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REPORT

Elucidating sources to aridland Dalhousie Springs in the Great Artesian Basin (Australia) to inform conservation

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Abstract

Dalhousie Springs is the largest spring complex in the western Great Artesian Basin (GAB), Australia. Aridland springs like Dalhousie provide the only aquatic habitats in regions lacking surface water and are globally threatened by unsustainable groundwater development. Groundwater use in the more densely populated eastern GAB historically was higher than that in the western GAB, where groundwater is primarily used for ranching; however, economically important mineral and energy industries have increased groundwater use. Throughout the western GAB, groundwater development has reduced spring discharge and artesian head. Of concern are potential impacts on spring discharge from future pumping; thus, an understanding of groundwater sources to springs is needed to develop effective groundwater management strategies that maintain spring flow. The generally accepted hydrogeologic model suggests Dalhousie Springs discharge is entirely composed of Jurassic-Cretaceous aquifer contributions; however, this study improves understanding of Dalhousie Springs by integrating new hydrogeologic and hydrochemical data with historic, previously unpublished petroleum exploration well-test data. A thermal model is used to estimate potential aquifer source depths of 270–802 m. $^{87}Sr/^{86}Sr > 0.715$ suggests water–rock interaction with radiogenic basement and the importance of faults for vertical fluid transfer across multiple aquifers. Results show that Dalhousie Springs discharge is sourced by the previously unreported Permian Crown Point Formation and the Jurassic-Cretaceous aquifer. Mitigating effects of future groundwater development on Dalhousie Springs requires managing groundwater from Jurassic-Cretaceous and Permian aquifers to preserve near-spring potentiometric surfaces. Expanded multiple-environmental-tracer monitoring could be used to further refine groundwater sources to Dalhousie Springs.

Keywords Australia · Groundwater management · Spring source assessment · Thermal modeling · Groundwater protection

Introduction

The massive Great Artesian Basin (GAB) aquifer extends across ~20% of Australia and provides critical water supplies to economically important mines, ranches, and towns in an otherwise arid landscape (Fig. 1; Ransley et al. 2015). Over 600 springs in 11 major groups discharge from the GAB, with Dalhousie Springs (Dalhousie) being the largest spring complex in the western GAB (Fig. 2; Habermehl 1982). Dalhousie, as with other springs in South Australia (Keppel et al. 2011, 2012), is composed of travertine mound-form springs (Fig. 3b; following nomenclature of Springer and Stevens 2009) with over 145 individual vents (White et al. 2013). Dalhousie is thought to account for ~40% of GAB spring discharge (Habermehl 1982) and supports groundwater-dependent ecosystems covering ~200 km^2 (White et al. 2013), with vegetation from the largest spring extending ~10 km (White et al. 2016). The immense size and

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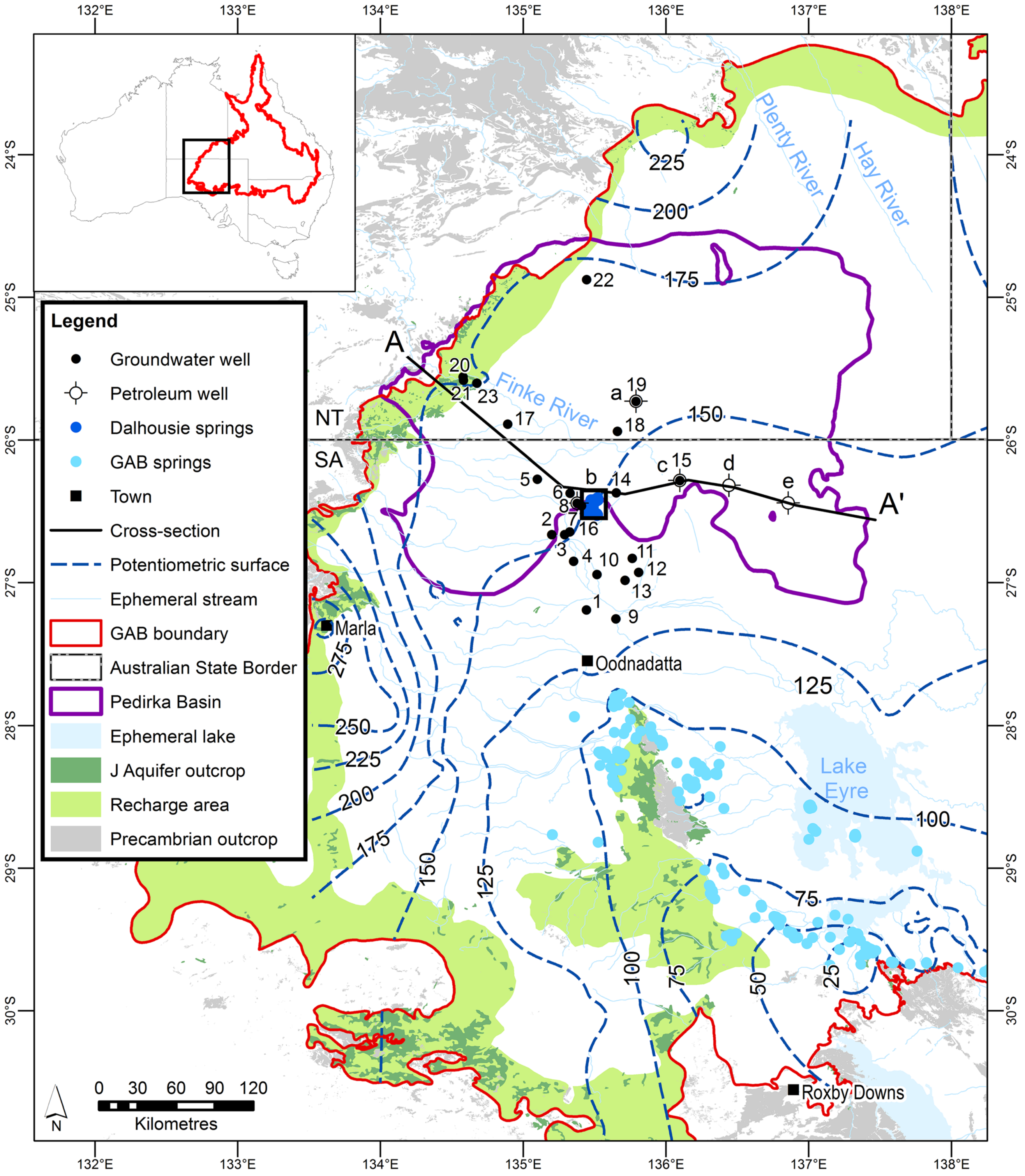


Fig. 1 Dalhousie Springs and western margin of the Great Artesian Basin, Australia. Dalhousie Springs is located at the South Australia-Northern Territory border (see inset; black square indicates extent of Fig. 3). Surface geology is composed primarily of sedimentary rocks of Jurassic–Quaternary age (Geoscience Australia 2012). To the west of the GAB boundary where Jurassic–Cretaceous rocks crop out (red line), surface geology is primarily composed of Precambrian–Paleozoic rocks. Line A–A′ shows the location of the hydrogeologic conceptual cross section (Fig. 9). Legend: Petroleum exploration wells: **a** McDills 1. **b** Mount Crispe 1. **c** Purni 1. **d** Mokari 1. **e** Macumba. Water wells: (1) Alberga; (2) Pedirka Siding; (3) Hamilton Creek; (4) Crans Grave; (5) Bloods Creek; (6) Opossum; (7) 3 O'Clock Creek; (8) Mount Crispe 1; (9) Macumba HS Bore 2; (10) Stevensons; (11) Apperinna Bore 2; (12) Onqueedinna 1; (13) Horseshoe; (14) Witcherrie 1; (15) Purni; (16) Junction; (17) Charlotte Waters; (18) Anacoora; (19) McDills (completed as water well); (20) Town Bore Apatula; (21) Apatula Community; (22) Andado Station; (23) New Crown Station. Table S1 of the electronic supplementary material (ESM) lists detailed hydrochemical data

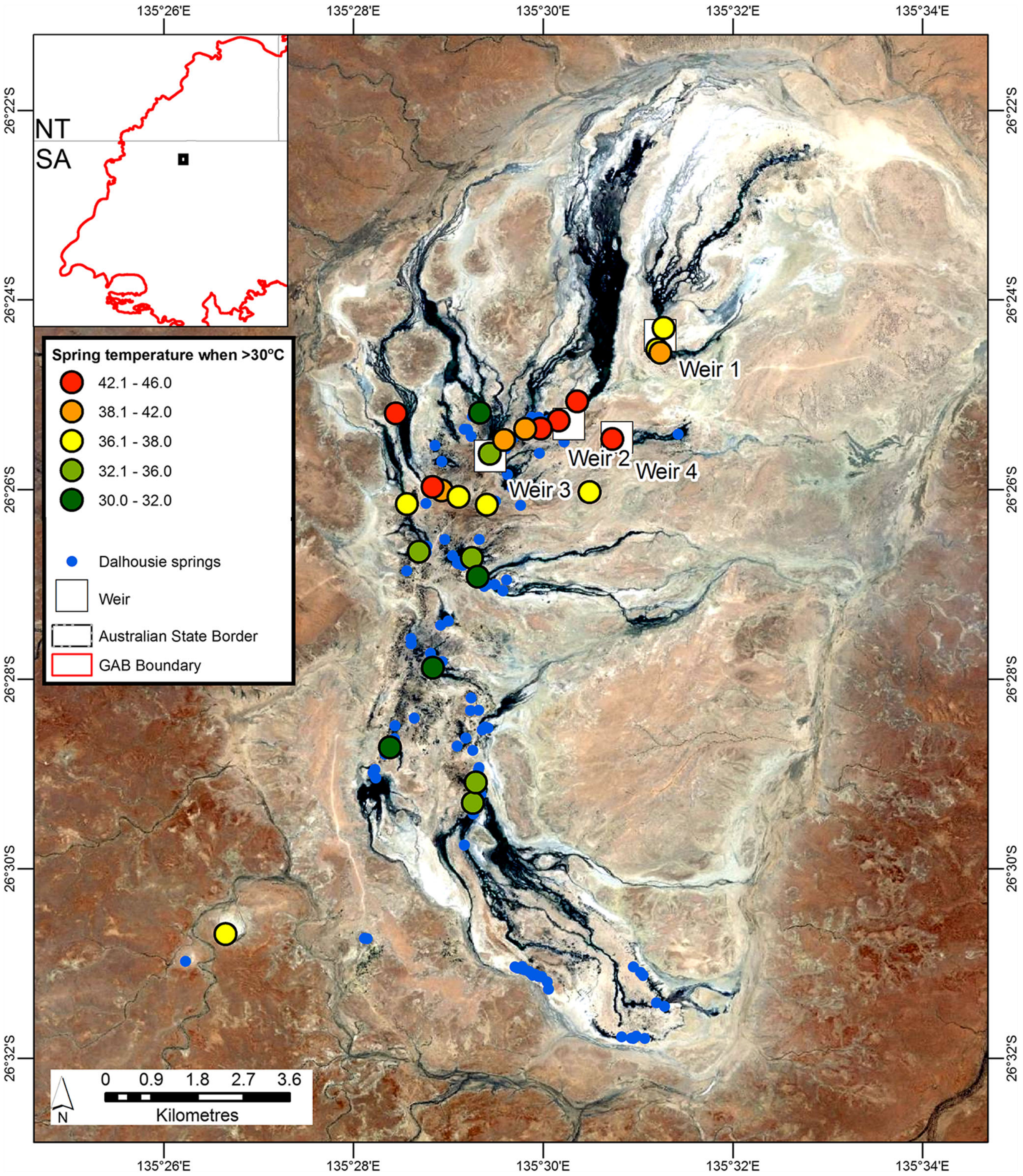


Fig. 2 Dalhousie Springs temperature measurements. Dalhousie Springs is situated in a breached anticline where the Cretaceous Bulldog Shale confining bed and overlying sediments have eroded. Only spring temperatures >30 °C (more likely to be actual spring vent temperatures) are shown (Table 1). Groundwater-dependent vegetation, called "spring tails", appears as dark green areas. Long-term discharge measurement locations at weirs are shown as black rectangles (Mark Keppel, Department of Environment, Water and Natural Resources, South Australian Government, Adelaide, Australia, unpublished data, 2019; see also Fig. 5). Background is a high-resolution multispectral aerial photo (Lewis and White 2013; White and Lewis 2011)

geographic isolation of aquatic and terrestrial habitats of the Dalhousie ecosystem permitted evolution of high taxonomic richness and diversity, with taxa quite dissimilar to other GAB springs (Kodric-Brown and Brown 2007; Rossini et al. 2018; Zeider and Ponder 1989).

