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Karst Conduit Networks, Connectivity and Recharge Dynamics of a Sinkhole

Nara Somaratne[1]

[1] South Australian Water Corporation, 250 Victoria Square, Adelaide, South Australia

Correspondence: Nara Somaratne, South Australian Water Corporation, 250 Victoria Square, Adelaide, South Australia. Tel: 61-8-7424-2379. E-mail: nara.somaratne@sawater.com.au

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Abstract

Management of karst aquifers is often limited by a lack of understanding of recharge and flow dynamics. This article presents the identification of conduit networks and the connectivity, dynamic nature of recharge and inherent uncertainties in recharge assessment in karstic settings. The study was carried out at two large sinkholes located in the Poocher Swamp fresh water lens, south east of South Australia. Point recharge to the sinkholes was calculated using stream flow data at gauging stations and water balance of the swamp. Conduit system and their interconnectivity in the vicinity of sinkholes were characterized by the use of transient electromagnetic survey (TEM) to identify high potential porosity zones of the aquifer. Resistivity data were used to estimate aquifer porosities using Archie's law. Recharge response to the karstic aquifer was monitored using four monitoring wells located at various distances from sinkholes. Measurements were taken during recharge and recession phases. Four dynamic stages of water level rise and fall were observed in response to filling of conduit zones, transmission and possible effects of entrapped air pressure within conduits. Electrical conductivity (EC) profiles were obtained at two stages. These confirmed interconnectivity of conduits, and re-adjustment to ambient groundwater quality following the recharge event. The lower EC water was found in the monitoring well furthest from the sinkholes indicating the complexity of conduit connection and the nature of mixing with ambient groundwater.

Keywords: karst aquifer, sinkholes, point recharge, conduit flow, recharge dynamics

1. Introduction

The flow behaviour of karst systems is characterised by recharge, storage and transmission (White, 1988; Ford & Williams, 1989). The existence of networks of interconnected dissolution enhanced conduits in karstic limestone aquifers may results in heterogeneous flow system (Steelman et al., 2013). The heterogeneous distributions of various types of porosities influence nearly all aspects of aquifer characteristics including storage and of permeability (Moore et al., 2009).

In karst aquifers, highly heterogeneous subsurface conduit systems cause groundwater flow magnitude and direction to vary along preferential flow paths. The architecture of conduit networks and their connectivity is generally unknown and difficult to assess. This is due to the complexity of the subsurface karstification process and the difficulty in tracing them at depth into the ground (Shaban & Darwich, 2011). Features and characteristics of the karst aquifer processes outlined here are well known and are provided here as a stepping-stone for assessing conduit networks, connectivity and the study of recharge dynamics. Karst groundwater systems are characterized by focused recharge and highly permeable conduit systems (Schmidt et al., 2013) with three types of porosity: granular matrix, small aperture conduits and fractures, and large cavernous conduits (Martin & Dean, 2001; Goldschider & Drew, 2007). The range of porosity and permeability influences many aspects of karst aquifer characteristics like recharge, flow path and velocity, storage and retention capacity (Eiche et al., 2016). Conduit porosity can be connected to the surface through cavernous openings such as sinkholes (Somaratne, 2015b). The presence of sinkholes gives a bimodal recharge regimes, diffuse and point recharge, to karst aquifer systems (Gunn, 1983; Taylor & Greene, 2001; Lerch et al., 2005; Geyer et al., 2008; Somaratne, 2015b). Thus in karst aquifers, groundwater flow primarily takes place in the conduit system while matrix porosity is mainly responsible for storage (Worthington et al., 2000). Somaratne (2015b) highlighted the view of Taylor and Greene (2001) and Bakalowicz (2005) that conventional study methods used in classical hydrogeology are generally invalid and unsuccessful in karst aquifers and that recharge estimation using the conventional methods do not accurately account for the complex hydrological processes in the system. Therefore, any ambiguities based on the presence of karstic features in groundwater basins should be explored and verified. Ke et al. (2013) stated that discrete turbulent groundwater recharge moves quickly through sinkhole drains. The complexity of water flow and uncertainty of hydraulic parameters create a great challenge to simulate the recharge process (Ke et al., 2013). Ke et al. (2013) highlighted that the estimation of the groundwater recharge in a karstic system becomes an important challenge due to the great hydrodynamic variability in both time and space.

From a karst connectivity point of view, sinkholes, springs and caves systems have been extensively studied through physical, chemical and isotopic variations in springs (Shuster & White, 1971, Krothe & Libra, 1983, Dreiss, 1989; Geryer et al., 2008). However, no work has been reported on dynamic behaviour of aquifer response to point recharge and the influence on recharge estimation in karst systems. Two distinct recharge assessment methods incorporating a bimodal approach warrant attention for further development. Gayer et al. (2008) and Ke et al. (2013) provide a technique for the time-continuous identification of recharge to karst aquifers based on the analysis of spring hydrographs. The methodology builds on the approach of cumulative storage accumulation and proposes a two reservoir conceptual model to simulate inflow into both the conduit system and the fissure network system based on the analysis of the spring hydrograph. The second approach is the generalised chloride mass balance (CMB) method (Somaratne, 2015b) incorporating duality of recharge, diffuse and point source, for karst aquifers.

