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Discussions

Hydrological functions of sinkholes and characteristics of point recharge in groundwater basins

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Abstract

Karstic limestone aquifers are hydrologically and hydrochemically extremely heterogeneous and point source recharge via sinkholes and fissures is a common feature. We studied three groundwater systems in karstic settings dominated by point source recharge in order to assess the relative contributions to total recharge from point sources using chloride and δ^{18}O relations. Preferential groundwater flows were observed through an inter-connected network of highly conductive zones with groundwater mixing along flow paths. Measurements of salinity and chloride indicated that fresh water pockets exist at point recharge locations. A measurable fresh water plume develops only when a large quantity of surface water enters the aquifer as a point recharge source. The difference in chloride concentrations in diffuse and point recharge zones decreases as aquifer saturated thickness increases and the plumes become diluted through mixing. The chloride concentration in point recharge fluxes crossing the watertable plane can remain at or near surface runoff chloride concentrations, rather than in equilibrium with groundwater chloride. In such circumstances the conventional chloride mass balance method that assumes equilibrium of recharge water chloride with groundwater requires modification to include both point and diffuse recharge mechanisms.

1 Introduction

Karst landscapes are often characterized by the presence of sinkholes, caves and underground conductive zones, formed primarily by dissolution of soluble limestone and dolomite. A distinct hydrologic feature of karst systems is the duality of flow regimes (Gunn, 1983; Taylor and Greene, 2001), which can be separated into: point (shaft and conduit dominated), and diffuse (matrix, meso- and macro-pore dominated) infiltration and recharge. Knowledge of recharge conditions is important if limestone aquifers are to be developed as water resources (Gunn, 1983). Two main forms of recharge to lime-

HESSD
10, 11423–11449, 2013

stone aquifers are recognised (Gunn, 1983; White, 2003; Gldscheider and Drew, 2007). Allogenic, where recharge water is collected from outside the aquifer area, whereas autogenic input water is derived solely from rainfall within the aquifer area. Hydrologic characteristics of karst aquifers are largely determined by the structures and organization of the conduits (White, 2003). Rapid flow through point sources in karst aquifers may create pathways for surface contaminants to enter and degrade groundwater resources (Hallberg and Hoyer, 1982; Tihnasky, 1999; Gordon, 2011; Hyland et al., 2006). These aquifers are highly heterogeneous and anisotropic (White, 2003; Bakalowicz, 2005) and are susceptible to further dissolution by circulating groundwater. The identification of groundwater flow paths in karst aquifers is therefore problematic (Tihnasky, 1999). Dissolution cavities have a distinct geomorphology, may have a wide range of sizes and become hydraulically interconnected, enhancing the movement of groundwater.

White (2003), Taylor and Greene (2008), Lerch et al. (2005) and Bakalowicz (2005) recognise the complex nature of flows resulting from the presence of karstic features. Taylor and Greene (2001) and Bakalowicz (2005) hold that conventional study methods used in classical hydrogeology are generally invalid and unsuccessful in karst aquifers, because the results cannot be extended to the whole aquifer nor to some parts, as is often possible in non-karst aquifers.

We examined hydrological functions of sinkholes in three karstic groundwater basins with particular reference to; chloride distributions in point and diffuse recharge zones, groundwater mixing, preferential flowpaths, prediction of groundwater recharge using the conventional chloride mass balance (CMB) method, and compare this to point recharge estimates. We critically evaluated the validity of conventional CMB for karstic aquifers, and suggests extending the method to include both point and diffuse recharge components.

HESSD
10, 11423–11449, 2013

2 Methods

Three groundwater basins in South Australia that are dominated by point recharge are examined in this study (Fig. 1). In the Uley South Basin, recharge is dominated by point recharge through solution features (Fig. 1). In the Mount Gambier Blue Lake capture zone, point recharge is mainly through 400 storm water drainage wells (small man-made sinkholes) (Fig. 2). In Poocher Swamp, recharge from a large volume of creek water concentrates into two sinkholes resulting in formation of a fresh water bubble (Fig. 3).

Hydrological functions of sinkholes and characteristics of point recharge were assessed using chloride Vs δ^{18}O relation, groundwater mixing, identification of groundwater flow paths, chloride distribution within and outside point recharge zones, estimation of volume of point recharge and comparison to total recharge predicted using conventional CMB method for the three study basins.

2.1 Uley South Basin

Uley South Basin, approximately 113 km^2 in area is located on the Southern Eyre Peninsula of South Australia (Fig. 1). Average annual rainfall is 550 mm and average annual pan evaporation is about 1550 mm. The basin has been used for reticulated town water supply since 1976, and currently about 6.8×10^6 m^3 per year of groundwater is extracted from the Quaternary limestone aquifer. The hydrogeology of Uley South Basin comprised of Quaternary limestone of an average thickness of 15 m, followed by a Tertiary clay unit of 5–25 m thickness, and a Tertiary sand aquifer (Evans, 1997). The Tertiary clay forms an aquitard between the Tertiary sand and the Quaternary aquifer systems. Groundwater flow direction is from north-east to south-west.