Dalhousie and other desert spring systems globally provide important ecological benefits, as they are often the only perennial aquatic environments maintaining biodiversity in otherwise arid areas (Davis et al. 2017; Hunter 2017). However, aridland springs are threatened by groundwater development and other anthropogenic threats because of their relatively small size and isolation. Species that inhabit aridland spring ecosystems are particularly at risk because they are found in only a few locations (i.e., low redundancy), and if a spring dries completely, the species cannot bounce back, even if water returns (i.e., low resiliency, following nomenclature of Smith et al. 2018); however, compared to larger aquatic ecosystems, conservation of desert springs may be a more tractable challenge (Davis et al. 2017). Dalhousie is culturally important to the Lower Southern Arrente peoples, who refer to the area as *Irrwanyere*, or "healing water." Determining the source of groundwater to the springs is essential to its conservation and is the main objective of this study.

Site physiography

Dalhousie is located in central Australia near the South Australia and Northern Territory border, ~350 km south of Alice Springs, ~1,000 km north of Adelaide, and near the western margin of the GAB (Fig. 1). Mean annual precipitation is ~175 mm/year (BOM 2010) and maximum annual temperature is 36–39 °C during summer and 18–24 °C in winter (Allan 1990), resulting in a semi-arid to arid climate. Land surface elevation ranges from ~400 to ~10 m below sea level at Lake Eyre. Ephemeral streams flow following summer monsoonal precipitation or winter frontal precipitation (Fig. 3f; Costelloe et al. 2007; McMahon et al. 2005); however, low gradients and high evaporation typically limit stream flow to headwater and middle reaches (Habermehl 1980).

Dalhousie is sited in a topographic depression along the axis of the breached Dalhousie Anticline (45 km by 35 km; Fig. 2). Pools and lakes (Fig. 3a) are associated with the ovoid-shaped central spring complex (20 km × 10 km; Krieg 1985, 1989), which is drained by Spring Creek and flows ephemerally for ~50 km before terminating in the Simpson Desert.

Geology

Dalhousie regional geology includes several stacked sedimentary basins that range in age from Neoproterozoic to Cenozoic, with basin names corresponding to different ages of stratigraphic units (i.e., Adelaide Geosyncline, Western Warburton Basin, Southeast Amadeus Basin, Pedirka Basin, Simpson Basin, Eromanga Basin, Lake Eyre Basin) (Figs. 1 and 4; Drexel and Preiss 1995; Drexel et al. 1993; Geoscience Australia 2012; Krieg 1985, 1989). This study focuses on Carboniferous–Cretaceous strata of the Pedirka and Eromanga basins because of their hydrogeologic importance (discussed in the next section). Surface geology generally includes Cretaceous and Cenozoic rocks east of the GAB margin, with Proterozoic and Paleozoic rocks exposed west of the GAB margin (Geoscience Australia 2012).

Two formations compose the shallow, foreland, intracratonic Pedirka Basin (Figs. 1 and 4; Middleton et al. 2005): The Carboniferous–Permian Crown Point Formation Sandstone is made up of siltstone and sandy–pebbly diamictite (Fig. 3e; Wells et al. 1966; Youngs 1975). The Permian Purni Formation (Youngs 1975) is divided into three facies with differing amounts of sandstone, shale, and coal (Wells et al. 1966). The lowest contains carbonaceous shale; the middle is a fining-upward, cross-bedded sandstone with minor shale and coal; and the upper is a fine-grained, silty sandstone.

The Pedirka Basin is overlain by terrigenous and marine sediments of the Eromanga Basin. The Early Jurassic–Early Cretaceous Algebuckina Sandstone (known as the *De Souza Sandstone* in the Northern Territory) is a fine- to coarse-grained, cross-bedded, fluvial, poorly consolidated, quartzose sandstone with pebble and coal layers, and minor shale and siltstone lenses (Fig. 3d; Krieg 1985; Wopfner et al. 1970). The Early Cretaceous Cadna-owie Formation includes a lower unit of fine- to medium-grained, well-sorted, porous, quartzose, cross-bedded/massive sandstone (Fig. 3c; Krieg 1985; Moore and Pitt 1982). The Early Cretaceous Bulldog Shale (Rumbalara Shale in the Northern Territory) is a bioturbated, fossiliferous, shaley, marine mudstone with thin parallel bedding and micaceous silt to very fine-grained sandstone interbeds (Freytag 1966). The Bulldog Shale is regionally extensive throughout the Eromanga Basin; however, it is eroded from the Dalhousie Anticline (Fig. 2).

Many springs are associated with Cretaceous Cadna-owie Formation exposures (Fig. 2). The rim of the breached anticline lies ~60 m above modern and relict spring-related sedimentation modified by fluvial activity (Fig. 3b). Within ~5 km of and higher than present-day springs are at least two levels of Quaternary travertines (Krieg 1985, 1986). Sedimentary morphologies of Dalhousie platform travertines resemble those formed in lakes, whereas mound-shaped deposits likely formed from single pools and vents similar to mound structures of Lake Eyre (Fig. 1; Keppel et al. 2011). Travertine dating using U-Th series suggests long-lived, episodic spring discharge since at least ~465 ka (close to the method's limit; Priestley et al. 2018), and stratigraphic relationships place the oldest Dalhousie spring activity at 2–1 Ma (Krieg 1985).

Fig. 3 Dalhousie Springs, aquifer outcrops, and Finke River ephemeral flow. **a** Main Spring at Dalhousie Springs. **b** Typical spring discharge vegetation and older travertine at Dalhousie Springs (mound at right of photo). **c** Fractured outcrop of Cadna-owie Formation in Dalhousie Anticline. **d** Algebuckina Formation in recharge zone along western margin of GAB near Finke, Northern Territory; **e** Crown Point Formation in recharge zone ~25 km west of Finke, Northern Territory; **f** Ephemeral flow of Finke River ~30 km west of Finke, Northern Territory in November 2008 (for Finke River historical discharge, see Fulton et al. 2013)

Hydrogeology

Aquifers and aquitards

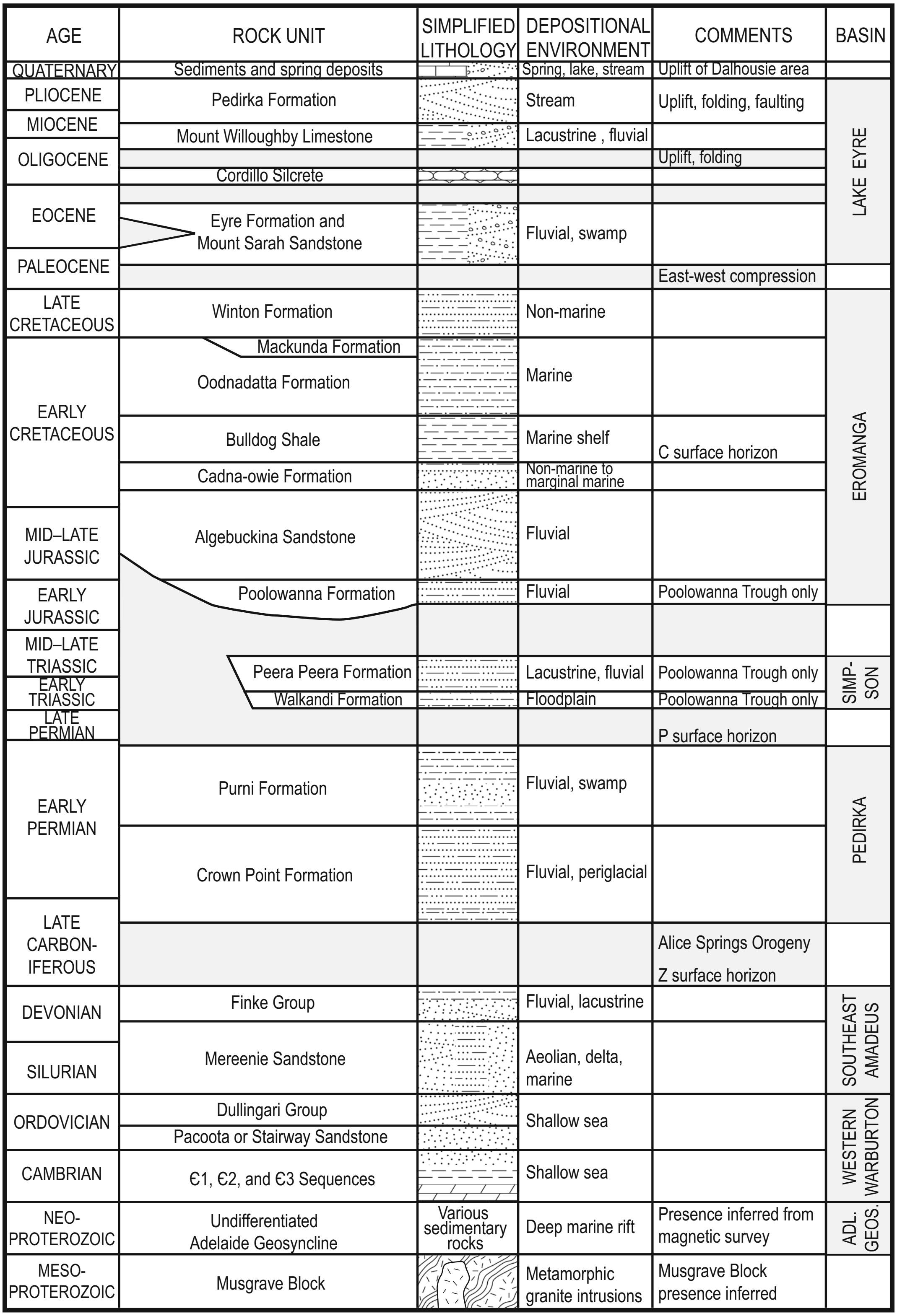
Jurassic–Cretaceous sandstone units of the Algebuckina Sandstone and the Cadna-owie Formation (generally known as the *J Aquifer* or *J-K Aquifer*) are considered the main source of springs at Dalhousie (Habermehl 1980). Erosion of the Bulldog Shale—the primary GAB confining bed—along the crest of the Dalhousie Anticline permits discharge from the J-K Aquifer via the Cadna-owie Formation. A detailed schematic of hydrostratigraphy for the western margin of the GAB is provided in Keppel et al. (2013) and in Fig. 4. The deeper Purni Formation and Crown Point Formation were not historically considered aquifers (Habermehl 1980 and later works); however, this study evaluates their input to Dalhousie discharge.

Potentiometric surface, recharge, and discharge

A density-corrected regional potentiometric surface map (Fig. 1; from Ransley et al. 2015) reveals generalized regional groundwater flow from postulated recharge zones where Jurassic–Cretaceous-age aquifer units crop out along the western GAB margin to discharge areas at topographic lows of Lake Eyre and other salt lakes (Fig. 1). However, monitoring wells drilled in close proximity to ephemeral channels suggest that modern-day groundwater recharge only occurs along the Finke and Plenty rivers (Figs. 1 and 3f; Fulton et al. 2013).

