Analysis of subsurface mound spring connectivity in shale of the western margin of the Great Artesian Basin, South Australia

Todd Halihan, Andrew Love, Mark Keppel & Volmer Berens

Hydrogeology Journal
Official Journal of the International Association of Hydrogeologists

ISSN 1431-2174
Volume 21
Number 7

Hydrogeol J (2013) 21:1605-1617
DOI 10.1007/s10040-013-1034-8

Springer

Your article is protected by copyright and all rights are held exclusively by Springer-Verlag Berlin Heidelberg. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your article, please use the accepted manuscript version for posting on your own website. You may further deposit the accepted manuscript version in any repository, provided it is only made publicly available 12 months after official publication or later and provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The final publication is available at link.springer.com".

Springer

Author's personal copy

Hydrogeology Journal (2013) 21: 1605–1617
DOI 10.1007/s10040-013-1034-8

Analysis of subsurface mound spring connectivity in shale of the western margin of the Great Artesian Basin, South Australia

Todd Halihan · Andrew Love · Mark Keppel · Volmer Berens

Abstract Mound springs provide the primary discharge mechanism for waters of the western margin of the Great Artesian Basin (GAB), Australia. Though these springs are an important resource in an arid environment, their hydraulics as they discharge from shale are poorly defined. The springs can include extensive spring tails (groundwater-dependent wetlands) and hundreds of springs in a given spring complex. Electrical resistivity imaging (ERI) was used to evaluate spring subsurface hydraulic-connectivity characteristics at three spring complexes discharging through the Bulldog Shale. The results demonstrate that fresher GAB water appears as resistors in the subsurface at these sites, which are characterized by high-salinity conditions in the shallow subsurface. Using an empirical method developed for this work, the ERI data indicate that the spring complexes have multiple subsurface connections that are not always easily observed at the surface. The connections are focused along structural deformation in the shale allowing fluids to migrate through the confining unit. The ERI data suggest the carbonate deposits that the springs generate are deposited on top of the confining unit, not precipitated in the conduit. The data also suggest that spring-tail ecosystems are not the result of a single discharge point, but include secondary discharge points along the tail.

Keywords Confining units · Fault hydraulics · Geophysical methods · Australia · Shale connectivity

Received: 27 November 2012 / Accepted: 3 August 2013
Published online: 12 September 2013

© Springer-Verlag Berlin Heidelberg 2013

Electronic supplementary material The online version of this article (doi:10.1007/s10040-013-1034-8) contains supplementary material, which is available to authorized users.

T. Halihan (✉)
Oklahoma State University,
School of Geology, 105 Noble Research Center, Stillwater, OK, USA
e-mail: todd.halihan@okstate.edu
Tel.: +1-405-7449248
Fax: +1-405-7447841

A. Love · M. Keppel
School of the Environment,
Flinders University, GPO Box 2100, Adelaide, South Australia, Australia

V. Berens
Department of Environment,
Water and Natural Resources, GPO Box 2834, Adelaide, South Australia, Australia

Introduction

Determining flow through low permeability units such as shales is difficult and that difficulty is compounded when the shales are structurally deformed by faulting (Hart et al. 2006; Neuzil 1994). Understanding the connectivity of these fracture zones is important for understanding the locations and rates that fluids migrate through these formations. The primary issue may be an understanding of whether these fluids can migrate up from depth to generate a negative impact (Warner et al. 2013), or whether these fluid flows can be maintained to preserve an ecosystem such as in the desert areas of South Australia (Murphy et al. 2009). The focus of this work is evaluating the hydraulic connection between the source water sandstones of the Great Artesian Basin (GAB) and the spring ecosystems that emerge from the confining Bulldog Shale using an analysis of resistivity data. The work is part of a broader investigation of the hydrogeology of the western margin of the GAB funded by the Australian National Water Commission.

Connectivity evaluation

Field approaches for evaluating connectivity through confining units include a variety of methodologies and approaches. Outcrop studies of faults can provide insight into structure that can allow an understanding of the connections between deformation and flow through confining beds (La Pointe and Hudson 1985). Unfortunately, if the confining bed is clay or shale, the outcrops may be poor to nonexistent (Hart et al. 2006). The only direct method of testing the connections across a confining unit is through well testing (Le Borgne et al. 2007). However, this requires a number of wells drilled through the systems to provide access locations. The results of the testing may also be difficult to interpret (Halihan et al. 2005).

Author's personal copy

Geophysical approaches can provide an indirect method of accessing connection between confined aquifers and springs. In general, seismic methods can determine the type of structure that is present, but is limited in determining fluid pathways (James and Freeze 1993). Electrical methods can provide additional insight in connections, as it can demonstrate an electrical contrast with the fluids in the fault and the existing damage zone (Demanet et al. 2001).

Chemical data on gases, major ions, or tracers can demonstrate connections from as deep as the mantle to demonstrate a connection to the underlying aquifers (Crossey et al. 2006; Warner et al. 2013). However, these studies are limited in that they demonstrate a point connection between an aquifer source and a discharge location. If a spring is no longer flowing, or predictions are required regarding future conditions based on head changes in the aquifer, these methods are limited.

Western margin springs of the Great Artesian Basin

The GAB is one of the great large aquifer systems in the world. Along the western margin of the system in South Australia, a series of springs discharge primarily along faults that bound the system. Waters from the underlying confined sandstones of the Jurassic Algebuckina and the Cretaceous Cadna-owie formations discharge as springs through the Cretaceous Bulldog Shale (Drexel and Preiss 1995; Habermehl 1980). Many of these springs deposit and accumulate material, dominantly carbonate precipitates and silica sand (Keppel et al. 2010, 2011; Habermehl 1986). The results of the chemical and physical processes are mounds that range in height and morphology with heights that tend to occur on the meter scale.

This spatial relationship between western margin GAB springs and structures within the Australian continent has been previously recognized. Sprigg (1957) noted that the springs in the region are located in the vicinity of the marginal faults and highs in the underlying basement. Waclawik et al. (2008) noted the occurrence of a spring in the vicinity of a neo-tectonic fault in the Neales River catchment area to the west of Lake Eyre. The most extensive discussion concerning the relationship between fault architecture and springs of the western margin of the GAB was provided by Aldam and Kuang (1988) who interpreted seismic profiles collected over a number of spring group systems. In all instances, faults were postulated to exist beneath the spring zones and in the majority of instances "trapdoor faults" (fault duplexes) were found. They concluded that such structures contain areas where tensile forces could create open fractures in the shale allowing spring conduit development. Karlstrom et al. (2013) provides a recent summary of the relationship between GAB springs and neotectonics, noting the relationship the springs have with deep-seated faulting along the Precambrian margin of eastern Australian known as the Tasman Line. Although there have been previous discussions concerning fault pathways within the GAB aquifers both as a general concept (e.g. Radke et al. 2000) and within sub-basin modeling work (e.g. Berry and Armstrong 1995), typically, fault networks have not been an important consideration in most GAB-related hydrogeological modeling to date.

The total number of springs is difficult to determine in this area as several factors make the count somewhat subjective with estimates ranging between 1,500 and 5,000 springs in the western margin of the GAB. Most flowing springs have only small discharge rates, some with channelized flow, but many exhibit sheet flows from and over broad carbonate mound features. Other areas are simply seeps that maintain moisture throughout the year (Habermehl 1982; Cobb 1975). Due to the arid climate, vegetation dependency on discharging groundwater is easy to determine. Some spring classification systems define each occurrence of groundwater-dependent vegetation as a spring. Additionally, over time, springs have been observed to cease to flow whilst others commence flow.