As carbonate rocks are globally distributed, cover an area of 17–22 million km^2 (Eiche et al., 2016) and up to 25 % of the world's population depend on karst water supply (Ford & Williams, 2007), it is imperative to understand and further improve the knowledge about recharge dynamics in karst systems. This is particularly so in areas hosting freshwater lenses that are formed due to point recharge, in otherwise brackish water aquifers. In order to make a further contribution to karst aquifer assessment, this study investigates potential conduit zones in the vicinity of a sinkhole by use of downhole geophysical techniques and transient electromagnetic (TEM) survey, quantifying point recharge volume to the sinkhole, and analysing the dynamic behaviour of recharge by the use of hydrograph response during recharge and recession phases. Studies of the dynamic behaviour of point recharge are scarce and this study forms the first known attempt in a complex karstic settings.

2. Study Site: Poocher Swamp Freshwater Lens and Sinkholes

The study site, Poocher Swamp fresh water lens, is located 275 km south-east from Adelaide (Figure 1) and is about 8 km west of Bordertown within the Tatiara Creek catchment. The fresh water lens supplies water to the township of Bordertown from a wellfield further 2 km west of the Poocher Swamp. Six town water supply wells are used to extract groundwater from the unconfined karstic limestone aquifer. Physiographically, Tatitara catchment is characterized by numerous Swamps and sinkholes. The freshwater lens is primarily recharged through two sinkholes located in the north-west corner of the Poocher Swamp. The freshwater lens is surrounded by brackish water. The catchment area extends across the South Australian border into western Victoria and previously described by Somaratne (2014) and Somaratne and Mann (2016). For brevity, a succinct summary of the study freshwater lens is provided here.

The Tatiara catchment area is approximately 500 km^2 (Herczeg et al., 1997) and the Tatiara Creek flows in a westerly direction through to Poocher Swamp and beyond. The catchment features an average annual rainfall of 450 mm and pan evaporation of 2000 mm. Surface soil is predominantly clays and sandy clay or loam overlying a fossiliferous, calcareous sand and sandstone up to 15 m thick occurring in the upper Quaternary Bridgewater Formation. Underlying the Bridgewater Formation is the Murray Group Limestone (MGL) unconfined aquifer which comprises a consolidated, highly fossiliferous and fine to coarse bioclastic limestone. The saturated thickness of the limestone unconfined aquifer is approximately 50-60 m and contains brackish water with average total dissolved solids (TDS) > 1400 mg.L^{-1}. Karst development is very common in the MGL and the study sinkholes in the Poocher Swamp are the largest known in the Tatiara catchment. In this catchment, freshwater with TDS < 1000 mg.L^{-1} occurs at locations where point recharge takes place through sinkholes. The Poocher Swamp freshwater lens, which is the largest of these freshwater plumes that float on brackish water, is a result of flows from Tatiara Creek that enter Poocher Swamp. The major recharge is through the two sinkholes located in the northwest section of the swamp (Herczeg et al., 1997). The area encompassed by the 1000 mg.L^{-1} salinity contour comprises approximately 13 km^2 in 2016. Surface water flows in Tatiara Creek are highly irregular (Figure 2a), with annual volumes of freshwater ranging between (0.05-2)×10^6 m^3 year^{-1}, but on rare occasions up to 19×10^6 m^3 year^{-1}. The salinity of the Tatiara Creek increases during low rainfall months due to the high evaporation (Figure 2b). Groundwater flow direction of the lens is from east to west. The study area is relatively flat terrain with ground elevations of 69.83 m AHD (Australian Height Datum) at WRG032 well near the Poocher Swamp (Figure 1), while the most down gradient well WRG046, is at 66.24 m AHD. Depth to water varies, about 19 m at WRG032 and 15.6 m at WRG046, with the overall average of the freshwater lens area about 17 m. Currently, an annual volume of 0.6×10^6 m^3 of groundwater is extracted from the freshwater lens for town water supply to Bordertown.