The basin is topographically closed and bounded by coastline and sand dunes to the west and inland to the north and east by topographic rises of dry limestone, except along the north-eastern edge. The low lying central part of the basin contains numerous sinkholes. Runoff is highly ephemeral, occurring only after moderate to high

HESSD
10, 11423–11449, 2013

intensity rainfall and persisting only tens to hundreds of meters before entering a sinkhole (Evans, 1997; Harrington et al., 2006; Ordens et al., 2012). A survey of a 4 km^2 area found a density of about one sinkhole per 0.07 km^2 of approximate size range of 0.4–2.5 m diameter (Somaratne, 2013). Groundwater chloride for this study is from Evans (1997) and water quality and stable isotope sampling and analysis in 2008. Data gaps were filled by linear regression of total disolved solids (TDS) to chloride ($R^2 = 0.98$) for monitoring wells where TDS are available but no chloride measurements have been undertaken. Selected monitoring wells are away from brackish water upward leakage areas or salinity stratified wells, the swamp and coastal monitoring wells.

2.2 Mount Gambier Blue Lake capture zone

The Blue Lake is a volcanic crater complex, and is the water supply reservoir for the City of Mount Gambier (Allison and Harvey, 1983). The lake is groundwater fed through an extensive karst aquifer (Waterhouse, 1977; Turner, 1979). Currently 3.6×10^6 m^3 is extracted annually for the town water supply. The main source of recharge to the Blue Lake is groundwater from the unconfined, karst Gambier Limestone aquifer underlying the urban area. Average saturated thickness of the Gambier Limestone aquifer is about 60 m. Storm water derived from the central 16.8 km^2 of the city area (26.5 km^2) is discharged to the unconfined aquifer through sinkholes and 400 storm water drainage wells (EPA, 2007). The average annual rainfall in Mount Gambier is 750 mm and average annual pan evaporation is 1400 mm. The Blue Lake capture zone is located about 20 km from the coastline. Regional groundwater flow direction is from north to south, however, the Blue Lake receives groundwater flow from the north-west to north-east direction of the capture zone.

For this study, groundwater chloride data were used from samples taken from unconfined aquifer monitoring wells within and outside the city. Selected sampling wells are away from historically known contaminated sites. In addition to the monitoring wells, groundwater samples were taken from drainage wells and surface runoff. Salinity pro-

HESSD
10, 11423–11449, 2013

files taken by sonding in 2011 and 2012 for selected monitoring and drainage wells were used to study vertical distribution.

2.3 Poocher Swamp fresh water bubble

The Tatiara catchment area extends across the South Australian border into Western Victoria, and features average annual rainfall of 400–500 mm and pan evaporation of 1700 mm. The catchment area is approximately 1000 km^2. The unconfined aquifer is Murray Group Limestone and contains brackish water with average TDS > 1400 mg L^{-1}, with a chloride concentration of > 500 mg L^{-1} (MacKenzie, 2013) (Fig. 3). Saturated thickness of the limestone unconfined aquifer is approximately 50–60 m. Fresh water with TDS < 1000 mg L^{-1} occurs at locations where point recharge takes place through sinkholes, locally known as runaway holes. There are a number of sinkholes in the catchment that potentially impact surface water yield. Poocher Swamp's fresh water bubble, which is the largest of these fresh water plumes that float on brackish water, is a result of flows from Tatiara Creek which enter two large sinkholes in Poocher Swamp (Fig. 3). The area encompassed by the 1000 mg L^{-1} salinity contour comprises approximately 20 km^2. This catchment generates irregular annual volumes of freshwater (50–2000 × 10^3 m^3) per year, but on rare occasion up to 19 × 10^6 m^3 per year. Poocher Swamp is located some 200 km north of Mount Gambier and 100 km from the nearest coastline to the west. Groundwater flow direction is from east to west. Currently, an annual volume of 0.6 × 10^6 m^3 of groundwater is extracted from the fresh water bubble for town water supply with average salinity 490 mg L^{-1} and chloride concentration of 115 mg L^{-1}.

HESSD
10, 11423–11449, 2013

3 Results and discussion

3.1 Characteristics of point recharge – chloride to δ^{18}O relation

Knowledge of the relative contribution from point recharge through solution features to total recharge is an important factor in managing karst aquifers. Enrichment of stable isotopes, δ^{2}H and δ^{18}O and conservative tracers such as chloride, is used as an indicator of water loss by evaporation and transpiration (Abdalla, 2009; Van der Akker, 2010). In their study of Uley South Basin, Ordens et al. (2012) used the chloride Vs δ^{18}O relationship to determine relative contribution. These authors argued that the contribution to recharge by flow through sinkholes is only a small fraction of total recharge. This conclusion was based on a lack of intermediate data points between groundwater chloride and rain water chloride in the chloride Vs δ^{18}O plot (Fig. 4a).