Longevity of the spring systems is variable. Age dating of spring carbonates suggest ages of 10,000–740,000 years, indicating a long-term system (Prescott and Habermehl 2008). Keppel et al. (2011) demonstrated that emergent spring water was undersaturated with respect to carbonate, thus limiting potential conduit blockage due to precipitation. There is active tectonism in the area that correlates with the spring locations and may allow the system to continue over the long time periods the springs are known to have existed (Karlstrom et al. 2013). During modern observations, some springs have been reported to flow and stop over time, sometimes over short time periods. There are also reports of a seismic experiment on a spring that caused one spring to cease to flow and another that began to flow after a dynamite source was used.

The 'mound springs' are characterized by the mound structure which may be an isolated deposit or a broad mound complex which can extend over hundreds of meters and is generally composed of several springs. The mound is generally composed of plant and microbial tufa (swamp or wetland carbonate), but is a complex deposit composed of several mineral species and a complex depositional history (Keppel et al. 2011). The mound springs may also have a depression forming a pool at the main vent. This pool may be several meters deep and provide a unique habitat for the arid environment. Springs with discharge great enough to form channels can have a significant tail zone which extends from a spring for tens to hundreds of meters. All of these geomorphic areas may contain significant plant or animal species that are associated with one or more of these areas. For this work, the springs contained little vegetation other than wetland vegetation supported by groundwater discharge.

The springs of the western margin of the GAB are important for a variety of reasons. Many of the species located at the springs are endemic to only a small number of the springs and exist nowhere else in the world (Ponder 2002). For the indigenous people of Australia, these springs provided a long-term stable water source used for thousands of years (Ah Chee 2002). Many of the

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

springs are littered with stone tools from pre-European settlement. European explorers used these springs as water sources to allow a route (now the Oodnadatta track) to cross through central Australia and placed the original telegraph line and Ghan railroad along the deformation zone that allows the springs to flow (Fig. 1). Currently, tourism and ranching are the primary industries along this zone.

The GAB is also of interest to mining companies in the region as few other fresh water sources exist. South Australia's largest mining operation, the Olympic Dam site has wellfields located within the southern extent of the spring zone. As water is one of the primary economic limits on production, the amount of water that can be withdrawn without significant effects on the springs is of interest to a wide range of stakeholders.

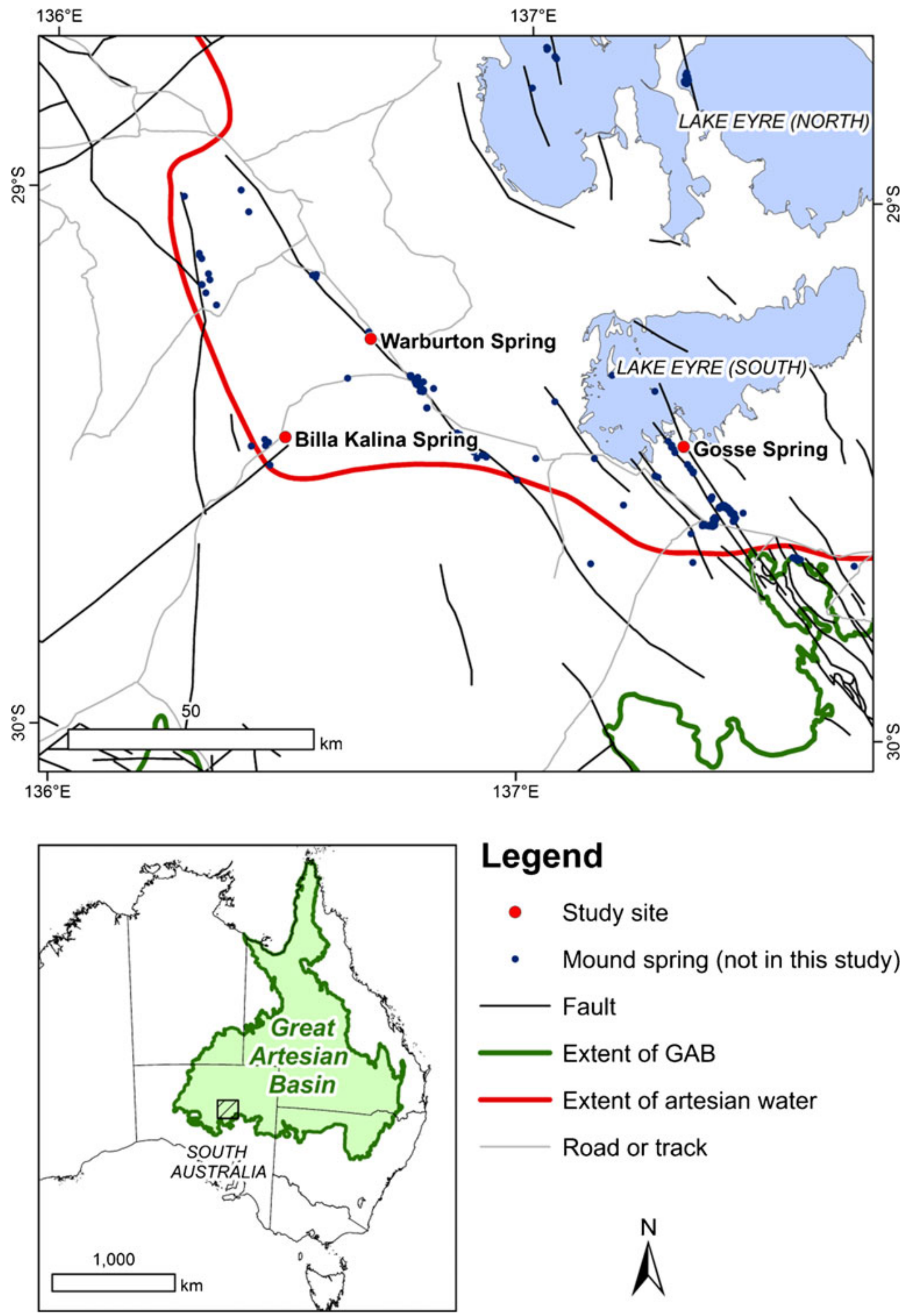

Fig. 1 Mound springs of the Lake Eyre Region of the western margin of the Great Artesian Basin. The majority of the springs are discharging from the aquifer under confined conditions with hydraulic heads existing up to 80 m above land surface. The three sites used for this study are *in bold type*. *Inset map* illustrates the location in Australia of the GAB and the study area

DOI 10.1007/s10040-013-1034-8

Author's personal copy

Hydrogeophysical approach

For this research, electrical resistivity imaging (ERI) was applied to evaluate the subsurface hydrogeologic structure of three sets of mound springs. An initial objective was to determine if the geophysical technique could perform well in the highly saline surface environment and provide useful fluid data to depths of 100 m. As the lithology was the same over the deeper limits of the technique, the uniformity of the data were used as a measure of data quality along with the RMS error of the ERI data inversion models.

The secondary objective was to use the ERI data to test hypotheses about the distribution of GAB groundwater beneath the mound springs. Were the springs connected by isolated conduits to the aquifer or were there broad regions of upwelling fluid? A common hypothesis is that the carbonate precipitation can clog a spring and block the flow, so knowing the hydraulic structure of the mound is important for predicting mound discharge longevity (Hancock et al. 1999). Are the discharge locations stable (unique), or are alternate locations for discharge possible? Are spring-tail wetland areas' surface-water features from a discharging spring or are there additional points of groundwater discharge along these zones?

In order to address these questions, ERI datasets were collected in multiple orientations across three spring systems to evaluate how the data changed with the orientation relative to structure. The hypothesis is that ERI will provide evidence for the distribution of GAB fluid upwelling that covers broad areas beneath mound spring systems constrained by fault locations. The structures that allow water to move through the subsurface allow GAB fluids to move up along linear domains that are not constrained to the location of the current surface discharge features.