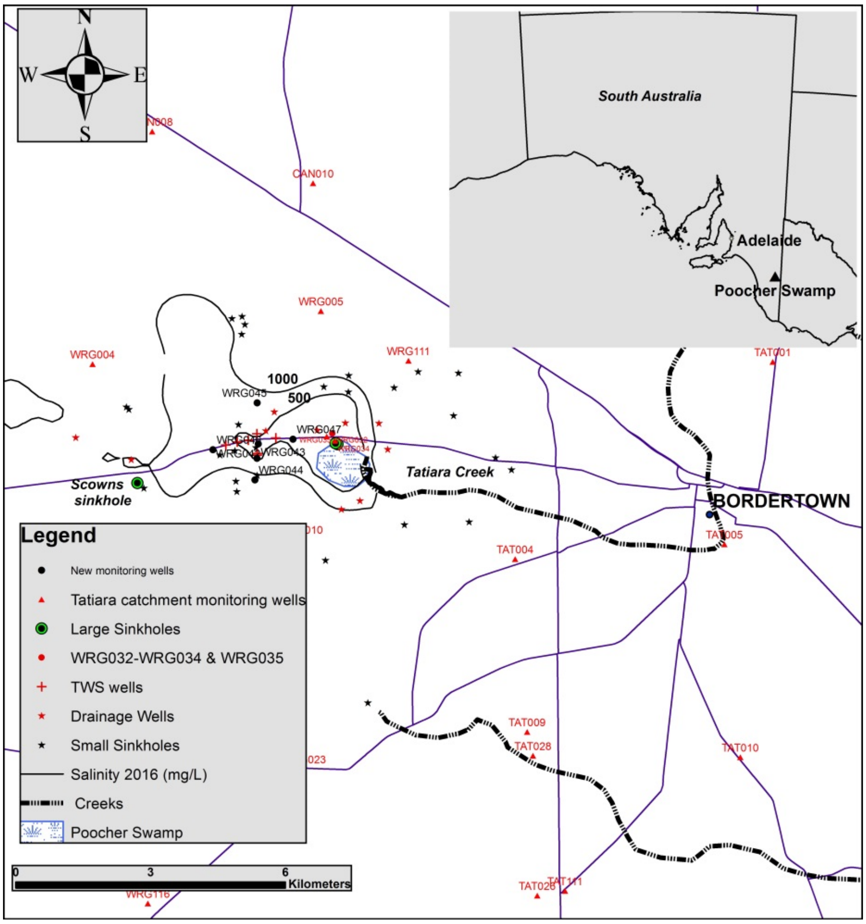
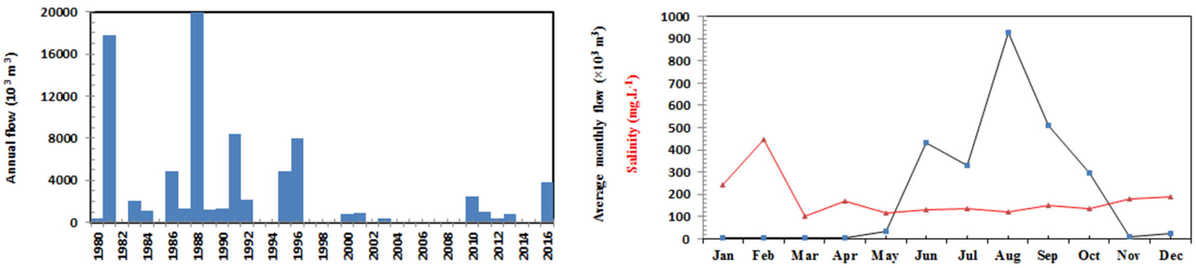


Figure 1. Poocher Swamp freshwater lens



(a) (b)

Figure 2. Tatiara Creek flow and salinity (a) annual flow at Bordertown (b) average monthly flow (1980-2010) and salinity (average 2006-2007) at Bordertown

During high flows in the Tatiara Creek, Poocher Swamp overflows through the outlet channel and continues on through a series of natural water courses, minor swamps and sinkholes up to Scowns sinkholes, about 4 km further west (Figure 1). Based on the average annual flow data of Tatiara Creek near Bordertown for 1980-2010, Somaratne (2014) suggested annual recharge to the lens through the sinkholes at Poocher Swamp may be approximately 2.5×10^6 m^3, but this figure could not be quantified with any reliable precision. This study narrows down recharge estimates for 2016 and discusses the way forward for future refinement of long-term estimates.

In addition to town water supply, the groundwater is also extracted within and from surrounding areas for irrigated agriculture. Mainly pasture, legumes and viticulture. Dryland grazing is common within the lens area and the surroundings. As such, prudent management of the Poocher Swamp fresh water lens is vital for sustaining local economic activities (Somaratne & Mann, 2016).

3. Method

In order to characterize the aquifer conduit zones, two geophysical investigations were performed; downhole geophysical and TEM surveys. The downhole geophysical logs were obtained using a borehole logging unit of the South Australian Department of Environment, Water and Natural Resources. The unit consists of a data processing unit, winch, cable, and logging tools installed in a van. Gamma ray (GR) and neutron tools were run simultaneously and an electrical conductivity (EC) probe was run separately. The surface unit controls the logging and movement of the probe and displays and stores data. The probe is connected to the surface unit via a cable that conveys the electrical signals (Wonik, 1990).

Ten high resolution TEM lines of varying orientation (Figure 3) were used with station spacing of 25 m with infill to higher resolution (12.5 m) over areas of surface features such as sinkholes. A Zonge International GDP-32ii receiver equipped with NanoTEM cards were used to acquire all data for this study. Data were sensed using a single turn 5×5 m wire loop placed at the center of each transmitter loop and were recorded over two channels, with the second gained up to improve late time decay resolution. Decay data were recorded over 31 time windows to approximately 2 milliseconds after transmitter turnoff. Transmitted fields were generated with a Zonge NT-20 geophysical transmitter energizing a single turn 25×25 m loop. This transmitter provides an output of 3 Amps, at 32 Hertz with a turn-off ramp time of 1.5 μs. Synchronisation was controlled directly using the GDP-32ii receiver. Data were then used to produce 1D inversion model sections of resistivity using Zonge International's STEMINV modelling program (Somaratne & Mann, 2016). The survey was conducted on 5-13 January 2017, allowing two months of draining of the soil profile following the rain or irrigation.