Alternatively, lack of intermediate data points may result from monitoring bias. Aquifer water level monitoring bores are not necessarily near sinkholes or they are located outside the small pockets of fresh inflow associated with the sinkholes. In general, small catchments contributing to sinkholes may not generate sufficient runoff volume to develop fresh water plumes that reach measurement points.

In Fig. 4, chloride Vs δ^{18}O plots are given for the Uley South, Blue Lake capture zone at Mount Gambier and the Poocher Swamp freshwater bubble in the Tatiara catchment (Somaratne, 2011). All the above systems are dominated by point recharge. The widest gap between groundwater chloride and rain water chloride is about 83 mg L^{-1} in the Uley South aquifer (Fig. 4a). In the Blue Lake capture zone where average annual rainfall is about 160 mm greater than Uley South, a gap of 43 mg L^{-1} exists, even with a high number of point recharge sites, principally through the 400 drainage wells directly recharging the aquifer (EPA, 2007). Intermediate data points between rainfall and groundwater chloride could be obtained via chloride measurements taken at drainage wells, which are discrete recharge points (Fig. 4b).

In Poocher Swamp in the Tatiara catchment, the freshwater bubble of 7 to 10 km length developed due to the high volume of annual creek flow ($\approx 2.5 \times 10^{6}$ m^{3}) recharg-

HESSD
10, 11423–11449, 2013

ing the limestone aquifer through the two sinkholes (Somaratne, 2011). The fresh water plume intercepted by a number of measurement points shows that there are no gaps between surface water and groundwater chloride (Fig. 4c) at the nearest measurement point. Therefore, a gap between groundwater and rainwater chloride data points in the chloride Vs δ^{18}O plot, is not necessarily an indication that sinkholes are not directly recharging the aquifer.

3.2 Groundwater mixing zones

The results of chemical analyses of groundwater in the fresh water bubble and the surface water samples taken from Tatiara Creek and Poocher Swamp are shown in the Piper diagram (Fig. 5). The major ion chemistry results show that sodium and calcium are the dominant cations and bicarbonate and chloride are the dominant anions in the Tatiara Creek (Na-Ca-Mg-HCO_3-Cl) and Poocher Swamp (Na-Ca-HCO_3-Cl) water types. However, at monitoring wells WRG 34 and WRG 35, water chemistry changes from sodium dominant to calcium dominant water (Ca-Na-HCO_3), as a result of dissolution of calcite. The calcium dominant water types (Ca-Na-HCO_3-Cl) are also found in town water supply (TWS) wells: TWS 10, TWS 9 and TWS 8, indicating a possible pathway of water movement from the Poocher Swamp. This observation is consistent with the gradual decrease of δ^{18}O enrichment due to mixing from Poocher Swamp (−0.34 ‰ VSMOW-Vienna Standard Mean Ocean Water) to −3.05, −3.08, −3.23 ‰ VSMOW at TWS 10, TWS 8, and TWS 9 respectively. Within the fresh water bubble, no other significant point recharge sources exist.

The extent of the Mount Gambier' Engelbrecht Cave was surveyed by the Cave Divers Association Australia and is depicted in Fig. 6. The contrast in salinity between the north-western and southern wings of the Engelbrecht Cave is due to the different levels of recharge entering the cave. The north-west wing is linked to drainage wells through a network of conduits, hence salinity of the water is lower (405 µS cm^{-1}) than in the south wing (640 µS cm^{-1}). The salinity profile of monitoring well BLA017 (Fig. 7) indicates a connection to the cave at depth 30.5 m.

HESSD
10, 11423–11449, 2013

Two conductive zones, indicated by low EC (Electrical Conductivity) in the profile, are found in monitoring well BLA164 located about 2 km west of BLA017 (Fig. 7). The lower conductive zone at 33–34.5 m depth (Fig. 7) is identified as the primary fracture pathway to the Blue Lake (Lawson, 2013). Salinity profiles obtained from drainage wells located in the zone of the primary fracture pathway further down gradient to BLA164 (Fig. 8) confirmed that low salinity water moves at greater depth. This indicates the existence of preferential pathways at different depths.

Overall, these results show that non-homogeneity exists at point recharge sources (drainage wells), aquifer monitoring wells, within conduits (Engelbrecht Cave) and along the flow paths themselves, even though the groundwater system is under steady-state in terms of salinity and chloride mass.

4 Recharge

4.1 Point recharge estimates

In Uley South basin, Ward et al. (2009) used LEACHM (Hutson, 2003), a variably saturated model of the soil profile that uses the curve number approach described by Williams (1991) to estimate surface runoff.