Field methods

Field methods for the study included ERI data collection, GPS and standard survey spatial data collection, spring discharge rates and fluid electrical conductivity (EC) measurements. The locations of groundwater-dependent vegetation were noted, but ecological assessment was not completed as part of the study. The focus of the ERI methods were utilized to assess the connectivity of the spring complexes with the underlying fluid sources and evaluate the mound structure.

ERI data were collected using a 56-electrode AGI SuperSting system. These data were collected during the period of May 5–May 21, 2009. Survey lines were labeled using the spring complex name and the line orientation in degrees. The system used a switchbox and seismic takeout cables to collect the data. Two electrode spacings were utilized for the surveys, but the majority of surveys used 10-m electrode spacings providing 550-m-long survey lines and a depth of investigation of approximately 110 m. Two survey lines were collected with an electrode spacing of 2 m providing a 110 m dataset with a depth of investigation of approximately 22 m. Acquisition and processing was performed using the Halihan/Fenstemaker method to create two-dimensional (2D) pseudosections of electrical resistivity (Halihan and Fenstemaker 2004). The method was developed to improve the resolution of subsurface insulators and applied for the GAB spring environment where spring water is a relative electrical insulator to the surrounding terrain. All datasets were topographically corrected.

The ERI and springs were surveyed using a handheld GPS, tape measurers, and a Leica DNA03 digital level. The handheld GPS provided a low accuracy elevation for a single point, and the digital level was used to get the relative elevation along the ERI lines. The datum for the study was UTM grid 53 using a GDA 94 datum.

Discharge data were collected at the springs using a saline dilution method or a tarp method (Moore 2004, 2005). GAB springs do not generally discharge via a defined channel, often flowing through stands of vegetation, and thus are not conducive to traditional gauging methods. Saline dilution methods utilized fluid conductivity data (EC) collected with a calibrated YSI multiparameter sonde.

Site descriptions

Three sites were utilized for this study. These sites were selected to provide data over a range of surface environments for springs of the western margin of the GAB (Fig. 1). All of the sites generally consist of Bulldog Shale overlying the sandstone aquifer beds (Cadna-owie Formation) with discharge occurring through faults in the shale (Wopfner et al. 1970; Wopfner 1972; Krieg et al. 1995). All of the sites had nearby wells to obtain head data for the aquifer in the area of the springs. The sites included: a spring system located in an area dominated by sand dunes over the springs (Gosse); a spring system with carbonate mound located directly on the Bulldog Shale in a closed depression (Warburton Spring); and a spring system located adjacent to a surface-water channel (Billa Kalina). The naming convention for the springs adopts a three-letter and three number code where the letters are defined by the area or spring complex in which they occur. The three-letter complex indicates a group of nearby springs assumed to be associated with the same discharge structure. The three-digit number serves to create a unique identifier for each spring within a complex. Many of these springs also have common names.

The Gosse spring complex located near the southern shores of the ephemeral Lake Eyre South, is characterized as a barren salinized plain with a handful of distinct vegetated dunes at which GAB waters emerge—Figs. 2–4, electronic supplementary material (ESM), ESM1. The area is located below sea level with highly saline soils and obvious salts crusting at the surface.

The Gosse mounds are sand rich and spring discharge tends to seep over broad areas rather than being focused point discharge at the tops of the mounds. One obvious small

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

Fig. 2 View of Gosse site spring LGS001 looking towards the south. The *foreground* shows the salt flat between LGS001 and LGS002 (Fig. 3) and the *background* shows the vegetated mound that rises approximately 5 m above the background terrain

pool is present at LGS002 with a depressed area 2 m wide and 0.5 m deep with focused discharge from a sandy area on the mound. This spring also has a distinct tail that drains northwards along the trend of the largest two springs (LGS001 and LGS002). The largest spring feature, LGS001, has no distinct tail; however, there are several locations around the mound where fluid pathways drain. The third spring on the site, LGS003, has no measurable flow or defined tail. It is characterized as a mound spring as it is supporting limited vegetation at its crest and has a similar morphology to the flowing mounds. The mound springs are elevated relative to the surrounding topography, but are not the highest elevations in the region (Figs. 2 and 4). The lower elevation spring, LGS002, appears to have the highest discharge of 10.0 L/min, but is difficult to quantify given the radial broad, diffuse discharge of LGS001, which has a peak elevation over 2 m higher. LGS003 is also nearly 2 m higher than LSG002 with no active flow.

The area between the flowing springs is a completely unvegetated moist salt flat (Figs. 2 and 3). Vegetation only exists on the mounds themselves. The remaining area is either gibber plain or sand dunes. The nearest well is the Gosse Spring Bore (No. 6339–09), which is 1.2 km from the site and is 96 m deep. In addition, an interpolation of estimated thickness of the confining Bulldog Shale in the vicinity of Gosse Springs using geophysical and bore log

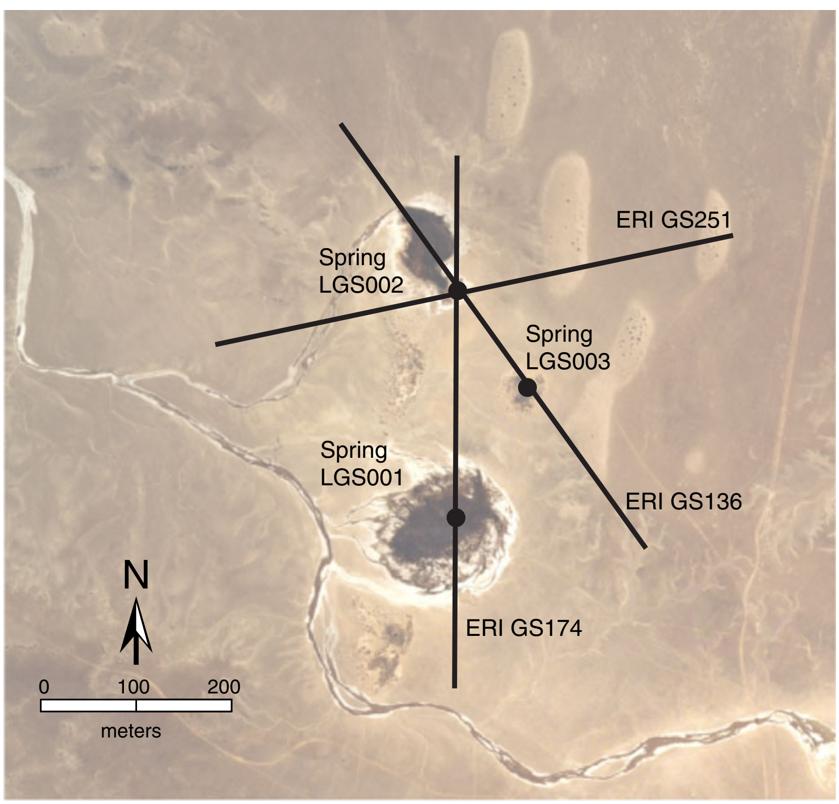

Fig. 3 Aerial view of Gosse Springs site. Orientation of three 550-m ERI lines is illustrated as well as the names of three vegetated springs on the site. Only *LGS001* and *LGS002* are freely flowing at the site. Four sand dunes are present northeast of line *ERI GS136*. The channel *at the bottom* of the image is the discharge from an adjacent set of flowing Gosse complex springs to the southeast