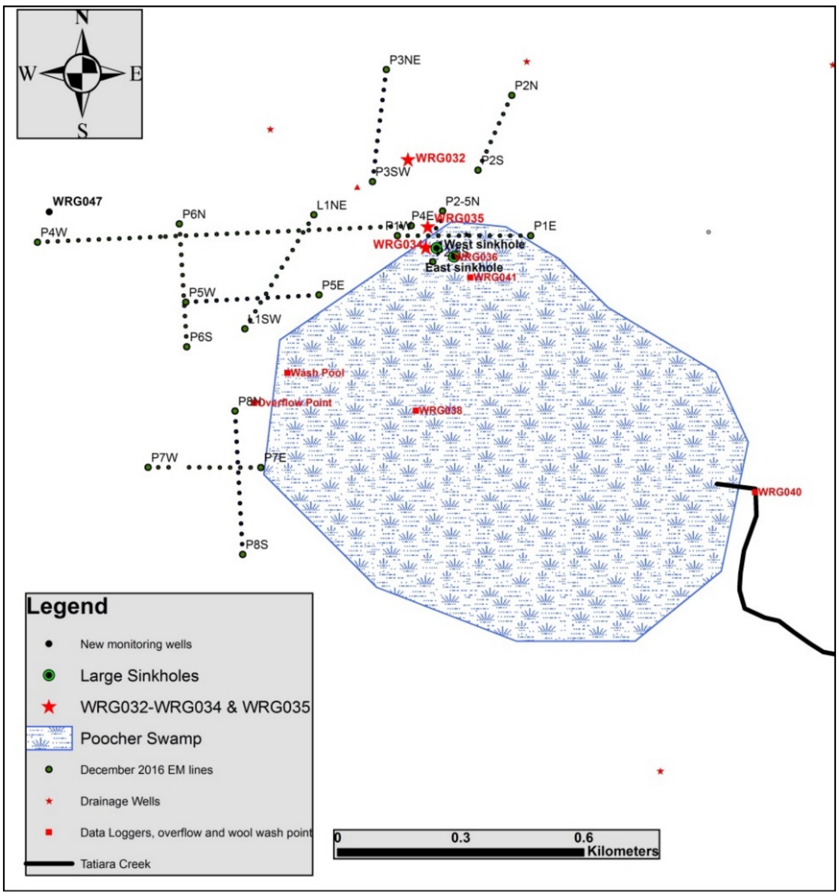


Figure 3. Locations of TEM lines and data loggers in the vicinity of Poocher Swamp (WRG036, WRG038, WRG041) and Tatiara Creek (WRG040)

Neutron porosity was calculated from neutron logs according to the method describe in Schlumberger (1972) using the equation (1):

$$\phi = \frac{Neutron\ (cps)*2.7*0.19}{1000} \tag{1}$$

where ϕ is the aquifer porosity, 2.7 is for API (American Petroleum Institute) units per cps (counts per second) for a 16 inches neutron tool spacing ; and 0.19 is for the response of a logging tool in the 19% porosity water-filled limestone which is defined as the 1000 API (Schlumberger, 1972).

Using resistivity data, the aquifer porosity is estimated using the Archie's Law (Archie, 1942) which is valid for saturated non-clay media and relates bulk resistivity of the aquifer to pore water resistivity and aquifer porosity by:

$$\rho = \alpha \rho_w \phi^{-m} \tag{2}$$

where ρ (Ω.m) is the bulk resistivity of saturated rock, ρ_w (Ω.m) is the resistivity of pore water, α is the tortuosity factor and m is the cementation coefficient (Shah & Sinh, 2005, Hernandez-Espriu, 2017). Values for carbonate media, α=1 and m=2 (Hernandez-Espriu, 2017) were taken for the study aquifer.

Recharge to the aquifer was assessed using three methods; watertable fluctuation (WTF) (Delin et al., 2007), generalised CMB (Somaratne, 2015b) and the use of a MODFLOW (Harbaugh, 2005) based groundwater model (Wood, 2016).

The WTF method is based on relating changes in measured watertable elevation with changes in the amount of water in aquifer storage:

$$R(t_j) = S_y \Delta H(t_j) \tag{3}$$

where $R(t_j)$ is recharge (mm) occurring between time t_0 and t_j, S_y is specific yield and $\boldsymbol{\Delta} H(t_j)$ is the peak watertable rise (mm) attributed to the recharge period (Delin et al., 2007).

The generalised CMB method provides an alternative long-term net recharge estimation method for groundwater basins characterised by both point and diffuse recharge. Recharge is estimated for a closed basin where the ambient groundwater chloride concentration is much higher than the chloride concentration of surface runoff. The simplified generalised CMB equation for recharge volume estimate can be expressed as:

$$R = \frac{P c_{p+D}}{c_{gd}} \times A + Q_p \tag{4}$$

where R is the recharge (m^3), P is the long-term average annual rainfall (m), $c_{(p+D)}$ is the mean chloride concentration of rainwater ($mg.L^{-1}$) including contribution from dry deposition, c_{gd} is the groundwater chloride concentration ($mg.L^{-1}$) in the diffuse recharge zone , A is the area (m^2) and Q_p is the point recharge volume (m^3).

In order to track the recharge and through flow within the lens, data loggers were installed; within the Poocher Swamp for surface water level measurement; in observation wells, for obtaining groundwater levels; and at the gauging station WRG040, for automatic water level and flow velocity measurements. In addition, up to three manual gauging and velocity measurements were undertaken at the overflow channel and Tatiara Creek at WRG040 station.

4. Results and Discussion

4.1 Gamma ray (GR) and Neutron Logging of Selected Monitoring Wells

Interpretation of geophysical logs is challenging as the subsurface geology and its composition can vary. Since geophysical logs have no unique response, logs need to be interpreted with geological information obtained from boreholes (Keys, 1990). The stratigraphic correlation using GR and neutron logs with EC are shown in Figure 4.