The Uley South model considered four surface cover scenarios from flat slope to steep sites with a slope of 0.15. The surface cover included deep rooted vegetation with high cover and a steep slope; deep rooted vegetation with high cover on a flat surface; shallow rooted vegetation cover with a steep slope and shallow rooted vegetation cover on a flat ground surface. Potential evapotranspiration was calculated using the methods of Linacre (1977) and four different soil and sub-soil profiles were considered in order to include the significance of the soil and the presence of calcrete at near surface depths of up to 2 m. Unsaturated zone properties have been assumed, based on prior knowledge of similar soil and sub-soil types. In Uley South about 90 % of the basin features are flat ground surface. For the average annual rainfall of 550 mm,

HESSD
10, 11423–11449, 2013

Ward et al. (2009) obtained an average annual runoff volume of 8.5×10^6 m^3 or basin equivalent depth of about 75 mm that flows through sinkholes to the watertable.

Nguyen (2013) used the urban storm water model MUSIC (2009) for quantifying storm water runoff to drainage wells. In the study, MUSIC modelled rainfall and runoff process for the period 2007–2012 using a daily time step with daily rainfall and evaporation data. For sub-catchments with drainage wells, the average percentage of impervious (51 %) and pervious (49 %) areas were determined using digital maps of the city using Geographic Information System (GIS) tools. A rainfall threshold of 1 mm was used for impervious areas. Uniform soil storage capacity and field capacity values of 120 mm and 80 mm were used for the pervious areas. The initial soil storage capacity was set to 30 %. For the average annual rainfall of 750 mm, 6.6×10^6 m^3 of runoff volume flows through drainage wells to groundwater from a catchment area of 16.8 km^2. Out of this, 5.1×10^6 m^3 of runoff volume is generated from the impervious areas of the catchment.

Based on the annual flow of Tatiara Creek for the period 1980–2010, average annual recharge to groundwater in Poocher Swamp is estimated to be about 2.5×10^6 m^3 through the two sinkholes. A similar estimate of about 2.3×10^6 m^3 was made by Stadter and Love (1987) in 1987.

4.2 Chloride distributions in diffuse recharge and point recharge dominant zones

Chloride is regarded as a conservative tracer. In diffuse recharge zones, chloride in recharging water is in equilibrium with groundwater. This is the basic premise of the conventional CMB method. In point recharge dominant zones, both point and diffuse recharge processes contribute to the concentration of groundwater chloride. For comparison, the chloride concentrations of groundwater in diffuse and point recharge dominant areas are given in Table 1. In the Uley South basin, diffuse zone chloride samples were taken from monitoring wells located within 2 km from the basin boundary (Fig. 1).

HESSD
10, 11423–11449, 2013

In the Mount Gambier Blue Lake capture zone, monitoring wells outside the city were used (Fig. 2). For the Poocher Swamp fresh water bubble, chloride concentrations from monitoring wells outside the fresh water zone were taken (Fig. 3). Sinkhole areas in the Uley South basin where groundwater chloride is derived from both diffuse and point recharge are on average 10 $mg\,L^{-1}$ lower compared chloride concentration in areas where diffuse recharge is the only contributor (Table 1). In the Mount Gambier capture zone, such difference could not be confirmed. There are three influencing factors for this observation:

1. In diffuse recharge zones, recharge water is aerially distributed across the surface of watertable and the chloride concentration in recharge water is in equilibrium with groundwater. Any local difference between these chloride concentrations tends to homogenise through dispersion.

2. In point recharge sources, chloride concentration in recharge water remains at, or close to that of surface runoff and hence is not at equilibrium with groundwater chloride concentration. Point recharge through sinkholes or drainage wells spreads through interconnected conduits with mixing occurring throughout the flow paths. The degree of heterogeneity and the extent of network of conduits is usually unknown, and therefore it is generally not possible to get a representative average, or weighted average of chloride samples by measurement.

3. Average annual volume of point recharge is much smaller than the typical aquifer storage volume. Therefore, surface runoff with low concentrations of chloride reaching groundwater is insufficient to cause noticeable changes in chloride concentrations, unless a large volume of recharge takes place at a single location as in the Poocher Swamp fresh water bubble.

Following Goldscheider and Drew (2007), a recharge conceptual model was developed for the Uley South Basin (Fig. 9) that illustrates the duality of infiltration and recharge (point and diffuse).

HESSD
10, 11423–11449, 2013

4.3 Recharge calculation by the conventional CMB method

The conventional CMB method is frequently used for recharge estimation and is given by Allison and Hughes (1978) and Allison (1988):

$$R = \frac{P c_{\mathrm{p+D}}}{c_{\mathrm{g}}} \tag{1}$$

where R (mm yr^{-1}) is average annual recharge, P (mm yr^{-1}) is average annual rainfall, $c_{\mathrm{p+D}}$ (mg L^{-1}) is representative mean chloride concentration of rain water including contributions from dry deposition (Ordens et al., 2012) and c_{g} (mg L^{-1}) is chloride concentration in groundwater. In the absence of direct measurement, the $c_{\mathrm{p+D}}$ can be estimated from Hutton (1976) using:

$$c_{\mathrm{p+D}} = 35.45 \times \left\{ \frac{0.99}{d^{0.25}} - 0.23 \right\} \tag{2}$$

where d is distance in km from the ocean in the prevailing wind direction.