Spring discharge rates and temperature

Dalhousie is the largest western GAB spring complex, with discharge ranging from <1 L/s to ~160 L/s (~5 GL/year) at Main Spring (Fig. 3a; Habermehl 1982; Radke et al. 2000). Erosion of the Cretaceous Bulldog Shale confining bed and overlying sediments (red-colored land surface in Fig. 2) permits discharge through fractures in the exposed Cadna-owie Formation (Fig. 3c), forming dozens of springs (Figs. 2 and 3a,b). Spring discharge measured at weirs was relatively stable from late 1997 to mid-2012 (Fig. 5). Spring-vent temperature measurements range from ~29 to 46 °C (Fig. 2; Table 1; Radke et al. 2000; Smith 1989). Warmer springs are found to the north along a northeast trend that may reflect springs emerging along faults in the core of the anticline. Springs get cooler to the south (Department for Water 2010; Radke et al. 2000; Smith 1989) and approach mean annual air temperature (approximately 20 °C), suggesting cooling from vent to sample location. A high-resolution multispectral image collected as part of efforts to develop remote-sensing techniques



AGE	ROCK UNIT	SIMPLIFIED LITHOLOGY	DEPOSITIONAL ENVIRONMENT	COMMENTS	BASIN
QUATERNARY	Sediments and spring deposits		Spring, lake, stream	Uplift of Dalhousie area	
PLIOCENE	Pedirka Formation		Stream	Uplift, folding, faulting	LAKE EYRE
MIOCENE	Mount Willoughby Limestone		Lacustrine , fluvial		
OLIGOCENE				Uplift, folding	
	Cordillo Silcrete				
EOCENE	Eyre Formation and Mount Sarah Sandstone		Fluvial, swamp		
PALEOCENE				East-west compression	
LATE CRETACEOUS	Winton Formation		Non-marine		EROMANGA
EARLY CRETACEOUS	Mackunda Formation Oodnadatta Formation		Marine		
	Bulldog Shale		Marine shelf	C surface horizon	
	Cadna-owie Formation		Non-marine to marginal marine		
MID–LATE JURASSIC	Algebuckina Sandstone		Fluvial		
EARLY JURASSIC	Poolowanna Formation		Fluvial	Poolowanna Trough only	
MID–LATE TRIASSIC	Peera Peera Formation		Lacustrine, fluvial	Poolowanna Trough only	SIMP-SON
EARLY TRIASSIC	Walkandi Formation		Floodplain	Poolowanna Trough only	
LATE PERMIAN				P surface horizon	
EARLY PERMIAN	Purni Formation		Fluvial, swamp		PEDIRKA
	Crown Point Formation		Fluvial, periglacial		
LATE CARBON-IFEROUS				Alice Springs Orogeny Z surface horizon	
DEVONIAN	Finke Group		Fluvial, lacustrine		SOUTHEAST AMADEUS
SILURIAN	Mereenie Sandstone		Aeolian, delta, marine		
ORDOVICIAN	Dullingari Group Pacoota or Stairway Sandstone		Shallow sea		WESTERN WARBURTON
CAMBRIAN	Є1, Є2, and Є3 Sequences		Shallow sea		
NEO-PROTEROZOIC	Undifferentiated Adelaide Geosyncline	Various sedimentary rocks	Deep marine rift	Presence inferred from magnetic survey	ADL. GEOS.
MESO-PROTEROZOIC	Musgrave Block		Metamorphic granite intrusions	Musgrave Block presence inferred	

Fig. 4 Stratigraphic column of western margin of Great Artesian Basin. The Algebuckina Sandstone and Cadna-owie Formation (Fig. 3d,e, respectively) are considered primary aquifers providing flows to Dalhousie Springs and confined by the Bulldog Shale; however, this study suggests that the Purni and Crown Point formations (Fig. 3e) also discharge to the springs (after Carne and Alexander 1997 using information from Drexel and Preiss 1995; Drexel et al. 1993; Krieg 1985, 1986). In the Northern Territory, the Algebuckina Sandstone is known as the "De Souza Sandstone" and the Bulldog Shale as the "Rumbalara Shale"

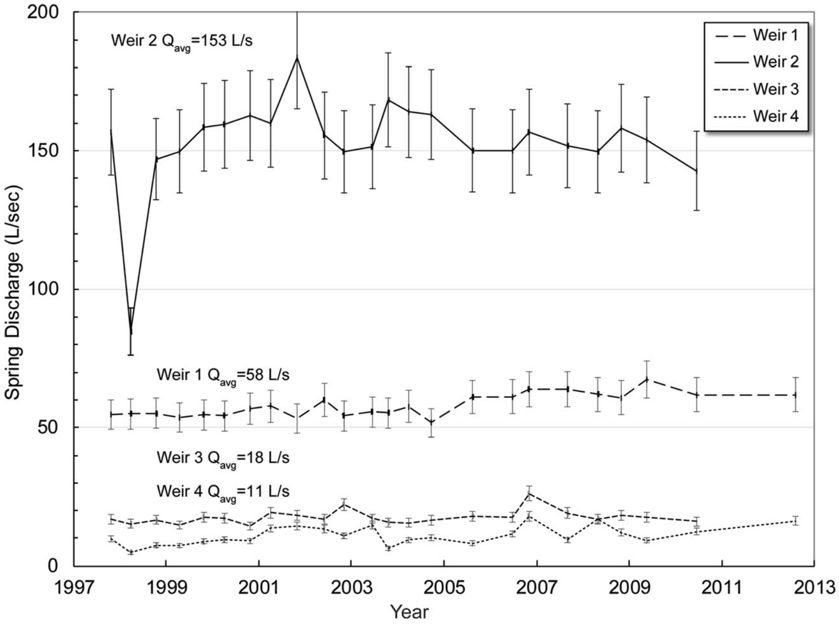


Fig. 5 Selected discharge at Dalhousie Springs. Long-term discharge measured with weirs at selected larger springs (locations shown on Fig. 2; South Australia Department of Environment and Water, "Dalhousie Springs weir gauging"). Unpublished dataset provided by Mark Keppel (2019). Bars indicate ±10% to account for field sampling uncertainty. Overall trend of Dalhousie Main Spring (Weir 2) shows a possible decrease in discharge since 2000

to monitor temporal changes in spring-dependent ecosystems (Lewis and White 2013; White and Lewis 2011) reveals groundwater-dependent vegetation (dark green in Fig. 2) in spring tails up to 5 km long.

Structural controls on Dalhousie Springs

Dalhousie is situated within a region of complex crustal and lithospheric weakness along a rifted passive continental margin (Kennet et al. 2004; Shaw et al. 1991). Intersecting northwest- and northeast-trending structures in the study area are representative of normal faults inverted during contractional events. Such structures have been documented to produce complex bending monoclines and intersecting fault-and-fold networks in similar structural settings (Martel et al. 1989). The Pedirka Basin (Fig. 1) is bisected into the western Eringa and eastern Madigan troughs by the McDills-Dalhousie Ridge, which is a major north–northeast trending, folded and faulted structural ridge composed of Devonian and older rocks (Drexel and Preiss 1995). Seismic surveys through Dalhousie confirmed the presence of faults in close proximity to springs (Aldam and Kuang 1989). Normal faults were reactivated in the middle–late Carboniferous to create compressional, high-angle, north-northeast striking reverse faults (Drexel and Preiss 1995; Youngs 1976). During the Oligocene–Miocene, reverse faults were further reactivated, with fold amplitudes increasing in the Pliocene–Pleistocene (Krieg 1985).

Using spring temperature to estimate aquifer source depth

Anderson (2005) highlighted the importance of heat as a groundwater tracer, including the evaluation of spring systems. Thermal springs are found around the world in a variety of geologic settings and require a heating mechanism, fracture permeability, groundwater source, and pressure gradients (Waring et al. 1965). Groundwater-heating mechanisms include recent volcanism, magmatic intrusion, and deep circulation of groundwater heated by Earth's geothermal gradient—the only mechanism considered here (Waring et al. 1965). Fracture permeability caused by recent faulting is an important influence on thermal spring locations (Curewitz and Karson 1997; Hancock et al. 1999; Waring et al. 1965).

Objectives

This study elucidates aquifer sources to Dalhousie Springs by integrating current hydrogeologic and hydrochemical data with historic, previously unpublished test data from petroleum exploration wells. Specifically, the study:

1. Compiles spring locations, discharge rates and temperatures, surface and subsurface geologic characterization, and mapping of potentiometric surfaces
2. Evaluates hydrochemistry and hydrogeology of springs, groundwater, and data collected from petroleum exploration wells, including formation water samples, drill-stem tests, sidewall cores, and geophysical logs
3. Assesses potential aquifer source depths to springs using a thermal model
4. Updates the hydrogeologic conceptual model of Dalhousie to inform potential groundwater management strategies

Although this approach is employed to identify sources to Dalhousie Springs, the methods developed by this study may

Table 1 Thermal spring source depth input data and results

Unit number		T_s (°C)	T_0 (°C)	Geothermal gradient (°C /100 m)	Spring source depth		C surface horizon depth		Z surface horizon depth	
					(m bgs)	(m AHD)	(m bgs)	(m AHD)	(m bgs)	(m AHD)
5945–3	DEA005	30.0	21.9	3.0	270	−129	94	47	387	−246
5945–55	DFA002	31.0	21.9	3.0	304	−173	93	38	356	−225
5945–10	DCD002	32.0	21.9	3.0	336	−214	158	−36	439	−317
5945–44	DDB002	32.0	21.9	3.0	336	−203	108	25	403	−270
5945–52	DDA002	34.0	21.9	3.0	403	−268	120	15	408	−273
5945–58	DGA003	34.0	21.9	3.0	403	−278	87	38	380	−255
5945–43	DDB001	34.5	21.9	3.0	419	−280	118	21	413	−274
5945–25	DCD001	35.0	21.9	3.0	436	−308	149	−21	433	−305
5945–57	DGA006	36.0	21.9	3.0	470	−347	82	41	374	−251
6045–5	DAA001	36.8	21.9	3.0	497	−378	199	−80	471	−352
5944–17	DHA003	37.0	21.9	3.0	504	−381	142	−19	389	−266
6045–4	DAA004	38.0	21.9	3.0	535	−422	200	−87	470	−357
5945–39	DCB005	38.0	21.9	3.0	535	−401	136	−2	425	−291
5945–31	DCC006	38.0	21.9	3.0	535	−403	132	0	423	−291
5945–48	DCC003	38.0	21.9	3.0	536	−407	132	−3	413	−284
6045–14	DCB004	38.0	21.9	3.0	537	−412	143	−18	435	−310
5945–26	DCA013	40.0	21.9	3.0	602	−477	160	−35	440	−315
5945–30	DCC001	40.0	21.9	3.0	602	−470	137	−5	426	−294
6045–16	DBA001	41.0	21.9	3.0	637	−518	162	−43	445	−326
6045–6	DAA003	41.7	21.9	3.0	659	−542	196	−79	469	−352
5945–19	DCD010	42.0	21.9	3.0	669	−543	153	−27	436	−310
5945–29	DCC002	43.0	21.9	3.0	702	−574	136	−8	420	−292
6045–16	DBA001	43.0	21.9	3.0	703	−584	166	−43	446	−326
6045–8	DCA009	43.0	21.9	3.0	703	−587	162	−50	445	−330
5945–68	DCA011	43.0	21.9	3.0	703	−575	165	−37	443	−315
6045–11	DCA001	43.8	21.9	3.0	730	−613	157	−40	437	−320
5945–47	DCC004	46.0	21.9	3.0	802	−686	151	−35	430	−314

Thermal spring temperatures (T_s) are from this work and the literature (Radke et al. 2000; Smith 1989). Mean annual air temperature (T_0) is from nearby stations (BOM 2010). Geothermal gradient (3.0 °C/100 m) is interpolated from Cull and Conley (1983). Elevation of top of C surface horizon (top of Cadna-owie Formation) and Z surface horizon (bottom of Crown Point Formation) seismic reflectors are from maps in Appendix 1 of Keppel et al. (2013). Table S1 of ESM lists additional data.