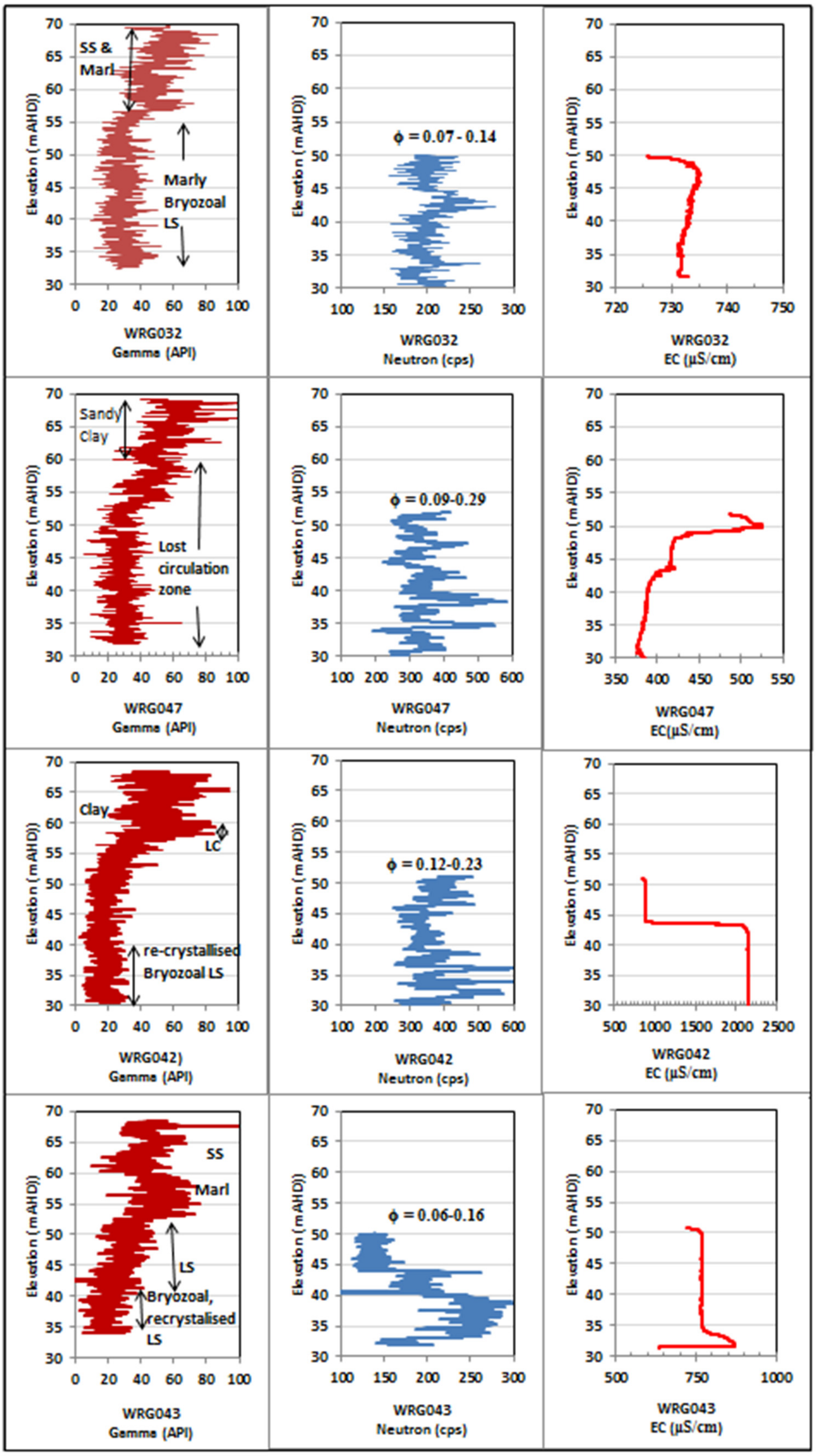


Figure 4. Gamma ray, neutron and EC profiles (LC=Lost circulation, LS=Limestone, SS=Sandstone)

There can be a mismatch between lithological logs when directly compared to downhole geophysical logs. This is because lithological samples are typically collected at certain depth intervals (in this case 3 m) and hence represent an average of the samples collected within the depth interval. Therefore, combining geophysical logs with lithological logs is more useful for interpretation than relying on only one set of logs (Somaratne & Mann, 2016). Because of lost circulation below 22.5 m depth, two wells critical to this study; WRG034 and WRG035 (Figure 3) have no lithological information. The wells could not be accessed for downhole geophysical logging but EC profiles were taken and are discussed in detail later in the paper under bore hydrograph response to recharge. Of the other monitoring wells, WRG032 is located 200 m north of the Poocher Swamp, WRG047 is located 860 m downgradient (west) of WRG032, and WRG042 a further 750 m west. Monitoring well WRG043 is 320 m south of WRG042 (Figure 1). For all wells neutron and EC readings are presented below the casing and static water levels. GR signals in the upper 18-22 m yielded higher (40-80 API) values, usually indicating the presence of clay rich materials. This is in good agreement with clayey/marly zone of the Bridgewater Formation given by the stratigraphic description. Below this zone, GR readings are stable (10-40 API), representative of more open limestone, with observed lost-circulation in WRG047. Neutron curves presented in Figure 4 are the response of neutron counters which are highly sensitive to the amount of hydrogen around the sonde and thus the porosity. Under saturated conditions, neutron logs provide a measure of aquifer porosities that are used for delineation of porous zones of aquifers and determination of their porosity. The range of porosity for each well was obtained using equation (1). Several factors affect neutron logging including; borehole diameter and the casing, formation density, water chemistry and aquifer porosity (Peterson and Sehgal, 1974). Calculated porosity values are therefore used to compare the relative difference in the profile rather than the absolute porosity values. Higher counts of neutron are found at 40-45 m AHD and 34 m AHD in WRG032 well, and throughout the profile of the saturated zone in WRG047 well. These aquifer zones are characterized by high porosity and hence indicate more productive zones of the profile with possible conduits. Lithological descriptions between 37-32 m AHD in WRG042 well and below 40 m AHD in WRG043 well indicate the presence of recrystallized limestone with some cementation but neutron logs indicate higher porosity zones. It is possible that the high count of neutron in this part of the aquifer is due to the presence of a high proportion of bound water or the existence of high a porosity zone within the recrystallized limestone. A large variation of neutron counts throughout the profiles is an indication of the degree of heterogeneity present in the aquifer.