For the three case studies described in this paper, the conventional CMB estimated total recharge is less than the point recharge component (Table 2). Application of conventional CMB to estimate recharge to the Poocher Swamp fresh water bubble requires further consideration. Average chloride concentration in the fresh water bubble of 91 mg L^{-1} or a recharge value of 14 mm per year are not representative of recharge to fresh water bubble. In fact vertical recharge (3 mm yr^{-1}) that crosses the watertable plane, corresponds to a diffuse zone groundwater chloride concentration of 550 mg L^{-1}. The fresh water bubble's recharge water is generated outside the fresh water plume area. Low salinity and chloride concentrations found in the fresh water bubble results from a lateral flux moving from point source recharge down gradient. Taking chloride measurements from a lateral flux to estimate vertical recharge is essentially estimating "apparent" recharge. This is because the estimated recharge never crossed the watertable plane at the location.

HESSD
10, 11423–11449, 2013

5 Conclusions

This paper presents case studies that concur with the findings of Hallberg and Hoyer (1982), Gunn (1983), Tihnasky (1999), White (2003), Bakalowicz (2005), Goldscheider and Drew (2007) and Taylor and Greene (2008) that karst systems have a distinct hydrologic function resulting from a duality of flow regimes in infiltration and recharge, and in preferential groundwater flow paths. This study suggests that the presence of a gap between groundwater and rainwater chloride in the chloride Vs $\delta^{18}O$ plot, is not necessarily indicative of sinkholes not directly recharging the aquifer. Even though diffusion and dispersive mixing continues over time, non-homogeneity exists at point recharge sources and along flow paths. Given that the extent of fresh water pockets at point recharge locations and along conduits may not be completely known, it is not possible to get representative salinity or chloride samples for groundwater systems dominated by point recharge. Estimated recharge using the conventional CMB method is less than the point recharge estimates for the study basins. It is perceived that simplified assumptions in the conventional CMB and the inability to obtain representative chloride concentrations make direct application of the conventional CMB method to point recharge dominant groundwater basins questionable. The duality of the recharge mechanism in karst aquifers suggests that modification to CMB method may be required in order to include both point and diffuse recharge components into the CMB method.

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HESSD
10, 11423–11449, 2013

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HESSD
10, 11423–11449, 2013

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HESSD
10, 11423–11449, 2013

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HESSD
10, 11423–11449, 2013

Table 1. Comparison of groundwater chloride concentrations in diffuse and point recharge zones in mg L^{-1} with standard deviation (number of samples in brackets).

Groundwater basin	Chloride in diffuse recharge zone (mg L^{-1})	Chloride in point recharge zone (mg L^{-1})
Uley South	147 ± 28 (19)	137 ± 19 (45)
Blue Lake capture zone	62 ± 9 (13)	63 ± 26 (16)
Poocher Swamp fresh water bubble	770 ± 470 (5)	Varies from 40–550

HESSD
10, 11423–11449, 2013

Table 2. Comparison of conventional CMB method estimated recharge to point recharge in m^3 (equivalent $mm\,yr^{-1}$ in brackets).

Groundwater basin	Groundwater chloride concentration ($mg\,L^{-1}$)	Recharge from the conventional CMB method	Point recharge
Uley South	137	6.3×10^6 (56)	8.5×10^6 (75)
Blue lake capture zone	63	1.6×10^6 (95)	6.6×10^6 (390)
Poocher Swamp fresh water bubble	91	0.28×10^6 (14)	2.5×10^6 (125)