BGS below ground surface; AHD Australian Height Datum

be applied to improve conservation outcomes for similar aridland spring systems by identifying linked aquifers.

Methods

Oil and gas exploration wells: geophysical logs, side-wall cores, and drill-stem tests

This study presents a new conceptual model for the hydrogeology of the Dalhousie spring region by evaluating previously overlooked data obtained from 1960s and 1970s-era petroleum exploration wells (Fig. 1), including Witcherrie 1 (Magnier 1964b), Purni 1 (Magnier 1964a), McDills 1 (Amerada 1965), Mokari 1 (Jacque 1966a), Mount Crispe 1 (Jacque 1966b), and Macumba 1 (Wiltshire 1978). Geologic data considered include interpretation of subsurface stratigraphy from lithologic and geophysical logs, permeability tests of side-wall cores, and estimates of formation water salinity from geophysical logs. Geophysical estimates of formation porosity were calculated from gamma and sonic logs during drilling; however, of greatest value were hydrochemical analyses of groundwater samples collected during drill-stem tests (DSTs) or artesian flow that tested sediments of the Pedirka and Eromanga Basins. These data were used to identify potential aquifers in Pedirka Basin sediments that previously had not been characterized by existing groundwater wells.

Hydrochemistry

Previously unpublished hydrochemical analyses of groundwater samples collected from petroleum exploration ($n = 6$) wells were compiled (Amerada 1965; Jacque 1966a, b; Magnier 1964a, b; Wiltshire 1978), as were publicly available data from Dalhousie springs ($n = 17$; only springs with temperature > 30° to omit springs with excessive cooling), groundwater wells ($n = 23$), and Lake Eyre springs (for regional context, $n = 11$; Radke et al. 2000). Parameters assessed included total dissolved solids (TDS) and concentrations of major anions and cations–see Table S1 of electronic supplementary material (ESM). Potential hydrogeologic connections between springs and groundwater were evaluated by comparing hydrochemical facies of Dalhousie-area DSTs, wells and springs with hydrochemical facies of wells from the larger region, and springs of the Lake Eyre complex. Refer to Priestley et al. (2013) and (2019, this issue) for a detailed evaluation of the use of hydrochemical variations of springs and groundwater to understand the regional groundwater flow system of the western GAB.

Thermal model of spring aquifer source depth

Spring discharge temperatures (Fig. 1; Table 1; Radke et al. 2000; Smith 1989) were used to estimate the depths of aquifers sourcing thermal springs, defined here as a point of naturally occurring groundwater discharge at greater than mean annual surface air temperature (but not warm enough for two-phase fluid conditions).

The traditional adiabatic approach to estimating spring source depth in an aquifer considers spring discharge temperature, mean annual air temperature, and an assumed geothermal gradient (Fig. 6). It also ignores heat loss by assuming that source temperature is the same as spring outlet temperature and that the ground surface temperature is the same as the atmospheric air temperature. The earliest known reference to the adiabatic approach is McCallie (1913), and the method has persisted in the literature with, for example, Alfoldi et al. (1985) and Sanz and Yélamos (1998), as noted by Manga (2001). Whether or not heat losses in the spring conduit are considered, all models estimating spring source depth require geothermal gradients, which is estimated by subtracting temperatures measured in a well at two depths and dividing by the measurement depth difference (Polak and Horsfall 1979). Ground surface temperature (T_e) is estimated by extrapolating the well-depth-temperature slope to ground surface and is often 1–4 °C above the mean annual surface air temperature (T_0) (McCutchin 1930).

Aquifer source depth was estimated by comparing measured mean annual spring discharge temperature (T_s) to T_0 and assuming a geothermal gradient, γ, defined by:

$$T = T_a - \gamma z \tag{1}$$

where T is the linear aquifer rock matrix temperature at a given depth; T_a is the aquifer top surface temperature; and z is the distance from aquifer top in a vertical direction. At the top of an aquifer where depth $z = 0$, the temperature in the matrix surrounding the bottom of the spring conduit is the same as at the top of the aquifer, $T = T_a$. The distance from aquifer top to ground surface in the z direction is L. The temperature at the ground surface where $z = L$ is assumed to be the same as ground surface temperature, $T = T_0$. If it is assumed that there is no heat loss in the spring conduit, then the spring temperature measured at the ground surface is the same as the temperature at the top of the aquifer, and $T_s = T_a$. At the top of the aquifer (spring source depth $z = L$), the geothermal gradient is $T = T_a - \gamma L$. Aquifer source depth (L_0) can be found by setting $T_a \rightarrow T_s$, $T \rightarrow T_0$, and $L \rightarrow L_0$ (after Alfoldi et al. 1985):

$$L_0 = \frac{(T_s - T_0)}{\gamma} \quad \text{i.e.,} \quad T_s = T_0 + \gamma L_0 \tag{2}$$

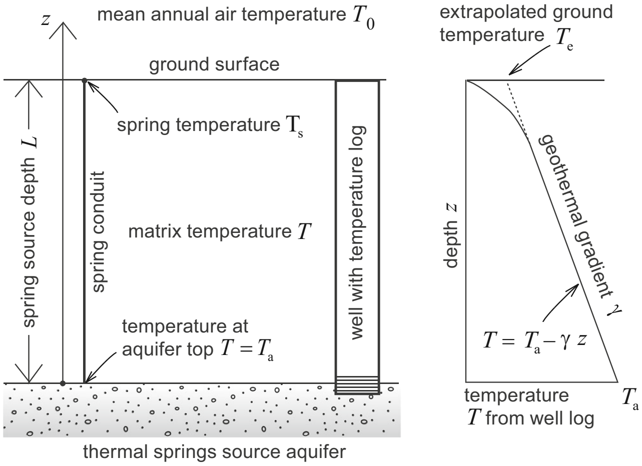


Fig. 6 Spring geothermal schematic. Steady-state geothermal conditions of a linear rock matrix temperature T are noted where L (e.g., 270 m) is the depth from the top of an aquifer to ground surface where a thermal spring discharges with temperature T_s (e.g., 30.0^0). Temperature at the top of the aquifer T_a is located at vertical distance $z = L$. No heat losses are assumed to occur in the spring conduit; thus, $T_a = T_s$. Matrix temperature T at $0 < z < L$ is controlled by the geothermal gradient γ (3.0 °C/100 m). Mean annual air temperature is T_0 (i.e., 21.9 °C). Refer to Table 1 for thermal spring source depth model input data

This study uses measurements of thermal spring temperatures obtained during this study and values available in the open literature (Table 1; Radke et al. 2000; Smith 1989). The geothermal gradient for each spring location is interpolated from Cull and Conley (1983). Mean annual air temperature was interpolated from stations near Dalhousie (BOM 2010). Calculated aquifer source depths were compared with stratigraphic depths inferred from surface horizons in seismic surveys (refer to maps in Appendix 1 of Keppel et al. 2013). Because seismic surveys were acquired by the oil industry during 1960s-era exploration under difficult field conditions using now-antiquated equipment, some uncertainty is to be expected in interpreted stratigraphic depths.

The top of the Cadna-owie Formation corresponds to the C surface horizon, and the bottom of the Crown Point Formation corresponds to the Z surface horizon. The Cadna-owie Formation only crops out in the highest portion of the Dalhousie Anticline; otherwise, the C surface horizon is located stratigraphically below the Bulldog Shale and younger spring deposits.

Results

Oil and gas exploration wells: geophysical logs, lithologic logs, and drill-stem tests

Previously unpublished petroleum exploration well-testing data allowed for evaluation of the hydrogeologic properties of deeper formations than those available in Dalhousie-area groundwater wells (Fig. 1 and Table 2; Amerada 1965; Jacque 1966a, b; Magnier 1964a, b; Wiltshire 1978). Well-completion reports for Witcherrie 1, Purni 1, and McDills 1 revealed formation water quality (650–2,400 mg/L TDS), porosity (up to ~30%), and lithology that indicate that the Permian-age Crown Point Formation is a high-quality aquifer. Witcherrie 1, Purni 1, and McDills 1 were ultimately completed as groundwater supply wells in the Algebuckina Sandstone, producing groundwater TDS of 750, 2,750, and 2,750 mg/L, respectively (however, McDills 1 now has a corroded casing and discharges mixed Jurassic–Permian groundwater; Matthews 1997). Testing of deeper sediments in the southeast Amadeus Basin, western Warburton Basin, and Adelaide Geosyncline did not reveal fresh formation water or high permeability. Refer to Appendix 1 of Keppel et al. (2013) for full results of water-quality analyses of samples collected at petroleum exploration wells, springs, and groundwater wells.

Hydrochemistry

Hydrochemistry of springs at Dalhousie, selected nearby groundwater wells, formation fluids produced during petroleum exploration well testing, and Lake Eyre springs (provided for regional context) are presented in a Piper plot (Fig. 7; well locations on Fig. 1; full data set in Table S1 of the ESM). Spring water at Dalhousie primarily belongs to Na-Cl and Na-Cl-SO_4 hydrochemical facies and are distinct from Lake Eyre springs, which are predominantly Na-Cl-HCO_3. Witcherrie Bore (screened in the J-K Aquifer) and artesian flow collected at the McDills 1 petroleum exploration well during testing of the Permian Crown Point Formation (Na-Mg-Cl-SO_4 hydrochemical facies) exhibit similarities to spring waters at Dalhousie. Upgradient to Dalhousie (see Fig. 1 for potentiometric surface map), wells screened in Jurassic–Cretaceous formations at Charlotte Waters and Andado Station also show hydrochemical similarities to Dalhousie; however, other J-K Aquifer wells upgradient to Dalhousie and located near the Finke River at Apatula (Finke) Community and at New Crown Station belong to Ca-Mg-Cl-SO_4 hydrochemical facies. Approximately 10 km east of Dalhousie, a groundwater sample from Cambrian–Ordovician strata at Mount Crispe also belongs to the Na-Cl-SO_4 hydrochemical facies (DST No. 1; Jacque 1966b).

