2020). However, the ostracod collected close to the spring vents in water temperatures hotter than 45^{0}C is likely to be a thermophile as it was very abundant and actively consuming dead insects in the hot temperatures (Negus *et al*. 2020). The diatom *Rhopalodia musculus* may also be considered a thermophile, but experimental studies are needed to confirm this (Negus *et al*. 2020).

The interestingly finned ostracod collected in Wallaby Creek, *Cyprinotus cingalensis*, is a species found across Southeast Asia with several records in Western Australia and a record in Queensland from 1889 (Karanovic 2008). The purpose of the unique "finned" flanges of these ostracods has not been determined but they could be used to help move at speed or through muddy areas. The fin in this species is not always as noticeable as fins seen in the specimens at Talaroo, but several synonymous species have been grouped based on physical characteristics (Karanovic 2008), indicating a variable species complex.

Two of the snail taxa, *Gyraulus hesperus* and specimens from the family Lymnaeidae, are common and widespread in northern Australia. Water with high calcium carbonate concentrations often support high numbers of aquatic snails, although, they are less likely to be found where calcium deposition occurs at high rates (Pentecost 2005). Indeed, this was the case at Talaroo where snails were not collected on the travertine mound where calcium deposition is highest, but were abundant downstream in the flowing watercourses where mineralisation was less evident. Snail presence may also be affected by the higher temperature of the water closer to the vents, where temperatures are likely to exceed their thermal tolerance (Negus *et al*. 2020).

Gabbia affinis is currently known from a relatively small area in northwest Queensland. The Talaroo specimens are smaller than typical specimens which indicate that this is possibly a different and undescribed species and therefore should be considered *Gabbia* sp. There are often many species of snails in springs, wetlands and small spring watercourses. Gastropod species found in springs are also generally unique to a location (Ponder & Clark 1990; Ponder & Walker 2003; Strong *et al*. 2008). This gastropod group can be difficult to identify, and molecular (genetic) studies are needed to confirm if this is correct.

Terrestrial invertebrates

We identified five genera of ants from the area within 1 m from the spring vents or warm spring water, all of which are species also collected by Franklin and Morrison (2019) who conducted a study of ants from Talaroo Station. They sampled tea tree swamp forest associated with the overflow of the thermal springs, so it is possible that their sampling occurred further down the mound amongst the tea trees, as also suggested by a photograph representing the tea tree forest in supplementary material (Franklin & Morrison 2019). Of the native ant genera we identified, Franklin and Morrison (2019) identified five *Iridomyrmex* species, two *Rhytidoponera* species, two *Cardiocondyla* species, and three *Pheidole* species from the forest associated with the thermal springs, and it is likely that these species are the same as the taxa we collected. Franklin & Morrison (2019) also identified the non-native *Paratrechina longicornis* (Black Crazy Ant), which belongs to a genus we also identified from our samples. Franklin & Morrison (2019) state that this species is widespread around human settlements in northern Queensland, and from 24 sites sampled on Talaroo Station they only recorded the species from the area around the springs.

Of the remaining terrestrial invertebrates collected, the Aphididae, Coccoidea and Thysanoptera are possibly incidental specimens blown into the traps. All three groups typically feed on plant material, of which there was little available on the ground where the traps were set.

Threats to Talaroo Hot Springs

The motivation for undertaking these investigations of the Talaroo spring mound was to gain a basic understanding of the biota and ecology related of the springs to assist in their ongoing management by the Ewamian Aboriginal Corporation. It is therefore pertinent to discuss the potential threats to this unique spring ecosystem and its biota. The threats to GAB springs are similar to those important for management of Talaroo Hot Springs. These include changes to groundwater hydrology from human use of the water; introduced species (both aquatic and terrestrial) such as Plague Minnows (*Gambusia holbrooki*), Feral Pigs (*Sus scrofa*) and Cane Toads (*Rhinella marina*), and the alteration of surface water habitats by the excavation, compaction or disturbance of substrates (Ponder & Clark 1990; Noble *et al*. 1998; Fensham *et al*. 2004, 2010, 2011; Clifford *et al*. 2020; Peck 2020).