4.2 Conduit Porosity Zones from TEM Survey

TEM data were processed according to the method described by Somaratne and Mann (2016) using TEMAVGW (MacInnes, 2010) software. Channels that were considered of poor quality were skipped before averaging each station data. Ungained and gained data were merged to optimize early and late data to create a single sounding for each station. Data were then used to produce 1D inversion models of resistivity using STEMINV (MacInnes & Raymond, 2001) modelling program. Surveyed elevations at bore locations supplemented with additional topographic information (SRTM 2000) was used in modelling so sections are presented relative to elevations, comparable to m AHD. Ambiguity exists in interpreting resistivity data; firstly large variation occurs in the resistivity of particular minerals (Telford et al., 1990), secondly there can be overlapping of resistivity values in the saturated zone. For example, the resistivity of both fresh water and clay is about 10-100 Ωm (Palacky, 1987) and thus requires known features for interpretation of TEM sections. Other factors such as dissolved minerals in groundwater, fracture zone filled with air, water or consolidation of geologic materials influence the local changes to resistivity. According to Telford et al. (1990), a small change in the percentage of water affects the resistivity. In the shallow substructures, the presence of water controls much of the resistivity variations. Resistivity measurement in general, is a measure of water saturation, and therefore porosity of the each resistivity zones were calculated using Archie's equation (2). A lower resistivity zone is found in the upper unsaturated zone (depth 15-18 m) in all section indicating partially saturated clay in the upper Bridgewater Formation with possible salt accumulation in the unsaturated zone from pore water evaporation. The resistivity of pore water was taken as 10 Ωm for the groundwater zone with electrical conductivity (EC) of 600-1000 $\mu S\ cm^{-1}$.

Figure 5 shows the inverted resistivity sections for survey lines L1 and P01 to P04. Porosity values for distinct resistivity contrast zones are given in each section. In addition, variations of the watertable corresponding to arrival of flood water on 14/09/2016 (initial level), 18/09/2016 (rapid rise), maximum rise (14/12/2016) and, rapid drop (20/12/2016) are given for P01, P02-5 and P03 sections where at least one nearby monitoring well is available.