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

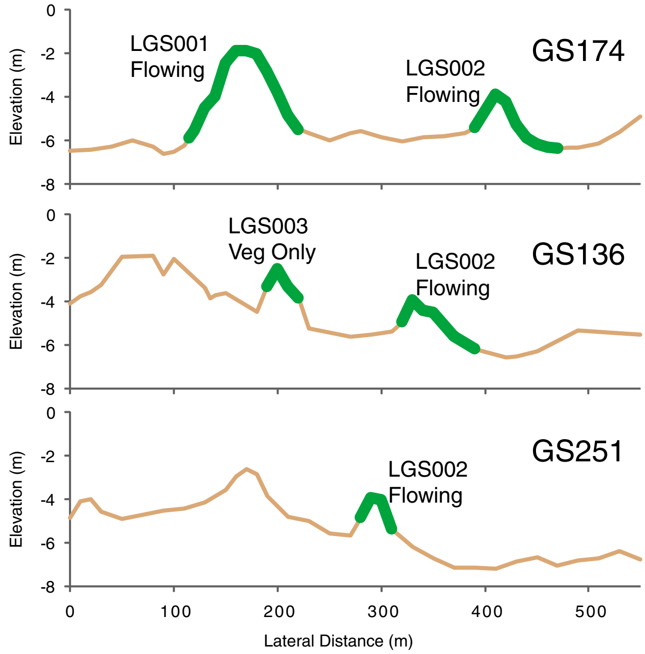

Fig. 4 Topographic profiles of ERI lines collected at Gosse site. *Green lines* indicate the location of groundwater-dependent vegetation at the site. Elevation in meters relative to the Geocentric Datum of Australia 1994

data is 64 m (Keppel et al. 2012). The two nearest bores with stratigraphic data, both approximately 31 km to the southwest (unit No. 633800025) and south (unit No. 633800026) respectively, contain reported Bulldog Shale thicknesses of 69 and 27 m. The aquifer pressure head in November 2004 was 61.26 m above the land surface or an elevation of 56.21 m amsl, approximately 60 m above the elevation of the top of the mound springs.

At the Gosse spring complex, three 550 m ERI surveys were collected at varying orientations using 10-m spacings centered around spring LGS002 (Fig. 3). Two surveys were collected to connect spring locations (GS136 and GS174). The third survey, GS251, was oriented approximately orthogonal to GS174, with the intent to avoid the local spring depression and characterize the elevated flanks of the sub-complex (Fig. 4).

The Warburton Spring System is located in the Beresford Hill Spring Complex, where 13 active springs have been identified and of which three have discernable flow (Fig. 5; ESM2). The Warburton spring discharges from a fault in a flower structure in the Bulldog Shale (Aldam and Kuang 1988). Significant landmarks of the Beresford Hill Spring Complex include three extinct spring mesas that are over 40 m above the elevation of the current shale surface.

Warburton Spring (BWS009) was noted to be nearly extinct in 1973 during a spring survey of the area (Cobb 1975). It is currently the largest discharge feature in the spring complex with a measured flow of 185 L/min. The pool at the spring is less than 1 m deep of open water and 25–30 m wide, but has a loose sediment and root layer over 4 m deep prior to reaching competent bedrock. Warburton Springs' vegetated tail extends 250 m westward orthogonally from the primary fault orientation. The tail is confined to a discrete calcium carbonate incised channel within the first 30 m, and then fans out to a broad carbonate alluvial fan (Fig. 5). The vegetated portion of the tail transitions into an extensive salt flat. The regional depression which houses the spring complex floods on a

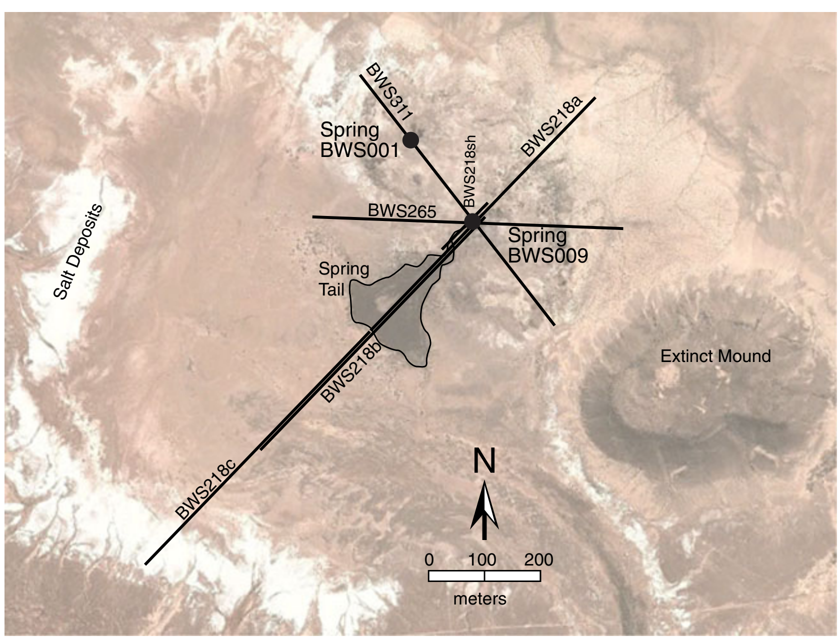

Fig. 5 Aerial view of Warburton Spring System. Orientation of five 550-m ERI lines is illustrated centered over Warburton Spring (*BWS009*, the largest spring on the site) which comprises approximately a quarter of the Beresford Hill Spring Complex. The large elevated travertine deposit to the southeast is an extinct mound deposit. The travertine for Warburton Spring System extends for nearly the entire width of *BWS311*. The salt deposits in the southwest vary over time, but maintain a similar arc

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

decadal scale and is thus postulated to interact with surface water on longer time scales.

Limited vegetation exists in the immediate vicinity of the mounds, but the remainder of the area is either shale or gibber plain. The nearest well, 4.1 km from Warburton Spring, is at the abandoned Beresford Railway Siding, which is now a historical site. The well (No. 6239–04) is 94.5 m deep. In addition, an interpolated estimated thickness of the Bulldog Shale in the vicinity of the Beresford Hill Spring Complex using geophysical and bore log data is 78 m (Keppel et al. 2012), while the nearest bore with stratigraphic data located 16 km to the southwest, (unit No. 623900047) contains a reported Bulldog Shale thicknesses of 62 m. The aquifer pressure head in September 2008 was 30.14 m above the land surface or an elevation of 60.13 m amsl, approximately 30 m above the top of the mounds.

At the Warburton site, ERI datasets were collected at three orientations using 10-m spacings (Fig. 5; ESM2). Two single lines were collected at orientations of 311° (the primary fault orientation of the flowing springs) and 265° (approximately 45° from the primary spring orientation and the spring-tail orientation). Along the spring tail, three roll-a-long survey lines at 218° were collected for a total line length of 1,110 m. To improve near surface resolution at the spring discharge point, a 110 m long, 2-m electrode spacing survey was also collected along this orientation.

The Billa Kalina Spring Complex is adjacent to the Margaret River (Fig. 6; ESM3) on the flood plain of the ephemeral river system. It is located at a 90° bend in the river course; here a waterhole of considerable volume and higher salinity than that discharging at the nearby associated springs is thought to be a nearly permanent water feature.

The complex has two distinct active springs and one large extinct spring. Other active and extinct springs can be found within 1 km of the study area. The active springs tend to have much smaller mounds in terms of elevation and volume compared to the extinct spring mounds, some of which still support vegetation. All springs have a classic carbonate mound and circular ridge surrounding a sunken spring pool zone. These are similar though smaller in size to those found at Warburton Spring.