The open pool of water surrounding Wallaby Vent was altered in 2015 to remove the modified rim of travertine used to direct flow. This altered the water flow on the mound and dried a large portion of the Wallaby Vent outflow fan and terraces. This unexpected event demonstrates the necessity to copy the slow, almost imperceptible character of flow changes that promote the growth of biofilms and the biomineralisation that produce the mound, when manipulating any parts of the mound likely to affect flow. Similar attempts to restore biofilms and calcite deposition of calcareous springs in Europe have failed (Grootjans *et al*. 2015), which highlights the need to delicately manage any potential alteration of surface water habitats and also the mound structure at Talaroo. The fact that terrestrial invertebrates inhabit the spring mound is another reason to reduce disturbance on the mound, including foot traffic by visitors.

Restoring the upstream connectivity of the Einasleigh River to the spring creeks and wetlands will allow for fish to move back into these habitats. However, this connectivity also brings the possibility of movement of potential pest species such as Plague Minnows into the spring wetlands. Plague Minnows have affected the biota of GAB spring ecosystems (Kerezsy & Fensham 2013), and will be a difficult pest to control in the palustrine wetlands surrounding the Talaroo spring mound if they establish.

At the time of surveying the springs a Feral Pig exclusion fence was in place around the spring mound and protected the wetlands surrounding the mound, including the small creeks. Feral Pigs damage wetlands by compacting soils, rooting and digging sediments and by the predation and consumption of biota (Marshall *et al*. 2020). Fences can be successful in protecting wetlands as long as the fences are consistently maintained (Negus *et al*. 2019b; Peck 2020). Maintenance of the fence will be essential to protect the wetland plants around the base of the mound, including the stands of Salt Pipewort which are known to be affected by pig rooting (Fensham *et al.* 2011).

Cane Toads, which are obvious in and around the springs complex, have been known to predate on small aquatic snails from springs even in the arid interior of Queensland (Clifford *et al*. 2020). This presents a likely difficult management issue for the spring complex given the proximity to the Einasleigh River where toads are abundant.

Springs that are not GAB discharge springs (like Talaroo) do not have formal conservation protection; however, this does not limit their conservation value. For example GAB recharge springs still have merit for conservation based on the composition of their vegetation (Fensham *et al*. 2004). In the case of Talaroo, the springs complex contains species that are found in few other places such as the Salt Pipewort (*Eriocaulon carsonii*), the cyanobacterial stromatolites *Ewamiania thermalis* and the snail *Gabbia* sp*.* Geologically, mound springs of this type are rare in Australia. Further biodiversity surveys are needed, especially for biota not already considered (e.g. Archaea) and also research into the taxonomy of the three species mentioned above and the ostracod, *Cyprinotus cingalensis*.

Conclusions

This study provides an initial survey focused on the physical features and aquatic biota of the Talaroo Hot Springs with the aim to support appropriate management and protection of this site. There are still many issues to research on the biogeochemical processes and biodiversity of this unique spring ecosystem that will contribute to an understanding and management of these springs. For example, one question has been pondered for many years, even dating back to the early colonial explorers:

> "I must leave the age of these springs to be determined by abler geologists than myself, though I am of opinion that it must be very great." (Botanist 1878)

Dating of the spring mound generally, and also individual travertine barrages, in combination with an investigation of the carbonate deposition rates and discharge variability, will contribute to the management of the spring mound. These two issues will provide an understanding of natural changes in flow paths and how quickly barrages and areas of the mound develop, which can be used to guide how rehabilitation of previously damaged areas can occur.

Talaroo represents a unique Australian geothermal site. Hot springs exist in Australia, for example the Paralana Hot Springs in South Australia (Brugger *et al*. 2005), and terraced springs have recently been discovered in Tasmania (Proemse *et al*. 2017); however, there are no known sites comparable to Talaroo, which has the combination of living travertine formation, thermal cyanobacterial and sulphur bacterial communities or with invertebrates living at such extreme temperatures. Scientific understanding of the ecology of hot springs is limited from Australian ecosystems. This lack of research is surprising as significant scientific discoveries have resulted from investigation of life at the extremes including the identification of Taq polymerase, an enzyme isolated from *Thermus aquaticus*, a cyanobacteria that was discovered in hot springs at Yellowstone National Park in the United States (Brock 1997). Taq polymerase is the basis of the polymerase chain reaction that became essential for DNA research (Brock 1997) and recently has been widely used in the testing of individuals for the severe acute respiratory syndrome coronavirus during the COVID-19 pandemic. Talaroo is amongst the relatively few geothermal systems on the planet where life in extreme environments can be studied and as such is a place of global significance.