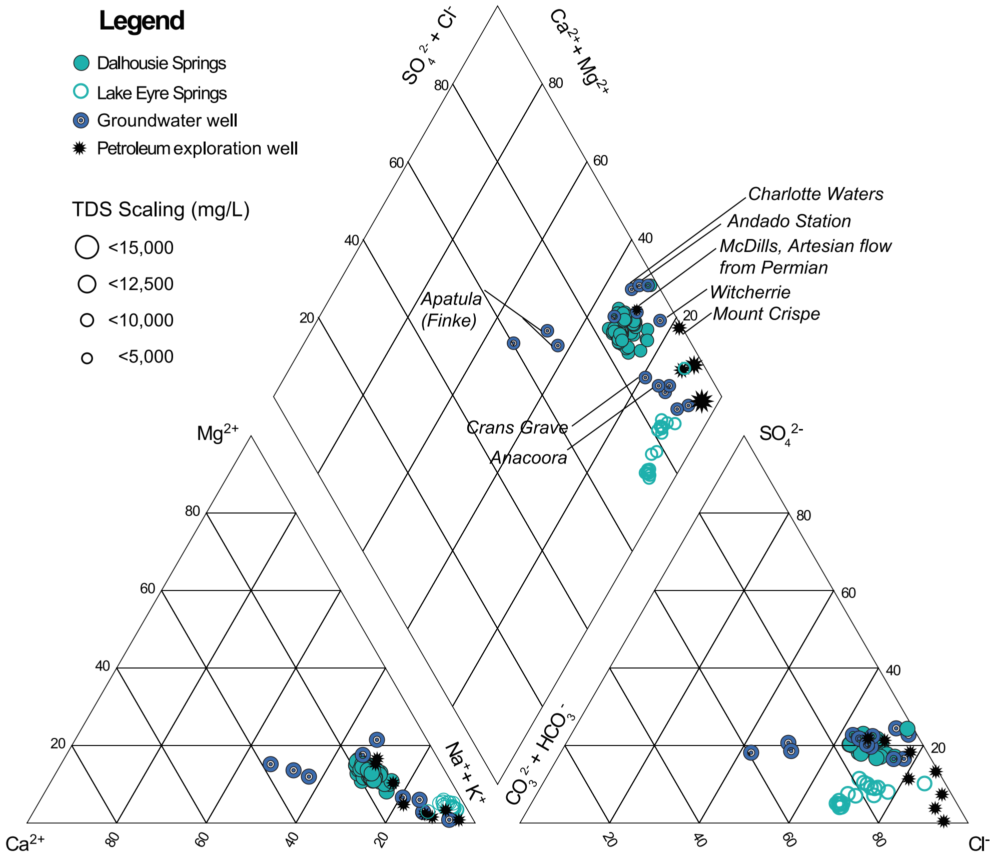
Table 2 Petroleum exploration well-test data

Well	Distance from Dalhousie	Formation	Depth (m)	Test type	Result	Comment
Witcherrie 1	~15 km east	Crown Point	778–790	DST	TDS 1,000 mg/L	–
		Crown Point	555–579	Sidewall core porosity	9–32%	"Fine reservoir series"
Purni 1	~60 km east	Crown Point	1,716–1,737	DST	TDS 650 mg/L	–
		Crown Point	1,450–1,544	Sidewall core porosity	10–17%	–
		Crown Point	Various	Geophysical log porosity	~18%	Lower Crown Point
		Purni	Various	Geophysical log porosity	19%	Upper Purni
McDills 1	~80 km northeast	Crown Point	724	Artesian flow	TDS 2,423 mg/L	–
		Crown Point and Purni	Various	Geophysical log porosity	15–25%	"Good reservoir sands"
Mokari 1	~110 km east	Purni	2,013–2,049	DST	TDS 11,248 mg/L	Top of middle member of Purni
		Crown Point	2,153–2,159	DST	TDS 10,634 mg/L	–
Mount Crispe 1	~10 km west	Western Warburton Basin sediments	1,137–1,151	DST	TDS ~9,600 mg/L	–
		Western Warburton Basin sediments	467–509	Geophysical log	TDS ~5,800 mg/L	–
		Southeast Amadeus Basin units	1,276–1,714	Geophysical log	TDS 7,500–8,100 mg/L	–

Water quality results are shown as total dissolved solids (TDS). Well locations are shown on Figs. 1 and 9. Refer to Table S1 of the ESM for latitude, longitude, and full results of water quality of analysis. Sources: Witcherrie 1 (Magnier 1964b), Purni 1 (Magnier 1964a), McDills 1 (Amerada 1965), Mokari 1 (Jacque 1966a), Mount Crispe 1 (Jacque 1966b)

DST drill-stem test, *TDS* total dissolved solids

Fig. 7 Piper plot of spring water and groundwater samples. Dalhousie Springs, Lake Eyre springs, and selected Dalhousie Springs-area bores (Radke et al. 2000) are synthesized with Dalhousie Springs–area petroleum exploration boreholes with drill-stem tests or artesian flow encountered during drilling (data provided in Table S1 of the ESM; Amerada 1965; Jacque 1966a, b; Magnier 1964a, b; Wiltshire 1978)



However, TDS approaches 10,000 mg/L and the unit is “nonporous”; thus, Cambrian–Ordovician formations are not likely to be major sources of Dalhousie water. Water samples collected during DSTs of other petroleum exploration wells have more Na^+ and K^+ and much more Cl^-, indicative of basinal brines.

Thermal model of spring aquifer source depth

In general terms, springs in the northern part of the Dalhousie Spring Complex have higher temperatures and lower salinities than those observed in the south of the region (Smith 1989). Estimated thermal-spring aquifer source depths range from 270 to 802 m below ground surface (bgs; Table 1), a greater depth than that of the J-K Aquifer. In addition, the top of the Cadna-owie Formation (i.e., C surface horizon) is found at shallower depths ranging from 82 to 200 m bgs (refer to maps in Appendix 1 of Keppel et al. 2013 for C and Z surface horizon depths). At spring locations, depth to the base of the Crown Point Formation (i.e., Z surface horizon) ranges from 356 to 471 m bgs. Thus, thermal-modeling results suggest that spring discharge also originates from the deeper, warmer Crown Point Formation at depths up to ~800 m.

Discussion

Hydrochemistry and petroleum exploration well-test data

This study evaluated the hydrochemistry of samples collected at Dalhousie-area springs and groundwater wells, as well as water quality and hydraulic properties from petroleum exploration well testing. The salinity and generalized water type of Permian Crown Point Formation waters at McDills 1 petroleum well and J-K Aquifer groundwater from the Witcherrie groundwater well (completed from the petroleum exploration well) are similar to those at Dalhousie, suggesting shared water sources. In addition, similarities in the hydrochemistry of groundwater in upgradient wells located to the north and northwest of Dalhousie are consistent with providing flows to the springs.

Groundwater samples collected from wells screened in the J-K Aquifer in the postulated recharge area along the Finke River at Apatula (Finke) Community and New Crown Station belong to the Ca-Mg-Cl-SO_4 hydrochemical facies, and wells at Andado Station and Charlotte Waters are also similar to Dalhousie, suggesting the wells belong to the same regional flow system that discharges at the springs. Groundwater movement from the Finke River area to Dalhousie, along with mixing of Permian Crown Point Formation groundwater, may qualitatively explain observed Dalhousie hydrochemistry. This interpretation is also consistent with prior studies (Abu Risha et al. 2009; Abu Risha 2016) that used chlorine, carbon, oxygen, hydrogen, and strontium isotopic analyses to infer flow paths from recharge zones along the western margin of the GAB to Dalhousie. Focused ephemeral stream recharge to the northeast and west of spring discharge at Dalhousie is also suggested by a persistent groundwater mound along >100 km of the Finke River, as well as mounds along Stevenson and Lindsay creeks (Ransley et al. 2015). Thus, results of hydrochemical analyses of spring water, groundwater, and Permian-age formation water from the Dalhousie Springs region indicate that Dalhousie Springs hydrochemistry is consistent with a Jurassic-Cretaceous-age or Permian Crown Point Formation aquifer source. This is the first study to suggest that the previously unidentified Permian Crown Point Formation is a regionally extensive aquifer that, in addition to the generally accepted J-K Aquifer, may also provide a significant component of the groundwater discharge to springs at Dalhousie.

Thermal model

A thermal model was used to test the hypothesis that groundwater from the Permian Crown Point Formation, as well as that from the J-K Aquifer, flows to Dalhousie Springs. All previous studies of Dalhousie (Habermehl 1982; Krieg 1985; Radke et al. 2000; Smith 1989) suggest that groundwater originates solely from the J-K Aquifer. Using spring temperature as a proxy for source depth, results of the model suggest that Dalhousie discharges a mixture of shallower, cooler groundwater from the Algebuckina Sandstone and deeper, warmer groundwater from the Crown Point Formation. This is a novel interpretation of the source of Dalhousie groundwater.

The thermal model used by this study has some limitations because of necessary assumptions—for example, Alfoldi et al. (1985) noted typical model input measurement errors of ±5–10% for geothermal gradient and ±0.1 °C for spring temperature measured using a handheld field water-quality meter. At Dalhousie, spring temperatures generally increase from south to north, suggesting a deeper source of northern springs or thermal diffusion cooling caused by slower water velocity in southern spring vents. Spring temperatures below mean annual air temperature should be treated with caution because they may have been caused by sampling during cool air temperatures when heat loss is too high or by the occurrence of near-surface lateral groundwater mixing. Thus, it is important that spring temperature measurements be taken at the greatest depth and as close to the vent as possible to minimize such errors. The model assumption that aquifer temperature and spring temperature are the same is reasonable, given relatively high discharge rates of springs at Dalhousie.

Additional model limitations include the assumption that groundwater flows from the source aquifer to the spring vent along a cylindrical vertical conduit (Figs. 6 and 8a,b) without contributions from other water sources (e.g., Fig. 8c–e). As such, this model assumes a thermal spring conceptual model composed of a vertical fault conduit cutting through an aquifer and its low-permeability upper confining bed with negligible displacement (Fig. 8a). It is also reasonable to assume that the thermal model presented here may also be applied when the fault associated with a thermal spring has a relatively small displacement of $\leq 0.1\ L$ (Fig. 8b). When fault displacement is large (e.g., $\geq 0.1\ L$), estimated spring source depths have higher uncertainty but are still useful to constrain the range of possible source depths (Fig. 8c). Similarly, when a fault intersects aquifers with multiple source depths and temperatures (Fig. 8d,e), spring temperatures reflect mixing of different aquifers and results have higher uncertainty.

The model also assumes homogeneity and isotropy of the rock matrix composing the spring conduit. Other modeling assumptions include that the spring conduit, spring vent, and place where geothermal gradient is measured are located away from other heat sources or sinks and that values for all input parameters are accurate. However, despite imperfect input data typical of hydrogeologic studies (e.g., the possibility of more than one aquifer source depth at Dalhousie), a reasonable first-order estimate of aquifer source depths may be generated with this approach.

Updated hydrogeologic conceptual model of spring discharge

Hydrogeologic data evaluated in this report reveal that springs at Dalhousie are sourced by a mixture of groundwater from the Carboniferous–Permian Crown Point Formation and J-K Aquifer. Fractures in the McDills-Dalhousie Ridge anticline, as well as erosion of the Bulldog Shale confining unit at this structural high, enabled formation of this spring system. A hydrogeologic cross section summarizing this conceptual model (Fig. 9) was constructed using published hydrogeologic data (Drexel and Preiss 1995; Krieg 1985; Questa 1990), seismic surveys (refer to maps in Appendix 1 of Keppel et al. 2013), and previously unpublished petroleum exploration well-testing data (Amerada 1965; Jacque 1966a, b; Magnier 1964a, b; Wiltshire 1978).

Aquifers of the Crown Point Formation and J-K Aquifer crop out along the Finke River northwest of Dalhousie (Figs. 1 and 3d,e). Groundwater recharge occurs during ephemeral stream flow of the Finke and neighboring streams (Fig. 3f; Abu Risha 2016; Fulton et al. 2013; Ransley et al. 2015). Groundwater flows down-gradient (i.e., northwest to southeast) and is confined by the Bulldog Shale and lower-permeability units of the Crown Point Formation (Fig. 9). Groundwater moves through the synclinal Eringa Trough, ascends along the western anticline limb of the McDills-Dalhousie Ridge, and flows to the surface through fractures associated with faults in the McDills-Dalhousie Ridge. An interpretation of faults cross-cutting multiple aquifers is consistent with $^{87}Sr/^{86}Sr > 0.715$, which suggests interaction with radiogenic basement rocks (Ring et al. 2016) and high total helium, high $^{3}He/^{4}He$ ratios, and excess CO_2 signifying deeply derived fluids (Crossey et al. 2013). This conceptual model of Dalhousie differs from those in previous studies, which only considered the J-K Aquifer as a Dalhousie source (Habermehl 1980). Thus, an important finding of this study is that groundwater management planning needs to consider the Permo-Carboniferous Crown Point Formation, as well as Jurassic–Cretaceous sediments.