HESSD
10, 11423–11449, 2013

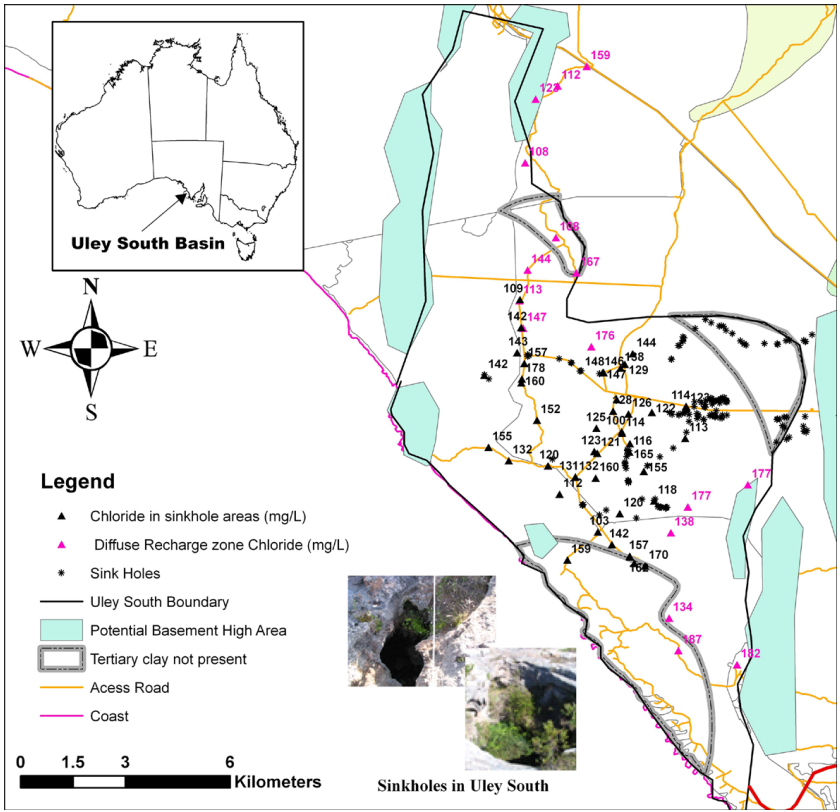

Fig. 1. Sinkholes in Uley South Basin and groundwater chloride.

HESSD
10, 11423–11449, 2013

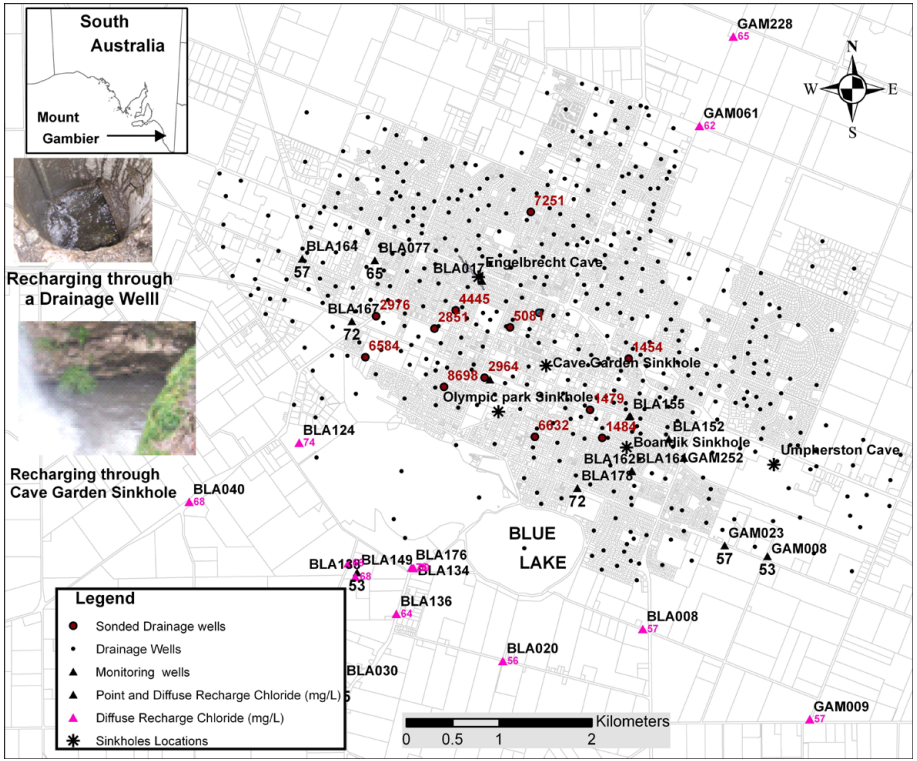

Fig. 2. Drainage wells and chloride in aquifer monitoring wells in the Blue Lake capture zone.