The immediate area surrounding the main Billa Kalina Springs (KBK001 and KBK002) is well vegetated and fenced off to protect it from cattle intrusion. Beyond the main springs, vegetation is limited. The measured discharges of KBK001 and KBK002 are 7.2 and 3.4 L/min, respectively. The nearest well (Margaret Creek 2, No. 6139–22) is located a few meters from spring KBK001 and is drilled to a depth of 28.5 m. The measured water level in this well is 11.01 m above the land surface or 53.09 m amsl. This places the head level in the area approximately 10 m above the top of the mounds. In addition, an interpolated estimated thickness of the Bulldog Shale in the vicinity of Billa Kalina Springs using geophysical and bore log data is 4.3 m (Keppel et al. 2012), while the nearest bore with stratigraphic data located 13 km to the south, (unit No. 613800055) contains a reported Bulldog Shale thicknesses of 33 m.

At the Billa Kalina site, six ERI datasets with, 10-m electrode spacings (total line length of 550 m) were collected at three orientations (Fig. 6). The research aim was to determine the spatial connectivity relationships between the various spring outlets, as well as with the abutting Margaret River. Sets of two lines were collected

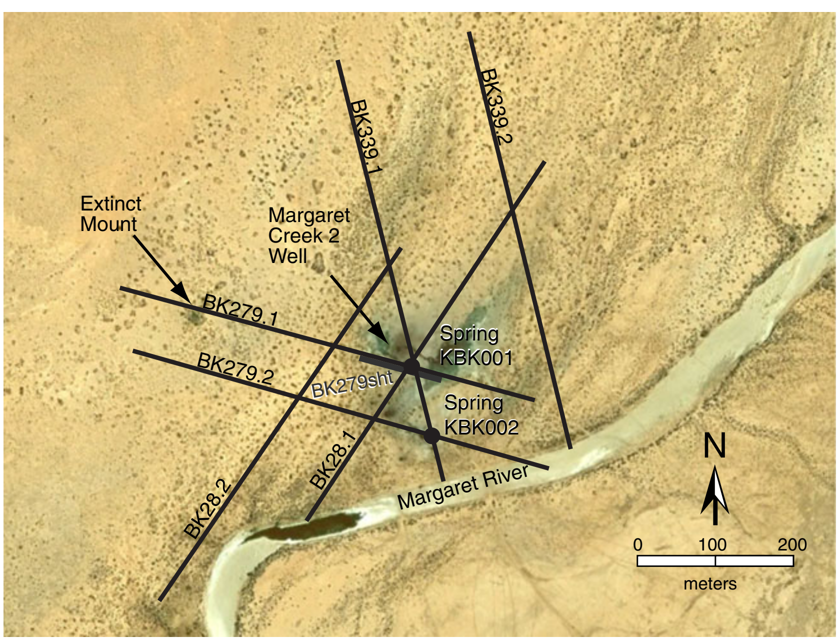

Fig. 6 Aerial view of Billa Kalina site. Two active springs and one extinct spring were included in the surveys. The active springs have two small tails that extend towards the NW along a 279° orientation. The nearby borehole being left open generated the other *large green area*. During the data collection, the bore had been shut in for some time

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

at 28, 279 and 339°. A 2-m electrode spacing line was also collected at 279° over the highest flowing spring-tail region (KBK001) for increased resolution.

Data analysis methods

ERI data were analyzed to determine if there was a quantitative relationship between ERI resistivities and fluid conductivity at the surface discharge locations. A connectivity analysis followed to determine the approximate number and location of connections between subsurface fluid reservoirs and surface discharge locations. Finally, the data were evaluated to examine the structure of the mound deposits at the sites.

ERI fluid analysis

To quantitatively evaluate the relationship between ERI data and fluid EC data, a number of models can be utilized. For this study, a simple power law evaluation was utilized as the data only needed to be qualitatively related to fluid location (Fig. 7). The ERI values at the spatial locations coincident with surface-water EC measurements were correlated for each site and for each ERI dataset that cross a point that fluid EC data were collected. The data were evaluated to determine if a statistically significant relationship existed for each site and between sites.

ERI connection analysis

To determine connectivity beneath the mound spring systems in an electrically conductive environment, the fluid flow pathways must dominate the ERI data signal. This assumption allowed resistors in the subsurface to be interpreted as discharging aquifer fluids. This assumption was tested by evaluating fluid EC values to measured ERI resistivity values at surface discharge locations.

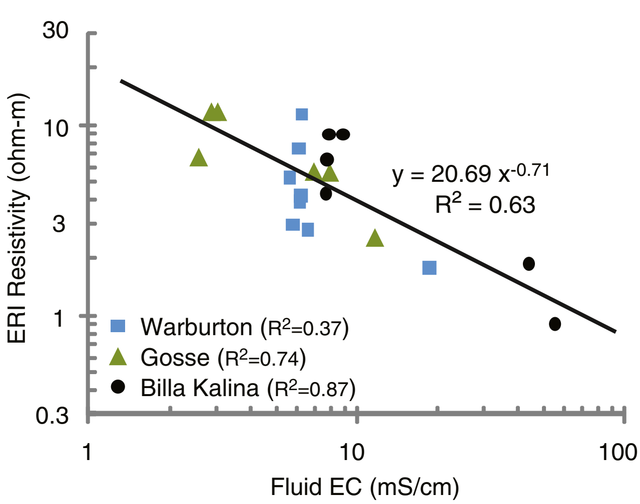

Fig. 7 Fluid electrical conductivity versus ERI resistivity values for three sites in the western margin of the GAB. The R^2 value for the overall fit for the three sites is 0.63, but ranges of values for the individual sites are provided in the legend

Within a spring complex, groundwater discharge occurred as a variety of springs, seeps, or vegetated areas, indicating that multiple connections to the confined Cadna-owie Formation aquifer should exist through the confining Bulldog shale. In the ERI datasets, this should result in a number of features if the data are providing evidence of the fluid connection geometry. First, the subsurface ERI connections to the surface should correlate with the location of springs and vegetated areas. The number of connections that are found should be greater along fault zones than orthogonal to them. The correlations should be consistent in location and magnitude between different ERI orientations over the spring zones.

The analysis of subsurface connection is constrained due to culturally protected status and the hydraulically sensitive state of the springs. The use of invasive, investigative methods such as drilling or other direct subsurface sampling techniques can damage and alter spring conditions, limiting the ability to test areas interpreted as connections with no obvious surface expression. As such, the results of connectivity analysis can only be confirmed where surface-feature evidence exists.

For these ERI datasets, a characteristic structure exists for the datasets. At the location of known discharge, ERI resistivity is higher than adjacent regions within the data profile even though the entire profile is conductive. Relative high resistivity is also observed at greater depth from the base of the profiles. Regions of low resistivity are typically observed in the middle depths of the profile and extend to the surface adjacent to the spring locations. This characteristic data distribution allows a connection evaluation to be performed between the deep and shallow resistive features (corresponding to discharging confined groundwater). Here, vertical connections can be established through the more conductive central region of the images between the top and base of the image profile. Vertical connections are quantified by creating a post map of the ERI pseudosection grid which did not post values less conductive than a defined ‘connection value’. If the connection value is too high, no connections will be identified between the top and bottom of the image. Using a low connection value, the data profile becomes mostly connected vertically from top to bottom. Varying the connection value provides bounds on the possible number of connections between the subsurface (aquifer) and surface (spring) features.