Implications for groundwater management: mitigating potential threats to springs discharge

Limited understanding of groundwater flow systems and hydrologic connections between aquifers and springs complicates successful groundwater management. In the eastern GAB, groundwater development since the late 1800s resulted in pressure declines >100 m and caused springs to dry (Habermehl 1980), in part because early groundwater users poorly understood the potential effects of excessive groundwater development. Thus, groundwater management decisions that maintain natural discharge of linked aquifer-spring systems such as Dalhousie must be based upon an accurate hydrogeologic conceptual model.

As suggested by Harrington et al. (2017), sustainable groundwater development may be informed by the construction of monitoring wells located between well fields and a groundwater discharge zone to provide an early warning of possible pumping effects on springs. Groundwater models may also be used to identify groundwater trigger levels at specific monitoring locations upgradient from springs below which pumping should be reduced or curtailed. Thus, the preservation of Dalhousie requires that any future groundwater development in the region be operated so that hydraulic heads around the complex and upgradient recharge areas are maintained in both Permian and Cretaceous aquifers. To this end, long-term monitoring, including hydrochemical mixing studies, in both aquifers is needed at a regional scale. In addition, numerical groundwater modeling could be used to assist in forecasting and mitigating the potential impacts of new wells on spring discharge. Thus, conservation of spring discharge at Dalhousie requires identifying and possibly mitigating potential future groundwater development threats, particularly groundwater pumping for mining and energy development.

Mines: dewatering and/or groundwater supply

Mines along the western margin of the GAB currently rely on groundwater for industrial processes—for example, the massive Olympic Dam mine maintains extensive GAB supply wells (Geoscience Australia 2013). BHP, the Olympic Dam mine owner, has also proposed nearly doubling current copper production to 350 kt/year, which would require an additional 50 ML of groundwater to be pumped from wells in the GAB (BHP 2019; DEM 2019a). While this new well field would be sited far from Dalhousie (>400 km), springs of the Lake Eyre group are closer (~100 km; e.g., springs listed in Keppel et al. 2011); thus, long-term pumping may affect artesian heads in the vicinity of these springs, potentially adversely affecting spring flow. Several other mines have been proposed along the western margin of the GAB, which could potentially increase GAB groundwater extraction (e.g., DEM 2019b). Thus, as part of a comprehensive risk assessment process (e.g., Green et al. 2013), groundwater wellfields for future mines should be sited and operated to minimize potential effects on GAB springs.

Coal seam gas

Most of Australia's coalbed methane industry is located in eastern Australia (Geoscience Australia 2018); however, production potential in the Pedirka Basin from the upper member of the Purni Formation is estimated at ~47 trillion cubic feet (TCF) (Goldstein et al. 2012; Meaney 2007). Development is also being investigated near the Hale River, ~225 km north of Dalhousie (Scott et al. 2012), and ~100 km north of Dalhousie and ~50 km to the north of the Finke River (Ebony Energy Ltd. 2017). Of interest to maintaining Dalhousie spring flows are the potential effects of groundwater pumping to dewater coal beds during gas production and the effects on the regional groundwater flow system. While development of Permian coal may be unlikely in the near-term, potential coalbed methane dewatering may still pose a risk to springs.

Unconventional shale and tight gas

In the US, development of unconventional oil and gas resources using directional drilling and hydraulic fracturing (HF) has been rapid and intense (Allred et al. 2015). Of concern are water demands of this process (e.g., Permian Basin median ~23 ML/HF well; Scanlon et al. 2017). In Australia, unconventional gas resources remain essentially undeveloped (Geoscience Australia 2018; IEA 2018). In the Pedirka Basin, shales are not currently exploited because they are generally thin, laterally discontinuous, and of low thermal maturity (Goldstein et al. 2012). In deeper parts of the Pedirka Basin (~100 km east of Dalhousie), thermal maturity is sufficient, but thermogenic gas shows were limited to thin coal seams

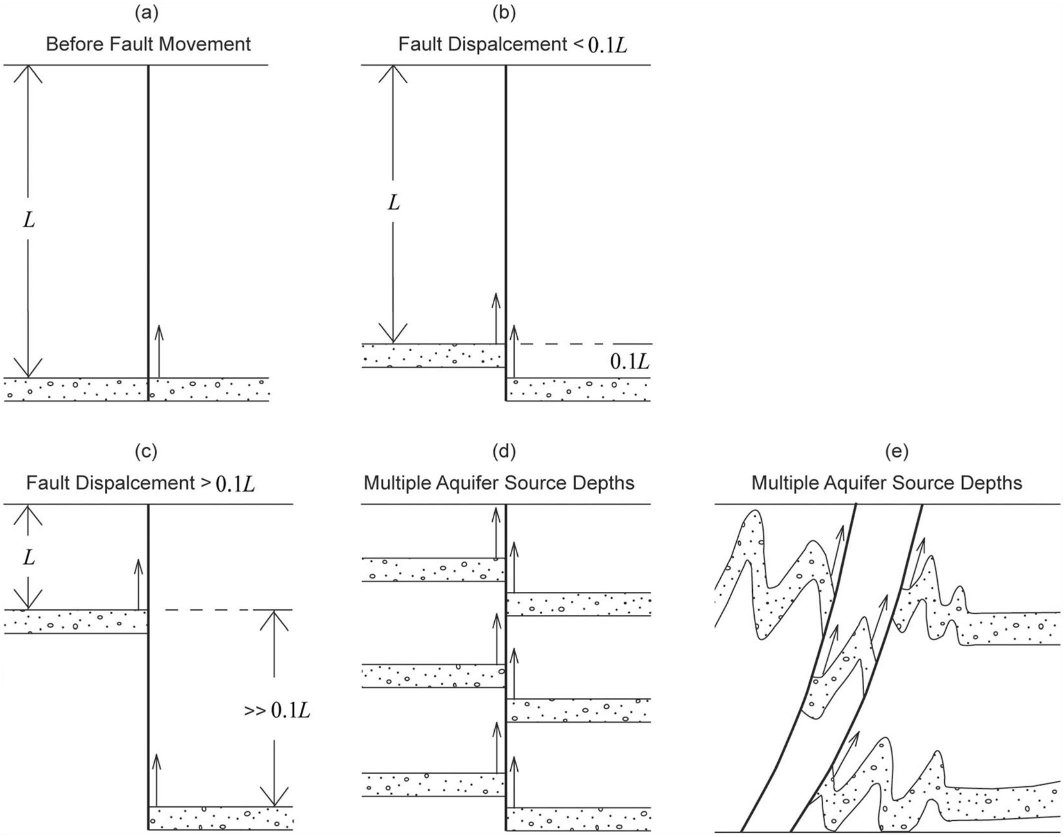


Fig. 8 Spring orifice conceptual models. **a** Vertical fault conduit cutting through an aquifer (dappled pattern) and its low-permeability upper confining bed (no fill) with negligible displacement. Groundwater flow direction is indicated by arrow, and distance from top of aquifer to ground surface is *L*. **b** Fault associated with a thermal spring with a relatively small displacement of ≤0.1 *L*. (**c**–**e**) Fault intersects aquifers with multiple source depths and temperatures. Diagrams after Van der Pluijm and Marshak (2004)

with shale partings (i.e., Oolarina 1 well; Goldstein et al. 2012; Menpes et al. 2012). During the drilling of McDills 1 (~80 km northeast of Dalhousie), gas was detected in the lower Rumbalara Shale (Amerada 1965) but was not subsequently developed. While Australian energy operators do not currently target prospective shale and tight gas resources (Geoscience Australia 2018), future commodity prices may incentivize their development. Thus, forecasts of where future development may occur may be warranted to mitigate potential impacts of HF water sourcing on groundwater resources and linked spring systems (e.g., Ikonnikova et al. 2017; Wolaver et al. 2018a).

Future work

In light of current and potential groundwater development in the Dalhousie region, conducting source aquifer assessments to “define the connection of springs to source aquifers” remains an important research topic required to manage groundwater development to maintain spring flows along the GAB western margin (Lai et al. 2016). To this end, continued monitoring of the existing well network should be continued and data openly shared with the public. Multiple geochemical tracers can be used to evaluate water quality and changes in source mixing. In addition, running groundwater models to quantify potential impacts of groundwater development on Dalhousie could be included as a condition of state well permitting, so that operations could be adjusted prior to construction to mitigate potential adverse effects on spring systems. In addition, groundwater modeling could be used to identify monitoring gaps to be filled by additional wells and triggers developed to reduce pumping prior to impacting springs. Conservation outcomes of aridland spring systems like Dalhousie could also be improved by developing science to inform decision-making before any groundwater development occurs as part of a public, transparent stakeholder-driven process (i.e., including state and federal agencies, private industry, nongovernmental organizations, ranchers, indigenous peoples, etc.). Facilitated science development sessions similar to the approach of Wolaver et al. (2018b) and Gulley (2015) could be used to gain early project buy-in and assure that the right science is developed to inform on-the-ground conservation actions that result in preservation of springs and associated groundwater-dependent ecosystems.