HESSD
10, 11423–11449, 2013

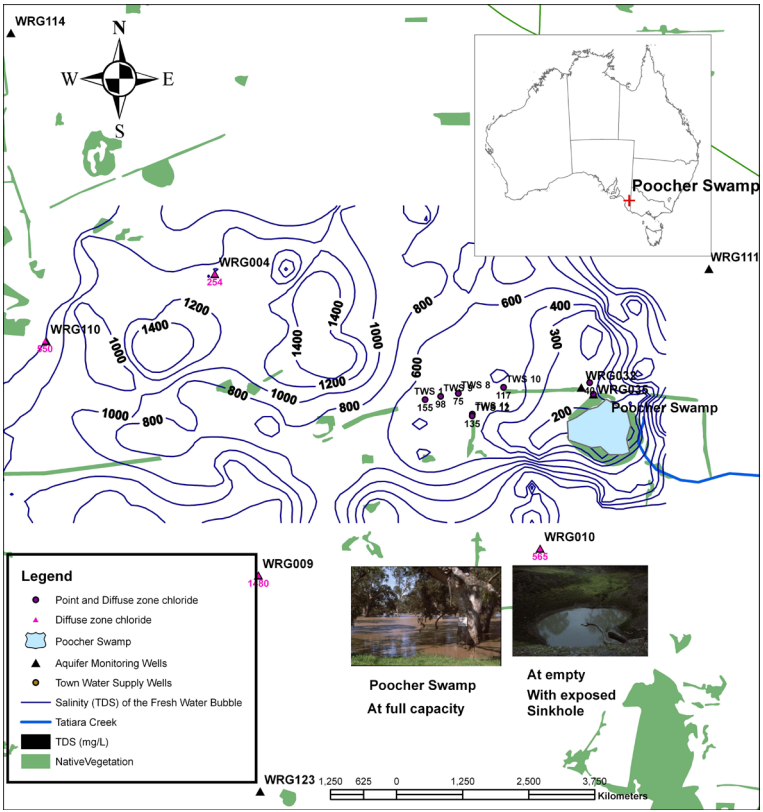

Fig. 3. Poocher Swamp fresh water bubble.

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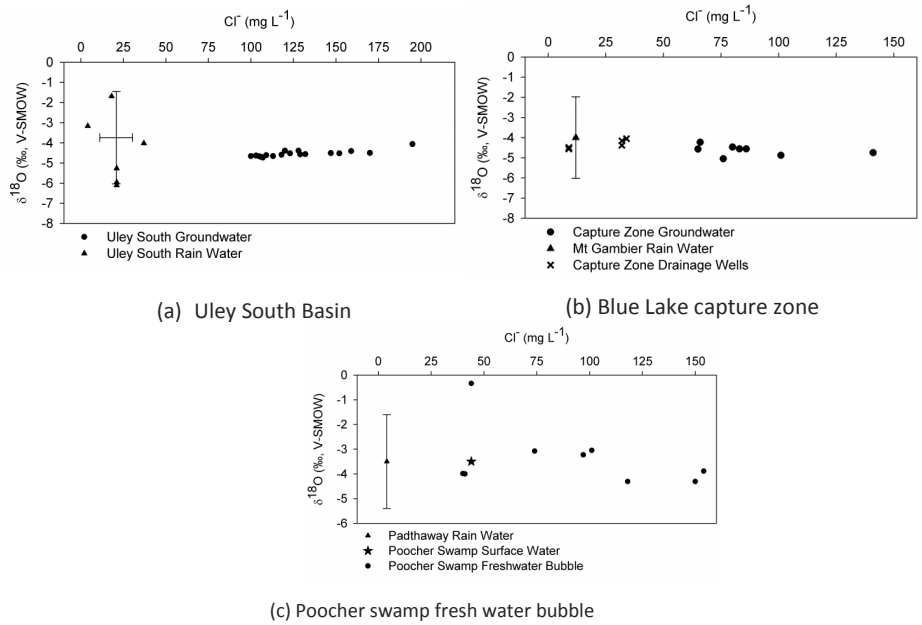

Fig. 4. Chloride vs. ^{18}O for point recharge dominant groundwater basins.

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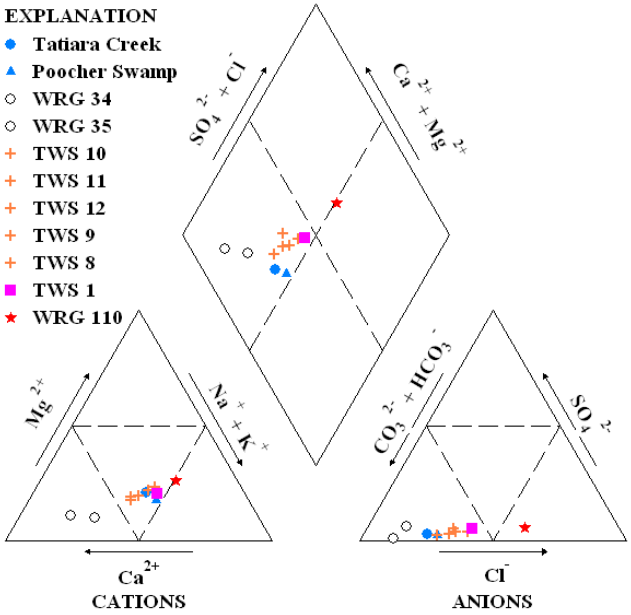

Fig. 5. Piper diagram for fresh water bubble.