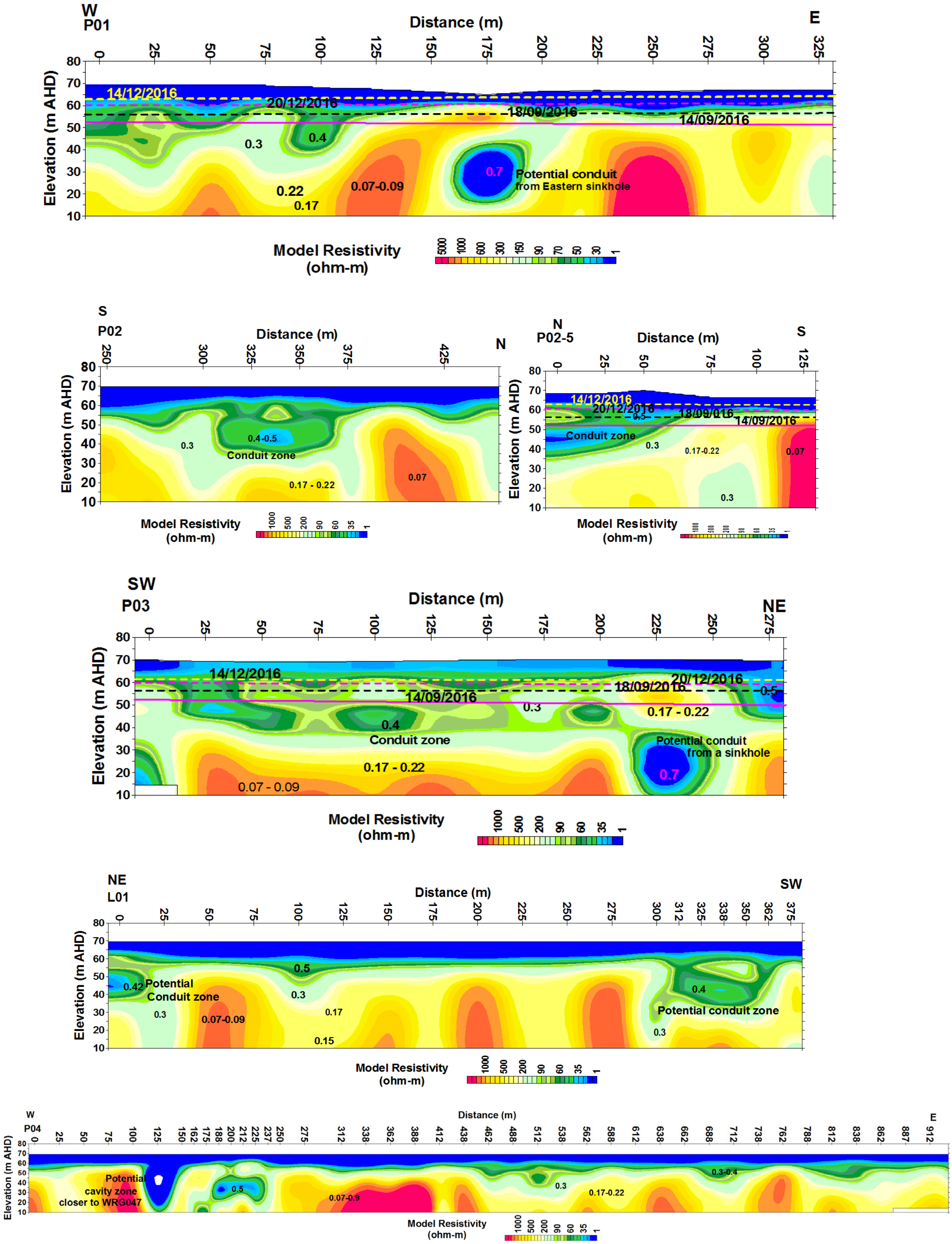


Figure 5. Inverted resistivity sections along TEM lines P01 to P04 and L01

In P01, a higher porosity zone (lower resistivity zone), exits in the limestone layer from 0-125 m station may be link to western sinkhole. A lower porosity zone is then found from 125-160 m. At 175 m along the P01 line, at 40-30 m AHD elevation a near circular high porosity zone intercept, is possibly the conduit feeding the aquifer from the eastern sinkhole. A second line (P02) crosses at the 175 m station of P01. In line P02, the high porosity zone is intercepted at 275-375 m interval. The line starts at station 250 m, which is directly opposite to the intercepted conduit at station 175 m on P01, indicating the possible direct link to the eastern sinkhole.