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Appendix 1. List of diatom species collected from the Talaroo spring mound complex.

Achnanthes exigua	*Gomphonema angustum* var. *subminutum*	*Nitzschia dubia*
Achnanthidium minutissimum	*Gomphonema clavatum*	*Nitzschia elegantula*
Achnanthidium sp.	*Gomphonema parvulum*	*Nitzschia fossilis*
Amphora libyca	*Gomphonema pseudoaugar*	*Nitzschia frustulum*
Anomoeneis sphaerophora	*Lemnicola hungarica*	*Nitzschia gessneri*
Aulacoseira distans	*Lemnicola hungarica* (small)	*Nitzschia inconspicua*
Brachysira brachysira	*Luticola goeppertiana*	*Nitzschia linearis*
Brachysira styriaca	*Luticola mutica*	*Nitzschia microcephala*
Cocconeis placentula	*Mastogloia elliptica*	*Nitzschia nana*
Craticula cuspidata	*Mastogloia smithii*	*Nitzschia palea* (thin)
Craticula halophila	*Mayamaea atomus*	*Nitzschia paleaceae*
Craticula riparia	*Meridion circulare*	*Nitzschia sinuata* var. *tabellaria*
Ctenophora pulchella	*Navicula capitatoradiata*	*Nitzschia subacicularis*
Cymbella cistula	*Navicula cryptotenella*	*Pinnularia gibba*
Diatomella balfouriana	*Navicula difficillima*	*Pinnularia intermedia*
Diploneis elliptica	*Navicula heimansoides*	*Pinnularia interrupta*
Diploneis ovalis	*Navicula leptostriata*	*Pinnularia legumen*
Diploneis parma	*Navicula praeterita*	*Pinnularia microstauron*
Diploneis smithii	*Navicula schroeterii*	*Pinnularia obtusa*
Diploneis smithii var. *rhombica*	*Navicula soehrensis* var. *muscicola*	*Pinnularia* spp.
Diploneis subovalis	*Navicula tripunctata*	*Placoneis elginensis*
Entomoneis alata	*Navicula vandamii*	*Planothidium granum*
Eolimna subminuscula	*Navicula veneta*	*Pleurosigma attenuatum*
Epithemia adnata	*Navicula viridula* var. *germanii*	*Psammothidium saccula*
Eunotia bilunaris	*Navicula viridula* var. *linearis*	*Reimeria sinuata*
Eunotia exigua	*Nitzschia accula*	*Rhopalodia brebissonii*
Eunotia faba	*Nitzschia acicularis*	*Rhopalodia musculus*
Eunotia incisa	*Nitzschia agnita*	*Synedra ulna*
Eunotia minor	*Nitzschia braunii*	
Gomphonema angustum	*Nitzschia capitellata*	

Appendix 2. List of aquatic invertebrate taxa sampled at the Talaroo spring complex.

Acarina	Epiproctophora	Leptoceridae	Pleidae
Aeshnidae	Gastropoda unknown	Libellulidae	Protoneuridae
Baetidae	Gelastocoridae	Lymnaeidae	*Pseudocordulia*
Caenidae	Gerridae	Mesoveliidae	Richardsonianidae
Ceratopogonidae	Gomphidae	Naucoridae	Simuliidae
Coenagrionidae	Hebridae	Nematoda	Stratiomyidae
Collembola	Hemicorduliidae	Nepidae	Tabanidae
Caldocera	Hirudinea	Noteridae	Thiaridae
Copepoda	Hydraenidae	Notonectidae	Veliidae
Corixidae	Bithyniidae	Ochteridae	Chironominae
Crambidae	Hydrochidae	Oligochaeta	Tanypodinae
Culicidae	Hydrophilidae	Ostracoda	Orthocladiinae
Dytiscidae	Hydroptilidae	Parasticidae	Urothemistidae
Ephydridae	Hydropsychidae	Planorbidae	Thaumaleidae