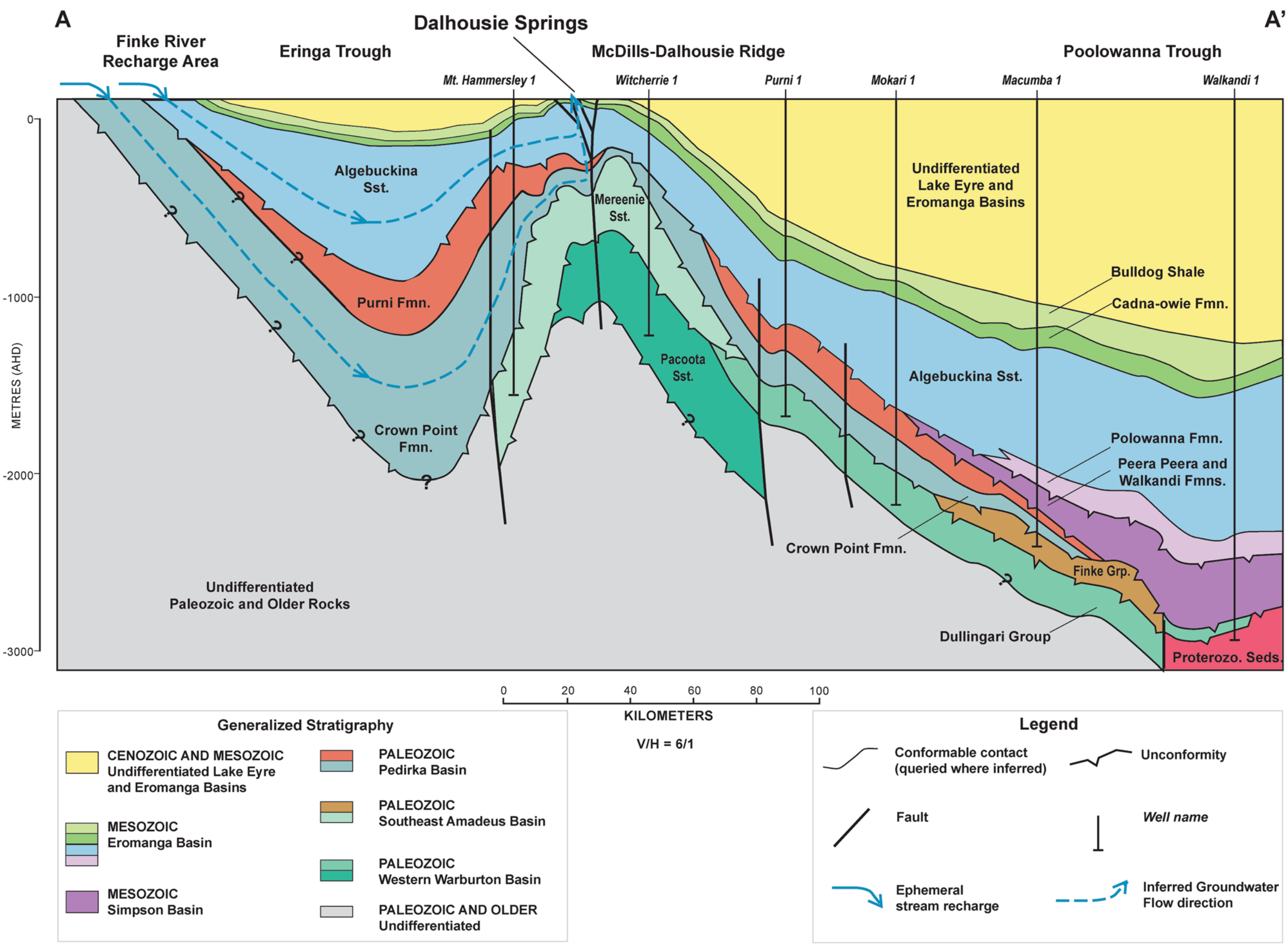


Fig. 9 Hydrogeologic conceptual model of groundwater flow to Dalhousie Springs. Cross section A–A′ location is shown on Fig. 1. Dalhousie Springs likely discharges a mixture of groundwater from the Crown Point Formation and Algebuckina Sandstone along fractures in McDills-Dalhousie Ridge. Groundwater recharge occurs where ephemeral streams flow over outcrops of the Crown Point Formation and J-K Aquifer along the western margin of the GAB (Fig. 3f). The Bulldog Shale and lower-permeability units of the Crown Point Formation confine groundwater flows down gradient from northwest to southeast until ascending along fractures of the western anticline limb of the McDills-Dalhousie Ridge. Cross section is after Figure 8.27 of Drexel and Preiss (1995)

Conclusions

Historic, previously unpublished drill-stem test data are integrated with current hydrogeologic and hydrochemical data to identify the Permian Crown Point Formation as an unrecognized and important contributor to spring discharge at the Dalhousie Spring Complex. The revised hydrogeologic conceptual model presented here is important because it identifies the overlooked Permian aquifer and other deep-fluid sources as providing groundwater discharge to Dalhousie, in addition to the previously accepted J-K Aquifer (Habermehl 1980).

The most plausible mechanism for Permian and Jurassic–Cretaceous aquifer discharge at Dalhousie is through fault-associated fractures in the McDills-Dalhousie Ridge anticline. Uplift in the anticline formed a topographic high and eroded the Bulldog Shale confining bed to expose the Cadna-owie Formation. Fracturing associated with interformational faulting permits both mixing of groundwater and discharge of groundwater at the surface to form the spring complex.

Preservation of Dalhousie requires that the potentiometric surface in the vicinity of Dalhousie be maintained at or near present levels in both Permian and Jurassic–Cretaceous aquifers. Consequently, any future groundwater development in the Dalhousie region should consider these two aquifer systems as contributors with respect to the maintenance of head in the vicinity of Dalhousie. While this approach is used to elucidate sources to springs at Dalhousie to inform groundwater management strategies resulting in their conservation, this technique may be applied to preserve other aridland spring systems globally.

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References

Abu Risha UA (2016) Radiocarbon dating and the 36Cl/Cl evolution of three Great Artesian Basin wells at Dalhousie, South Australia. Hydrogeol J 24:987–1000. https://doi.org/10.1007/s10040-016-1364-4

Abu Risha U, Clark I, Beecham S (2009) Evaluation of groundwater flow and travel times using ^{14}C. Paper presented at the Thirteenth International Water Technology Conference, ITWC 13, Hurghada, Egypt, 12–15 March 2009

Aldam R, Kuang KS (1989) An investigation of structures controlling natural discharge of artesian waters in the southwestern Great Artesian Basin. Report Book 88/4, Department of Mines and Energy, Adelaide, Australia, pp 2–9

Alfoldi L, Galfi J, Liebe P (1985) Heat flow anomalies caused by water circulation. J Geodynamics 4:199–217. https://doi.org/10.1016/0264-3707(85)90060-2

Allan RJ (1990) Climate. In: Tyler MJ, Twidale CR, Davies M, Wells CB (eds) Natural history of the North East deserts. Royal Society of South Australia, Adelaide, SA, Australia, pp 107–118

Allred BW, Smith WK, Twidwell D, Haggerty JH, Running SW, Naugle DE, Fuhlendorf SD (2015) Ecosystem services lost to oil and gas in North America. Science 348:401–402. https://doi.org/10.1126/science.aaa4785

Amerada (1965) Amerada Petroleum Company of Australia Limited (Amerada). Well completion report Amerada McDills no. 1, Open File Envelope no. 573, Northern Territory Minerals and Energy, Darwin, NT, Australia

Anderson M (2005) Heat as a ground water tracer. Ground Water 43:951–968

BHP (2019) South Australian Government major development declaration for Olympic Dam. https://www.bhp.com/media-and-insights/news-releases/2019/02/south-australian-government-major-development-declaration-for-olympic-dam. Accessed 26 March 2019

BOM (Bureau of Meteorology) (2010) Online climate data. http://www.bom.gov.au/climate/data/. Accessed 1 Aug 2010

Carne GE, Alexander E (1997) Eromanga Basin prospects inventory Blocks ER97-A to C. Report book 97/21, Mines and Energy Resources, South Australia, Adelaide, Australia, 137 pp

Costelloe JF, Shields A, Grayson RB, McMahon TA (2007) Determining loss characteristics of arid zone river waterbodies. River Res Appl 23:715–731. https://doi.org/10.1002/rra.991

Crossey LJ, Priestley SC, Shand P, Karlstrom KE, Love AJ, Keppel MN (2013) Source and origin of western GAB spring water. In: Love AJ, Shand P, Crossey LJ, Harrington GA, Rousseau-Gueutin P (eds) Groundwater discharge of the western Great Artesian Basin, allocating water and maintaining springs in the Great Artesian Basin. National Water Commission, Canberra, pp 11–33

Cull P, Conley D (1983) Geothermal gradients and heat flow in Australian sedimentary basins. BMR J Aust Geol Geophys 8:329–337

Curewitz D, Karson J (1997) Structural settings of hydrothermal outflow: fracture permeability maintained by fault propagation and interaction. J Volcanol Geotherm Res 79:149–168. https://doi.org/10.1016/S0377-0273(97)00027-9

Davis JA, Kerezsy A, Nicol S (2017) Springs: conserving perennial water is critical in arid landscapes. Biol Conserv 211:30–35. https://doi.org/10.1016/j.biocon.2016.12.036

DEM (Department for Energy and Mining) (2019a) Proposed Expansion of Olympic Dam declared a major development. Government of South Australia, DEM. http://www.energymining.sa.gov.au/minerals/latest_updates/proposed_expansion_of_olympic_dam_declared_a_major_development. Accessed 26 March 2019

DEM (Department for Energy and Mining) (2019b) South Australia's developing projects resource estimates and production statistics. Government of South Australia, DEM. https://map.sarig.sa.gov.au/CrystalRunner/Report/Export/2?exportName=DevelopingProjects. Accessed 9 January 2019

Department for Water (2010) Drillhole Enquiry System. Government of South Australia, Adelaide, Australia

Drexel JF, Preiss WV (1995) The geology of South Australia, vol 2: the Phanerozoic mines and energy, South Australia. Bull. 54, Geological Survey of South Australia, Adelaide, Australia

Drexel JF, Preiss WV, Parker AJ (1993) The geology of South Australia, vol 1: the Precambrian. Bull. 54, South Australia Geological Survey, Adelaide, Australia

Ebony Energy Ltd (2017) Relinquishment Report for EL29239, Pedirka Basin Project, Exploration for Thermal Coal, for the year 4/1/2016 to 3/1/2017. https://geoscience.nt.gov.au/gemis/ntgsjspui/bitstream/1/85163/1/EL29239_2017_P.pdf. Accessed 18 January 2019

Freytag IB (1966) Proposed rock units for marine lower cretaceous sediments in the Oodnadatta region of the Great Artesian Basin. Q Geol Notes 18:3–7

Fulton S, Wohling D, Love AJ, Behrens V (2013) Ephemeral river recharge. In: Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P, Ritter S (eds) Groundwater recharge, hydrodynamics and hydrochemistry of the Great Artesian Basin. National Water Commission, Canberra, pp 37–81

Geoscience Australia (2012) Surface geology of Australia 1:1 million scale dataset. https://data.gov.au/dataset/ds-dga-48fe9c9d-2f10-49d2-bd24-ac546662c4ec/details. Accessed 14 Jan 2019

Geoscience Australia (2013) OZMIN mineral deposits database. Bioregional Assessment Source Dataset. http://data.bioregionalassessments.gov.au/dataset/34247a24-d3cf-4a98-bb9d-81671ddb99de. Accessed 3 Sept 2019

Geoscience Australia (2018) Australian energy resource assessment. https://aera.ga.gov.au/#!/home. Accessed 18 Jan 2019

Goldstein B, Menpes S, Hill A, Wickham A, Alexander E, Jarosz M, Pepicelli D, Malavazos M, Staritski K, Taliangis P, Coda J, Hill D, Webb M (2012) Roadmap for unconventional gas projects in South Australia. Government of South, Australia Energy Resource Division. http://www.energymining.sa.gov.au/petroleum/roundtable_for_oil_and_gas#q=Roadmap. Accessed 26 March 2019

Green G, White M, Gotch T, Scholz G (2013) Risk assessment process for evaluating water use impacts on Great Artesian Basin springs, allocating water and maintaining springs in the Great Artesian Basin. National Water Commission, Canberra

Gulley RL (2015) Heads above water: the inside story of the Edwards Aquifer recovery implementation program. Texas A&M University Press, College Station, TX

Habermehl MA (1980) The Great Artesian Basin, Australia. BMR J Aust Geol Geophys 5:9–38

Habermehl MA (1982) Springs in the Great Artesian Basin, Australia: their origin and nature. BMR report, BMR, Canberra, 235 pp

Hancock PL, Chalmers RML, Altunel E, Çakir Z (1999) Travitonics: using travertines in active fault studies. J Struct Geol 21:903–916. https://doi.org/10.1016/S0191-8141(99)00061-9

Harrington R, Rainville K, Blandford TN (2017) Comment on "Drawdown 'triggers': a misguided strategy for protecting groundwater-fed streams and springs," by Matthew J. Currell (2016, groundwater 54[5]: 619–622). Groundwater 55:152–153. https://doi.org/10.1111/gwat.12503

Hunter ML (2017) Conserving small natural features with large ecological roles: an introduction and definition. Biol Conserv 211:1–2. https://doi.org/10.1016/j.biocon.2016.12.019

IEA (International Energy Agency) (2018) Australia production. https://www.iea.org/ugforum/ugd/australia/. Accessed 8 January 2019

Ikonnikova S, Male F, Scanlon BR, Reedy RC, McDaid G (2017) Projecting the water footprint associated with shale resource production: Eagle Ford shale case study. Environ Sci Technol. https://doi.org/10.1021/acs.est.7b03150

Jacque M (1966a) Mokari 1 well completion report. Open File Envelope no. 640, Primary Industries and Resources SA, Adelaide

Jacque M (1966b) Mount Crispe 1 well completion report. Open File Envelope no. 626, Primary Industries and Resources SA, Adelaide

Kennet B, Fishwick S, Reading A, Rawlinson N (2004) Contrasts in mantle structure beneath Australia: relation to Tasman lines? Aust J Earth Sci 51:563–569

Keppel MN, Clarke JDA, Halihan T, Love AJ, Werner AD (2011) Mound springs in the arid Lake Eyre south region of South Australia: a new depositional tufa model and its controls. Sediment Geol 240:55–70