In order to establish an appropriate connection value for a site, all the datasets at that site were evaluated over the range of possible connection values, such that the number and location of connections at each connection value setting could be assessed. For each ERI data profile, the connection value is plotted with the number of vertical connections it promotes (Fig. 8). As the connection value (related to the fluid properties) increases in resistivity, the number of possible vertical connection decreases. Considering all the data for a site, the site connection value is determined by evaluating the value which best corresponds to known surface-feature locations as well as a

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

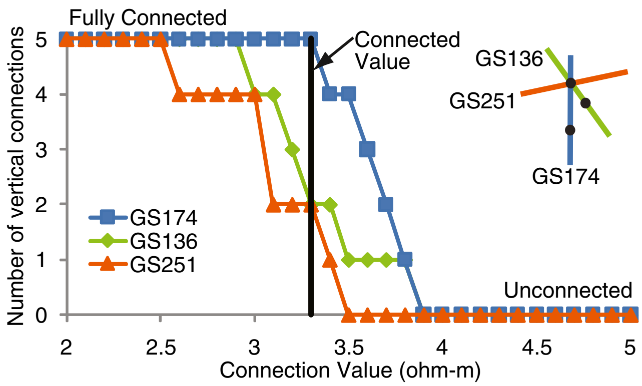

Fig. 8 Connection analysis for Gosse site. No resistive portions of the three ERI datasets collected at the site connected between the upper and lower portion of the images at values above 3.9 ohm-m. No significant conductive barriers remained between the top and the bottom of the image below 2.5 ohm-m. A 'connection value' was selected at 3.3 ohm-m, although other values between 2.5 and 3.9 ohm-m would also be reasonable. *Inset lines* illustrate relative orientation and springs along each line

result consistent for all datasets orientations collected at a site. The connection location to the surface was extrapolated along the angle that the connection exhibited in the dataset. This site connection value is subjective, but the results indicate that there is not significant variability in the selection of a connection value at a single site or for this hydrogeologic setting across sites. The connections may be oriented vertically or dipping.

Mound deposit analysis

Due partly to cultural and hydraulic sensitivities, GAB mound springs have rarely been cored to investigate structure. The ERI data were evaluated to estimate the dimensions of the carbonate portion of the spring mounds. The ERI data were compared against the mound topography to evaluate if any electrical evidence of a mound "root" was available. This could provide evidence for how the bottom of the mound may be connected to the surface discharge features.

Results

As part of the results, the overall quality of the ERI dataset is examined. Next, the results evaluate the assumption that the ERI dataset signals are dominated by fluid properties. Then, the connections from the aquifer to the surface are evaluated in the context of the site structural geology. Finally, the mound structure is evaluated to determine how it affects mound connectivity.

ERI datasets

The data quality for the ERI datasets was deemed very good as there were generally good electrode connections, measured as low contact resistance, across most of the study areas due to saline and/or moist conditions at the surface. In general, areas with poor (low) contact resistance due to dry or lithified surfaces resulted in higher inversion errors and greater data losses. Normal data losses occurred throughout the dataset, but were generally more frequent when associated with a poor contact resistance electrode. The data losses could not be correlated with deeper depths of investigation as may normally be the limiting factor.

The Gosse Site had the best ERI data quality. The RMS inversion error ranged from 5.6 to 6.6 % for the electrical pseudosection models. As part of the inversion, data losses were in the range of 6–11 % with an average of 9 % data loss. The site was highly electrically conductive with an ERI data range from 0.4 to 29.4 ohm-m.

The Warburton Site was similar to the Gosse site, but there were a few dry, lithified areas that affected contact resistance. The RMS inversion error ranged from 3.4 to 8.4 %. The inversion data losses ranged from 8 to 12 % with an average of 10 % data loss. The site was very conductive at depth, but had resistive carbonate deposits associated with the main discharge locations. The ERI resistivity of the site ranged from 0.4 to 39.5 ohm-m.

The Billa Kalina site had a significant number of dry areas and dunes which affected contact resistance. The RMS inversion error was slightly higher for this site ranging from 5.2 to 11.4 %. The inversion data losses ranged from 7 to 18 % with an average of 12 %. The ERI resistivity of the site ranged from 0.4 to 113.0 ohm-m.

ERI/EC relationships

The ERI data correlated to fluid electrical conductivity measurements collected at all three sites (Fig. 7). The Gosse site had several locations along ERI lines at which fluid EC could be measured with no highly conductive samples recorded from the salt flat region. Based on the available data, a power law fit with an R^2 value of 0.74 was available for the site. Billa Kalina also had a good fit (R^2=0.87) including high-salinity surface fluids collected from the pooled water within the riverbanks. The Warburton site yielded the lowest relationship. The majority of the fluid conductivity samples were collected from within the spring tail and nearby alternative research sampling sites. These sample sites were only 5–10 m from the ERI line, but the fluid EC may have varied more highly in the tail region than expected, decreasing the quality of the ERI relationship with fluid EC. Across the three sites an overall relationship is available that demonstrates a significant variation in ERI resistivity due to changes in fluid resistivity (R^2=0.63).

ERI connection analysis

The connection analysis results were similar across all three sites. At all three sites, the flowing springs or vegetated mound areas were represented in the subsurface with a relatively resistive set of values connecting the

DOI 10.1007/s10040-013-1034-8

Author's personal copy

spring areas to the deep portions of the ERI profiles, interpreted to coincide with a GAB aquifer source. Many of the springs at all three sites had multiple independent resistive connections to depth. Additionally, larger vegetated spring tails were also connected to the subsurface with vertical resistive pathways.

For the Gosse site, ERI resistivity connection values greater than 3.9 ohm-m does not yield any connection between the surface (springs) and profile base (aquifer; Fig. 8). ERI resistivity values above 3.9 ohm-m are considered unconnected and not a reasonable interpretation based on the known fluid connections between the aquifer and the springs. Resistivity for the central and generally least resistive regions of the profiles are below 2.5 ohm-m. Defining connection values lower than this threshold implies that fluid is moving from the aquifer to the springs at all locations in the subsurface. This condition would be considered fully connected and is not plausible, nor consistent with observations at the surface. At values between 2.5 and 3.9 ohm-m, the three Gosse Springs datasets present a range of connection in location and orientation. There are more “connections” at lower values than higher values. A value of 3.3 ohm-m was selected as the connection value for the Gosse site.

The ERI line GS174, orientated along the only two flowing spring features at the site yields more vertical connections for all connection values than is observed for the other two orientations (Figs. 8 and 9). ERI line GS251 which aligns over only one flowing spring consistently yields the fewest number of connections in the dataset. As the connection value decreases in the analysis, existing connections may become wider (more profile data points/pixels) and new connections are realized. As the values decrease, connections become wide enough to connect to other vertical resistors. For the Gosse site, no more than five connections can be separated in any of the images (Figs. 8 and 9). The locations of known springs and surface vegetation strongly correlate with the ERI determined connection locations and indicate that multiple connections may be occurring at flowing springs.

For the Warburton site, the range of connection values is between 2.0 and 3.3 ohm-m. A connection value of 2.6 ohm-m was selected for the site. Once again, the line oriented between two flowing springs (BWS311, parallel to the fault) always has a greater number of connections than line oriented in other directions. The line located only over a single spring (BWS265) always has fewer connections, consistent with the analysis for other sites. For this site that is not sand rich at the surface like the Gosse site, the connections remained narrower as the connection value was decreased, so the maximum number of connections was 10 narrower possible conduits.

At the Billa Kalina site, the range of reasonable connection values is between 2.5 and 4.4 ohm-m. An optimal connection value of 3.3 ohm-m was selected for the site, which is identical to the value assigned for the Gosse site. At Billa Kalina the greatest number of connections was interpreted for the line containing a flowing spring and a spring with limited vegetation and a limited amount of pooled water (BK279.1). This line incorporated the extended tail of spring KBK001. The line along the two flowing springs (BK339.1) and the line containing spring KBK002 and its spring tail (BK279.2) showed a similar number of connections. The two lines that did not cross springs showed the fewest connections (BK28.2 and BK339.2). As they only show limited connections below connection values of 3.2 ohm-m, the connection value was set at 3.3 ohm-m. Similar to the Warburton site, the connection widths did not vary greatly in response to variations in the estimated connection value, with 10 possible connections as the maximum observed with this dataset.