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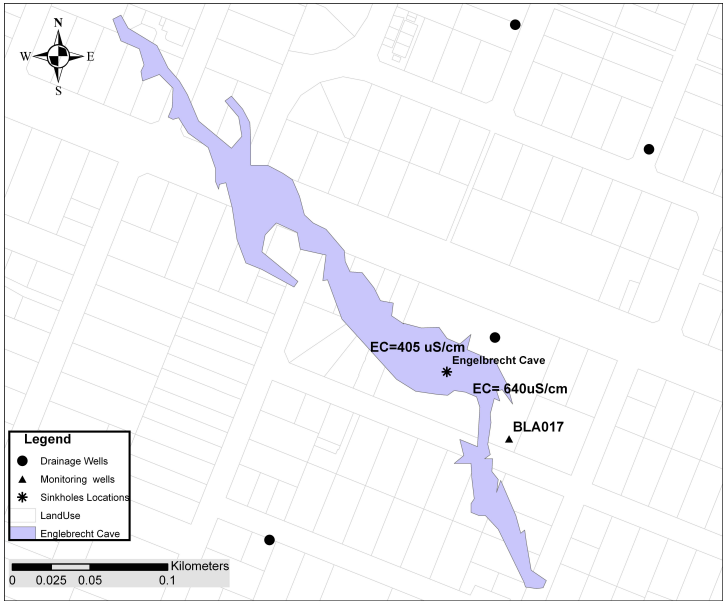

Fig. 6. Salinity contrast in Engelbrecht cave (after Cave Divers Association Australia).

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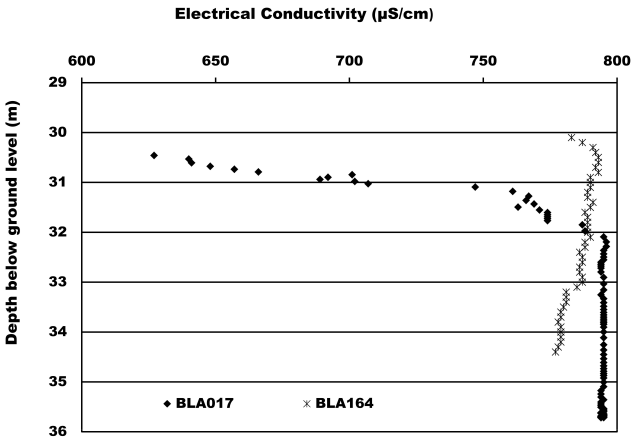

Fig. 7. Salinity profiles for BLA164 and BLA017.

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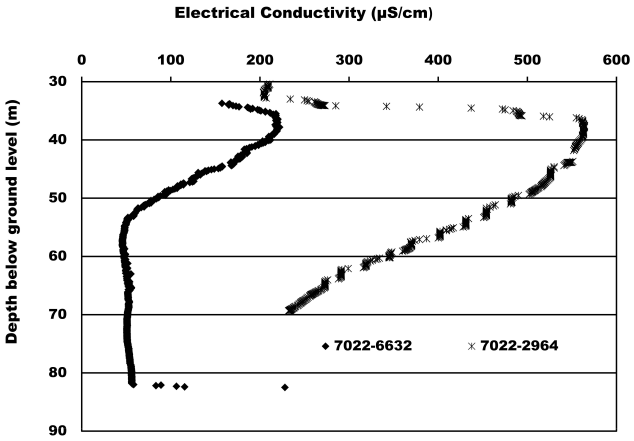

Fig. 8. Salinity profiles for drainage wells 2984 and 6632.

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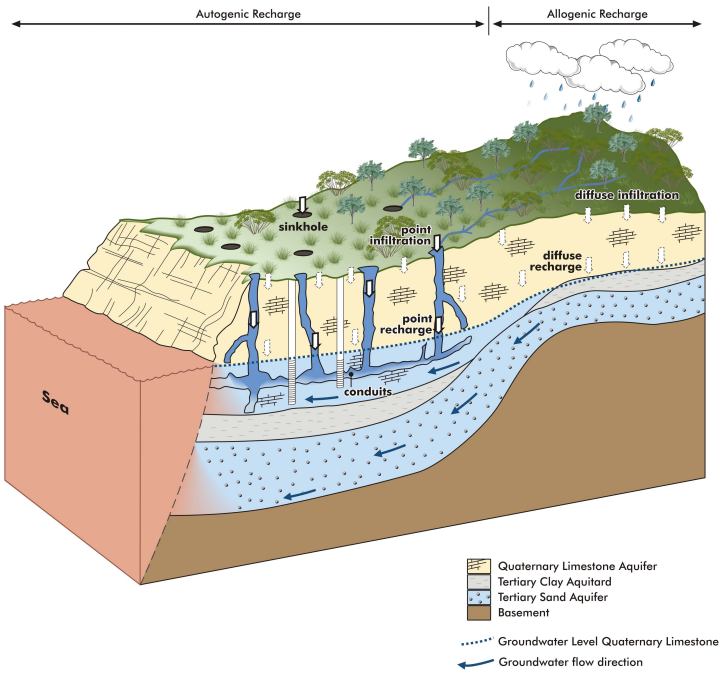

Fig. 9. Recharge conceptual model for the Uley South Basin (concept adopted from Goldscheider and Drew, 2007).

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