Keppel MN, Post VE, Love AJ, Clarke JD, Werner AD (2012) Influences on the carbonate hydrochemistry of mound spring environments, Lake Eyre south region, South Australia. Chem Geol 296:50–65

Keppel MN, Wohling D, Fulton S, Sampson L, Karlstrom KE, Nelson G, Ransley T, Love AJ (2013) Summary of hydrogeology and hydrostratigraphy. In: Keppel MN, Karlstrom KE, Love AJ, Priestley S, Fulton S, Wohling D, Ritter SD (eds) Hydrogeological framework of the western Great Artesian Basin, allocating water and maintaining springs in the Great Artesian Basin. National Water Commission, Canberra, pp 23–44

Kodric-Brown A, Brown JH (2007) Native fishes, exotic mammals, and the conservation of desert springs 5:549–553. https://doi.org/10.1890/070002

Krieg GW (1985) Dalhousie South Australia, Explanatory Notes, 1: 250000 Geologic Series—Sheet SG/53–11, Geological Survey of South Australia, Adelaide, 64 pp

Krieg GW (1986) Stratigraphy and tectonics of the Dalhousie anticline, southwest Eromanga Basin. In: Gravestock DI, Moore SP, PittGM (ed) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. Geological Society of Australia, Hornsby, Australia, pp 145–158

Krieg GW (1989) Geology. In: Zeider W, Ponder WF (eds) Natural history of Dalhousie Springs. South Australia Museum, Adelaide, pp 19–26

Lai ÉCS, Sundaram B, Evans R, Ransley TR, Evans TJ (2016) Summary of the Great Artesian Basin Research Priorities Workshop. Canberra, 27–28 April 2016. Record 2016/23, eCat 101440, Geoscience Australia, Canberra, 28 pp

Lewis MMW, White DC (2013) Evaluation of remote sensing approaches. In: Lewis MMW, Davina C, Gotch TB (eds) Spatial survey and remote sensing of artesian springs of the western Great Artesian Basin, allocating water and maintaining springs in the Great Artesian Basin. National Water Commission, Canberra, pp 103–106

Magnier P (1964a) Purni no. 1 well completion report. SA Dept. Mines Open File Envelope 352, South Australia Department of Mines, Adelaide

Magnier P (1964b) Witcherrie no. 1 well completion report. SA Dept. Mines Open File Envelope 347, South Australia Department of Mines, Adelaide

Manga M (2001) Using springs to study groundwater flow and active geological processes. Annu Rev Earth Planet Sci 29:201–228. https://doi.org/10.1146/annurev.earth.29.1.201

Martel DJ, Deak J, Dovenyi P, Horvath F, O'Nions RK, Oxburgh ER, Stegena L, Stute M (1989) Leakage of helium form the Pannonian basin. Nature 342:908–912

Matthews I (1997) Hydrogeology of the Great Artesian Basin in the Northern Territory Water Resources Division, Darwin, NT, Australia

McCallie SW (1913) A preliminary report on the mineral springs of Georgia. Bull. no. 20, Geological Survey of Georgia, Atlanta, GA, 190 pp

McCutchin JA (1930) Determination of geothermal gradients in Oklahoma. Bull Am Assoc Pet Geol 14:535–557

McMahon T, Murphy R, Little P, Costelloe J, Peel M, Chiew F, Hayes S, Nathan R, Kandel D (2005) Hydrology of Lake Eyre Basin. Sinclair Knight Merz, Armadale, VIC, Australia

Meaney R (2007) The unconventional petroleum potential of EP 93 and EPA's 130 & 131 and Pela 77, Pedirka Basin, onshore Northern Territory and South Australia, Australia. Mulready Consulting Services. http://www.territorystories.nt.gov.au/bitstream/10070/213140/1/cbm-evaluation-gas-liquids-potential.pdf. Accessed 18 Jan 2019

Menpes S, Hill A, Sansome A (2012) Unconventional hydrocarbon plays in the permian succession, South Australia. Eastern Australasian Basins Symposium IV, Brisbane, QLD, 10–14 Sept 2012, PESA, Perth, Australia

Middleton MF, Barker CE, Heugh H (2005) The geology of the western part of the Pedirka Basin: Madigan and Eringa Troughs. Central Australian Basins Symposium, Petroleum and Minerals Potential, Alice Springs, NT, Australia

Moore PS, Pitt GM (1982) Cretaceous of the southwestern Eromanga Basin: stratigraphy, facies variations and petroleum potential. In: Moore PS, Mount TJ (eds) Eromanga Basin Symposium Adelaide 1982 Summary papers, Eromanga Basin Symposium, Adelaide, 1982, pp 127–144

Polak EJ, Horsfall CL (1979) Geothermal gradients in the Great Artesian Basin, Australia. Bull Aust Soc Explor Geophys 10:144–148. https://doi.org/10.1071/EG979144

Priestley SC, Shand P, Love AJ, Crossey LJ, Karlstrom KE (2013) Hydrochemistry. In: Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P, Ritter SD (eds) Groundwater recharge, hydrodynamics and hydrochemistry of the western Great Artesian Basin, allocating water and maintaining springs in the Great Artesian Basin. National Water Commission, Canberra, pp 171–201

Priestley SC, Karlstrom KE, Love AJ, Crossey LJ, Polyak VJ, Asmerom Y, Meredith KT, Crow R, Keppel MN, Habermehl MA (2018) Uranium series dating of Great Artesian Basin travertine deposits: implications for palaeohydrogeology and palaeoclimate. Palaeogeogr Palaeoclimatol Palaeoecol 490:163–177. https://doi.org/10.1016/j.palaeo.2017.10.024

Priestley SC, Shand P, Love AJ, Crossey LJ, Karlstrom KE, Keppel MN, Wohling D, Rousseau-Gueutin P (2019) Hydrochemical variations of groundwater and spring discharge of the western Great Artesian Basin, Australia. Hydrogeol J. https://doi.org/10.1007/s10040-019-02071-3

Questa (Questa Australia) (1990) Northern Territory Geological Survey petroleum basin survey. Eromanga Basin GS90/008:40, National Library of Australia Collection, Canberra

Radke BM, Ferguson J, Cresswell RG, Ransley TR, Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadna-owie-Hooray aquifer Great Artesian Basin. Commonwealth Department of Agriculture, Fisheries and Forestry, Canberra, 229 pp

Ransley TR, Radke BM, Feitz AJ, Kellett JR, Owens R, Bell J, Stewart G, Carey H (2015) Hydrogeological atlas of the Great Artesian Basin.

Geoscience Australia, Canberra. https://doi.org/10.11636/9781925124668

Ring U, Tonguç Uysal I, Yüce G, Ünal-İmer E, Italiano F, İmer A, J-x Z (2016) Recent mantle degassing recorded by carbonic spring deposits along sinistral strike-slip faults, south-Central Australia, earth and planet. Sci Lett 454:304–318. https://doi.org/10.1016/j.epsl.2016.09.017

Rossini RA, Fensham RJ, Stewart-Koster B, Gotch T, Kennard MJ (2018) Biogeographical patterns of endemic diversity and its conservation in Australia's artesian desert springs. Divers Distrib 24:1199–1216. https://doi.org/10.1111/ddi.12757

Sanz E, Yélamos JG (1998) Methodology for the study of unexploited aquifers with thermal water: application to the aquifer of the Alhama de Aragón Hot Springs. Ground Water 36:913–923. https://doi.org/10.1111/j.1745-6584.1998.tb02098.x

Scanlon BR, Reedy RC, Male F, Walsh M (2017) Water issues related to transitioning from conventional to unconventional oil production in the Permian Basin. Environ Sci Technol 51:10903–10912. https://doi.org/10.1021/acs.est.7b02185

Scott J, Hinman M, Hepple A, Wetering Nvd, Israni S, Harmston D (2012) Hale River Project. Technical report, Global Ore Discovery, Ebony Coal Ltd., Eastwood, NSW, Australia, 71 pp

Shaw R, Etheridge M, Lambeck KJT (1991) Development of the late Proterozoic to mid-Paleozoic, intracratonic Amadeus Basin in central Australia: a key to understanding tectonic forces in plate interiors. Techtonics 10:688–721. https://doi.org/10.1029/90TC02417

Smith DR, Allan NL, McGowan CP, Szymanski JA, Oetker SR, Bell HM (2018) Development of a species status assessment process for decisions under the U.S. Endangered Species Act. J Fish Wildl Manag 9:302–320. https://doi.org/10.3996/052017-JFWM-041

Smith PC (1989) Hydrogeology. In: Zeidler W, Ponder WF (eds) Natural history of Dalhousie Springs. South Australia Museum, Adelaide, pp 27–40

Springer AE, Stevens LE (2009) Spheres of discharge of springs. Hydrogeol J 17:83–93. https://doi.org/10.1007/s10040-008-0341-y

Van der Pluijm BA, Marshak S (2004) Earth structure: an introduction to structural geology and tectonics, 2nd edn. Norton, London

Waring GA, Blankenship RR, Bentall R (1965) Thermal springs of the United States and other countries of the world: a summary. US Geol Surv Prof Pap 492, 383 pp

Wells AT, Stewart AJ, Skwarko SK (1966) Geology of the southeastern part of the Amadeus Basin, Northern territory. BMR Geology and geophysics report 88, Bureau of Mineral Resources, Canberra

White DC, Gotch T, Alaak Y, Clark M, Ryan J, Lewis MM (2013) Characterizing spring groups. In: Lewis MMW, Davina C, Gotch TB (eds) Spatial survey and remote sensing of artesian springs of the western Great Artesian Basin, allocating water and maintaining springs in the Great Artesian Basin. National Water Commission, Canberra, pp 13–24

White DC, Lewis MM (2011) A new approach to monitoring spatial distribution and dynamics of wetlands and associated flows of Australian Great Artesian Basin springs using QuickBird satellite imagery. J Hydrol 408:140–152. https://doi.org/10.1016/j.jhydrol.2011.07.032

White DC, Lewis MM, Green G, Gotch TB (2016) A generalizable NDVI-based wetland delineation indicator for remote monitoring of groundwater flows in the Australian Great Artesian Basin. Ecol Indicators 60:1309–1320. https://doi.org/10.1016/j.ecolind.2015.01.032

Wiltshire MJ (1978) Macumba 1 well completion report. Open File Envelope no. 3227, Primary Industries and Resources SA, Adelaide

Wolaver BD, Pierre JP, Ikonnikova SA, Andrews JR, McDaid G, Ryberg WA, Hibbitts TJ, Duran CM, Labay BJ, LaDuc TJ (2018a) An improved approach for forecasting ecological impacts from future drilling in unconventional shale oil and gas plays. Environ Manag 62:323–333. https://doi.org/10.1007/s00267-018-1042-5

Wolaver BD, Pierre JP, Labay BJ, LaDuc TJ, Duran CM, Ryberg WA, Hibbitts TJ (2018b) An approach for evaluating changes in land-use from energy sprawl and other anthropogenic activities with implications for biotic resource management. Environ Earth Sci 77:220–263. https://doi.org/10.1007/s12665-018-7323-8

Wopfner H, Freytag IB, Heath GR (1970) Basal Jurassic-Cretaceous rocks of the western Great Artesian Basin, South Australia: stratigraphy and environment. AAPG Bull 54:381–416

Youngs BC (1975) The early Permian Pumi formation of the Pedirka Basin.GSSA Quarterly Geological Notes, Geological Survey of South Australia, Adelaide, pp 8–12

Youngs BC (1976) The geology and hydrocarbon potential of the Pedirka Basin. GSSA Report of Investigations 44, Geological Survey of South Australia, Adelaide, 44 pp

Zeider W, Ponder WF (1989) Natural history of the Dalhousie Springs. South Australian Museum, Adelaide, 138 pp