Mound analysis

The carbonate mounds associated with the springs correlated with resistive portions of the ERI datasets. These are most evident in the two, shorter, 2-m electrode spacing ERI datasets collected at Warburton and Billa Kalina (ESM2 and ESM3). Some of the carbonate portions were as conductive as the underlying shale confining bed across the surface contact. However, none of the resistive portions of the mounds extended below the regional elevation of the top of the shale. The ERI data suggests that the mound carbonates are deposited on top of the shale and do not extend down into any of the conduits in the shale, consistent with chemical analysis of mound precipitation processes and structure (Keppel et al. 2011).

Discussion

These results must be evaluated in the context of the uncertainties in the ERI datasets, but have significant implications for the development and long-term maintenance of the mound springs of the western margin of the GAB.

ERI uncertainties

ERI data has two uncertainties than can affect the interpretation of the results for this study. First, bulk resistivity data incorporate a measurement of both fluid and rock properties. For the site, the majority of the lithology represented is the Bulldog Shale, with a limited extent of sandstone at the bottom of the datasets and limited extents of carbonate mound at the top. As the connection analysis is looking for vertical connections through the horizontally bedded shale, this variability is unlikely to be generated from a lithologic signature. If the vertically resistive paths are generated by fractures instead of fluid pathways, then the interpretation as potential conduits for groundwater flow is the same. However, with the range of resistivity in the images, this is unlikely. Based on the relationship between fluid EC and bulk resistivity data, the interpretation of resistive vertical features representing groundwater flow pathways seems

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

to be the most logical. This is also supported by the distribution of surface features which correspond to the vertical resistors in the datasets.

Secondly, the sensitivity of the resistivity dataset may be limited in the bottom of the image in environments that are as conductive as these. This means that the real values of resistors in the bottom of the dataset may be different from the pseudosection values even when no data loss occurs. For this study, the values at the bottom of the image correlated to the bulk resistivity values all along the vertical pathways. No significant change in bulk resistivity was observed along the interpreted vertical pathways. This suggests that this problem was not significant for these data.

Implications for conceptual model of springs

As invasive studies are no longer allowed at the mound springs, these datasets provide important information regarding the hydraulics of the mound systems. The data indicate that the pathways through the shale-confining layer are not a single fault plane or isolated conduit. The connections to the spring complexes appear to be best represented as a limited heterogeneous line that sources along faults with a seepage face at the surface. The larger discharges appear to occur at the intersection of these fault-line sources.

For mound spring longevity, the mound carbonate deposits appear to only reside at the surface, thus any clogging that occurs due to the deposition of minerals would appear to only affect the shallow portion of a spring. Even though the head difference between the mound springs and the aquifer ranged between 10 and 60 m, no significant differences appeared in the mounds. Thus with the multiple connections to the surface and lack of carbonate in the conduits, if sufficient head is maintained or reestablished, the springs should be able to continue flowing. For springs that were not flowing at the sites, resistive connections either were still located to those areas, or were close to those locations. The line at the Gosse site that crossed over the sand dunes in the northeastern portion of the site (GS251) illustrates this near connection (Figs. 3 and 9). The dune has a similar topography and elevation to the nearby active spring, but no vegetation. In the ERI dataset, however, there is nearly a resistive connection to that location. This implies that the extinct springs may still maintain connections in the subsurface. For the Billa Kalina site, line 279.1 illustrates a similar feature for the nearly extinct spring located to the left of the flowing spring (ESM3).

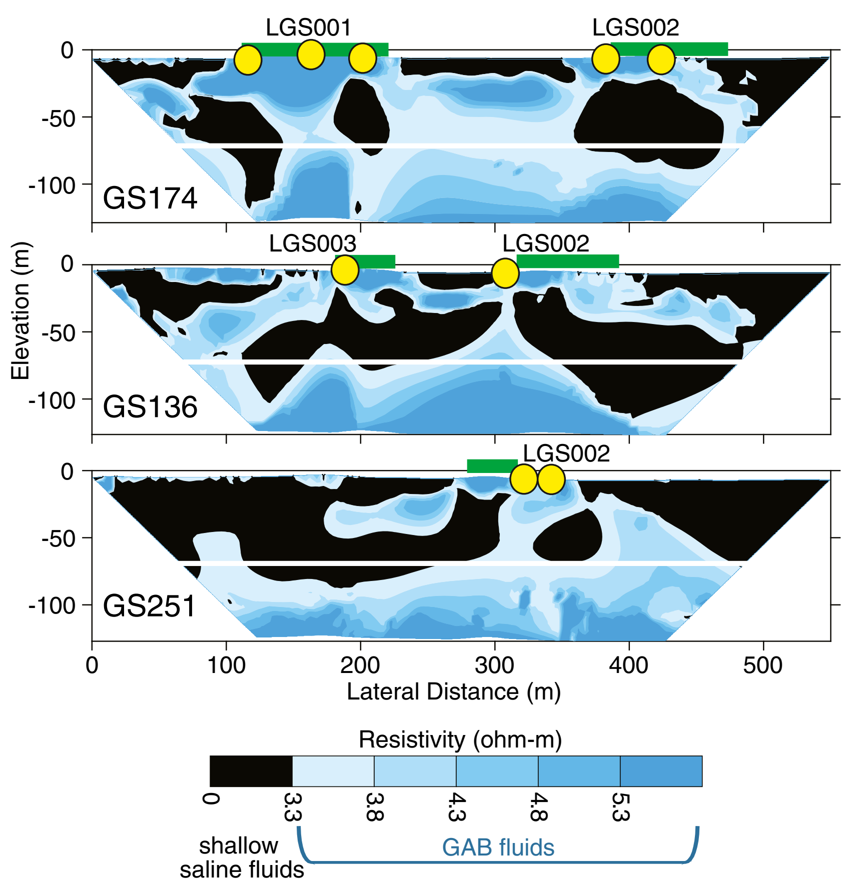

Fig. 9 ERI datasets for Gosse site. Data are contoured with values above the connection value in *blue* representing the interpreted distribution of upwelling of GAB fluids to the spring mounds. Surface locations of inferred connections are shown as *yellow circles*. Field observations of spring-dependent surface vegetation are presented as *green lines*. The *white line in center of images* indicates approximate lower boundary of the Bulldog Shale confining unit and upper boundary of the Cadna-Owie aquifer

 DOI 10.1007/s10040-013-1034-8

Author's personal copy

Finally, the ERI datasets provide clear evidence that extensive spring tails, which provide extensive groundwater dependent ecosystems in the area, are hydraulically more similar to a line source of springs than a surface channel coming from an isolated conduit. While these systems integrate surface flow from the main spring, additional groundwater is discharged along the tail environments. This has significant implications for both geochemical analyses and discharge data in spring environments and species mapping in these environments.

Conclusions

ERI data and surface fluid EC data were collected at three mound spring sites in the western margin of the Great Artesian Basin, South Australia. The site was highly conductive with ERI bulk resistivity values ranging from 0.4–113.0 ohm-m with most values below 10 ohm-m. The ERI data and fluid EC data have a quantitative power law relationship indicating the major signal present in the ERI data is a fluid EC signature.

A connection analysis was performed to determine the location and number of connections between the artesian aquifer at depth and the surface springs which discharge water from the artesian aquifer. The connection analysis was similar for all three sites, although the connections were wider at the Gosse site than the other two. All three sites showed connections that corresponded with surface discharges and vegetation. Additionally, all three sites had the greatest number of connections along orientations with the largest number of flow features. ERI datasets collected off of fracture orientations had fewer or no connections to the surface.

The analysis of ERI data suggest that the springs can be hydraulically interpreted as limited-length heterogeneous line sources, not single conduits from depth. The highest discharge locations corresponded to multiple subsurface connections and intersections of interpreted line sources. The data suggest that extensive spring-tail environments that exist at many mound spring sites are actually continuing groundwater discharge features, not simply surface water features. The results suggest that if head levels are maintained or regained in the aquifer the springs will continue to discharge from the aquifer.

Acknowledgments We would like to acknowledge the support of the Australian National Water Commission for support of this project. In addition, we would like to thank the station owners and personnel for their assistance with this work. We thank Daniel Wohling, Travis Gotch, Brad Wolaver, Stacy Priestley, and Sarah Doyle for field assistance. We would also like to thank Zach Riggins for editing assistance, and Dr. Stasko and an anonymous reviewer for their thoughtful comments. Dr. Halihan has a managed conflict of interest with regards to ERI developments.

References

Ah Chee D (2002) Indigenous people's connection with Kwatye (water) in the Great Artesian Basin. Environ South Australia 9(1):6

Aldam R, Kuang KS (1988) An investigation of structures controlling discharge of spring waters in the South Western Great Artesian Basin. Rept. Bk. 88/4. Department of Mines and Energy, Adelaide, Australia

Berry KA, Armstrong D (1995) Hydrogeological investigation and numerical modeling, Lake Eyre Region, Great Artesian Basin. WMC, Adelaide, Australia

Cobb MA (1975) Sampling and measurement of mound springs, Great Artesian Basin, South Australia. Progress report no. 2, Maree, Curdimurka and Billa Kalina sheets. Open file report, Department of Mines and Energy, South Australia, Geological Survey, Engineering Division, Adelaide, Australia

Crossey LJ, Fischer TP, Patchett PJ, Karlstrom KE, Hilton DR, Newell DL, Huntoon P, Reynolds AC, de Leeuw GAM (2006) Dissected hydrologic system at the Grand Canyon: interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine. Geology. doi:10.1130/G22057.1

Demanet D, Renardy F, Vanneste K, Jongmans D, Camelbeeck T, Meghraoui M (2001) The use of geophysical prospecting for imaging active faults in the Roer Graben, Belgium. Geophysics 66(1):78–89

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

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: their origin and nature. Report 235, Bureau of Mineral Resources, Geology and Geophysics, Canberra, Australia

Habermehl MA (1986) Mound Spring deposits of the Great Artesian Basin. Earth Resources in Time and Space: 8th Geological Convention. Peacock, Adelaide, Australia

Halihan T, Fenstemaker T (2004) Proprietary electrical resistivity imaging method, 20th edn. Oklahoma State University Office of Intellectual Property, Stillwater, OK

Halihan T, Love A, Sharp JM Jr (2005) Identifying connections in a fractured rock aquifer using ADFTs. Ground Water 43(3):327–335

Hancock PL, Chalmers RML, Altunel E, Cakir Z (1999) Travitonics: using travertines in active fault studies. J Struc Geol 21(8–9):903–916

Hart DJ, Bradbury KR, Feinstein DT (2006) The vertical hydraulic conductivity of an aquitard at two spatial scales. Ground Water. doi:10.1111/j.1745-6584.2005.00125.x

James BR, Freeze RA (1993) The worth of data in predicting aquitard continuity in hydrogeological design. Water Resour Res. doi:10.1029/93wr00547

Karlstrom KE, Keppel MN, Love AJ, Crossey L (2013) Chapter 4: Structural and tectonic history, chap 4. In: Keppel MN, Love AJ, Karlstrom KE, Priestley S (eds) Hydrogeological framework of the western margin of the great artesian basin. National Water Commission, Canberra, Australia

Keppel MN, Clarke JDA, Halihan T, Love A, Werner AD (2010) The hydrochemistry of selected mound spring environments, Lake Eyre South region, Great Artesian Basin, South Australia, Groundwater 2010. IAH, National Convention Centre, Canberra, Australia

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. Sedim Geol 240:55–70

Keppel M, Wohling D, Fulton S, Sampson L, Karlstrom K, Nelson G, Ransley T, Love A (2012) Summary of hydrogeology and hydrostratigraphy, chap 3. In: Keppel MN, Love AJ, Karlstrom KE, Priestley S (eds) Hydrogeological framework of the Western Margin of the Great Artesian Basin, Australia. National Water Commission, Canberra, Australia

Krieg GW, Alexander E, Rogers PA (1995) Eromanga Basin. In: Drexel JF, Preiss W (eds) The geology of South Australia. Geological Survey of South Australia, Adelaide, Australia, pp 101–105

La Pointe PR, Hudson JA (1985) Characterization and interpretation of rock mass joint patterns. Geol Soc Am Spec Pap 199

Author's personal copy

Le Borgne T, Bour O, Riley MS, Gouze P, Pezard PA, Belghoul A, Lods G, Le Provost R, Greswell RB, Ellis PA, Isakov E, Last BJ (2007) Comparison of alternative methodologies for identifying and characterizing preferential flow paths in heterogeneous aquifers. J Hydrol. doi:10.1016/j.jhydrol.2007.07.007

Moore RD (2004) Introduction to salt dilution gauging for streamflow measurement: part 1. Watersh Manag Bull 7(4):20–23

Moore RD (2005) Slug injection using salt in solution. Watersh Manag Bull 8(2):1–6

Murphy NP, Adams M, Austin AD (2009) Independent colonization and extensive cryptic speciation of freshwater amphipods in the isolated groundwater springs of Australia's Great Artesian Basin. Mol Ecol. doi:10.1111/j.1365-294X.2008.04007.x

Neuzil CE (1994) How permeable are clays and shales? Water Resour Res. doi:10.1029/93WR02930

Ponder W F (2002) Desert Springs of the Australian Great Artesian Basin. In: Sada D W, Sharpe S E (eds) Spring-fed wetlands: important scientific and cultural resources of the Intermountain Region. Desert Research Institute, Las Vegas, NV

Prescott JR, Habermehl MA (2008) Luminescence dating of spring mound deposits in the southwestern Great Artesian Basin, northern South Australia. Aust J Earth Sci 55(2):167–181

Radke BM, Ferguson J, Cresswell RG, Ransley TR, Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadna-owie-Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra, Australia, 232 pp

Sprigg RC (1957) The Great Artesian Basin in South Australia. J Geol Soc Aust 5(2):88–101

Waclawik VG, Lang SC, Krapf CBE (2008) Fluvial response to tectonic activity in an intra-continental dryland setting: the Neales River, Lake Eyre. Cent Aust Geomorp. doi:10.1016/j.geomorph.2007.06.021

Warner NR, Kresse TM, Hays PD, Down A, Karr JD, Jackson RB, Vengosh A (2013) Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville shale development, north-central Arkansas. App Geochem. doi:10.1016/j.apgeochem.2013.04.013

Wopfner H (1972) Depositional history and tectonics of South Australia sedimentary basins. Mineral Resources Review, 133. Department of Mines, South Australia, Adelaide, Australia, pp 32–50

Wopfner H, Freytag B, Heath GR (1970) Basal Jurassic-Cretaceous rocks of the Western Great Artesian Basin, South Australia: stratigraphy and environment. Am Assoc Petrol Geol Bull 54(3):383–416

 DOI 10.1007/s10040-013-1034-8