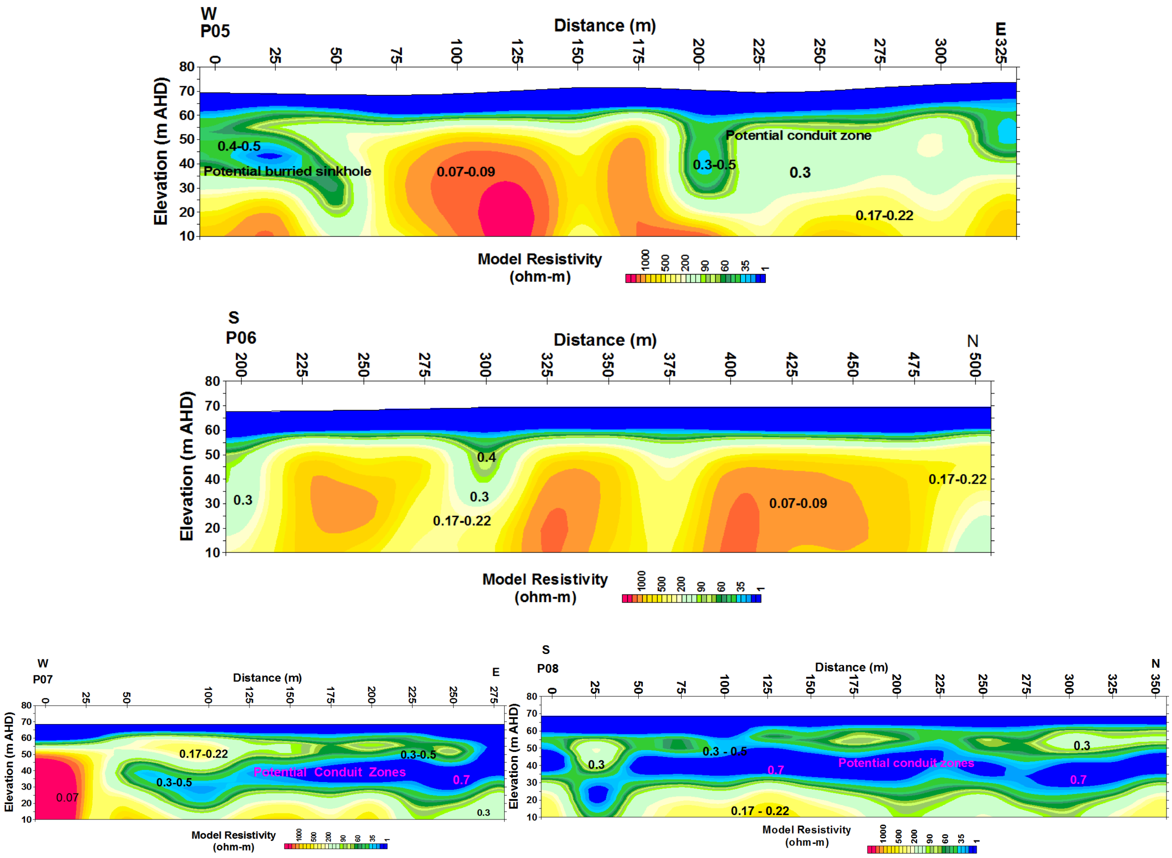


Figure 6. Inverted resistivity sections along TEM lines P05 to P08

The line P02-5 runs between the eastern and western sinkholes. At 75 m, the line crosses the centerline connecting the east and west sinkholes. The low porosity zone in the MGL at 75 m station indicates no direct interconnection between the two sinkholes, but the possible low porosity (0.3) zone at 10-30 m AHD between 75-100 m indicates a potential sediment filled cavity. The high porosity zone in line P03 extends up to 40 mAHD depth (upper 20 m saturated thickness in MGL). At 225 m, the line intercepts a potential conduit zone at 10-35 m AHD elevation, which may be a link to the buried sinkhole at the end of the line at 275 m. The potential conduit at 225 m may originate from a local sinkhole, or be connected to the Poocher Swamp sinkholes. The line L01 is west of the Poocher Swamp and was included in the previous study of Somaratne and Mann (2016). In this line, 0-25 m and 300-325 m intervals show higher porosity zones. The line P04 starts near WRG047 well and runs eastward. A potential major conduit is intercepted at station 125 m and a higher porosity zone found in the upper 10 m of the saturated zone throughout the length indicating zone of major water flow. The well WRG047 is in a conduit zone with similar hydrochemical and isotopic characteristics to the WRG032 well (Somaratne & Mann, 2016), indicating a possible link to WRG032 well. The TEM sections 5, 6, 7 and 8 are given in Figure 6. The lack of drillhole information in this area makes interpretations difficult they can be treated as potential conductive zones. The line P05 starts from the west and runs east towards the Poocher Swamp. In this section, high porosity zones are found at 0-50 m and 200-325 m (closer to Poocher swamp) intervals. TEM section 6 shows a typical granular porosity aquifer zone in MGL, except at the beginning (station 200 m) and at 300 m. The sections P07 and P08 mostly consist of high porosity zones. It is possible that this may be clay/water filled cavities or purely clayey limestone.

Based on higher porosity zones, the area covering lines P01 from 0-125 m; P02-5 from 0 to 75 m; P02 up to 325 m and P03 up to 200 m forms the 'northern conduits zone' in the vicinity of the Poocher Swamp (Figure 7). The area covering the high porosity zones of sections L01 from 300-375 m; P05 from 200-325 m; P07 from 50-275 m and the entire length of P08 forms the 'potential western conduit zone' of the Poocher Swamp. These major conduit zones near Poocher Swamp are shown in Figure 7.

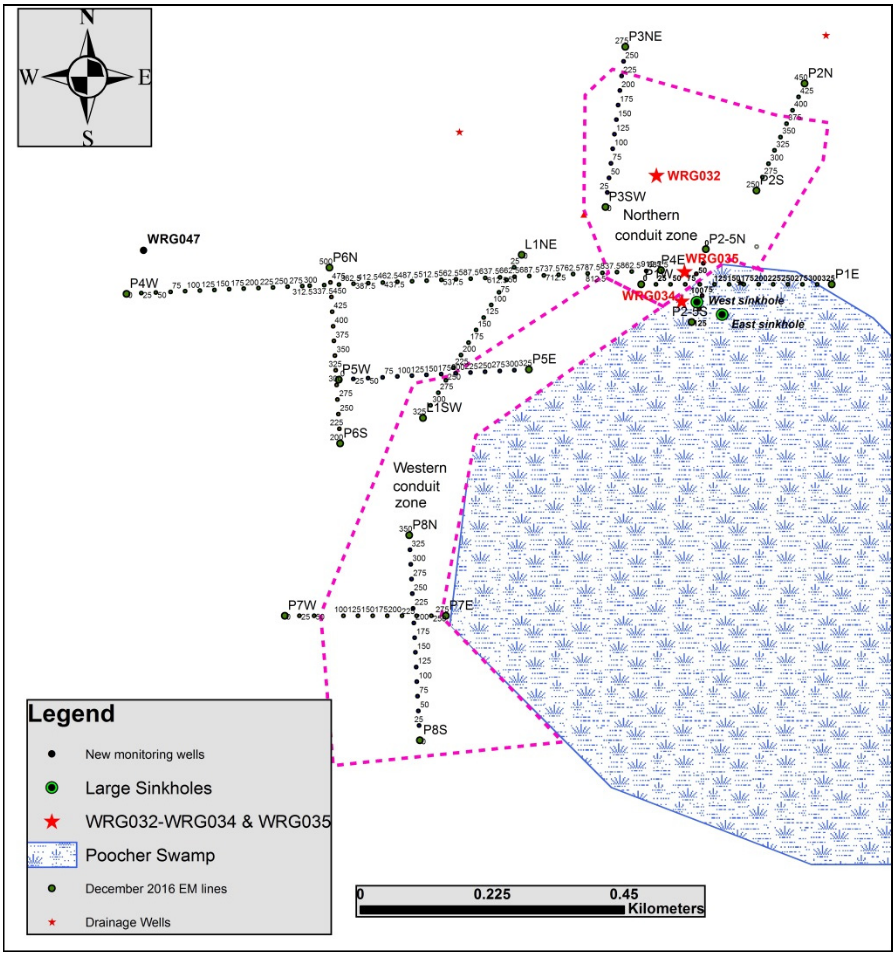


Figure 7. Major conduit zones surrounding the Poocher Swamp

4.3 Water Balance for the Poocher Swamp and Recharge via Sinkholes

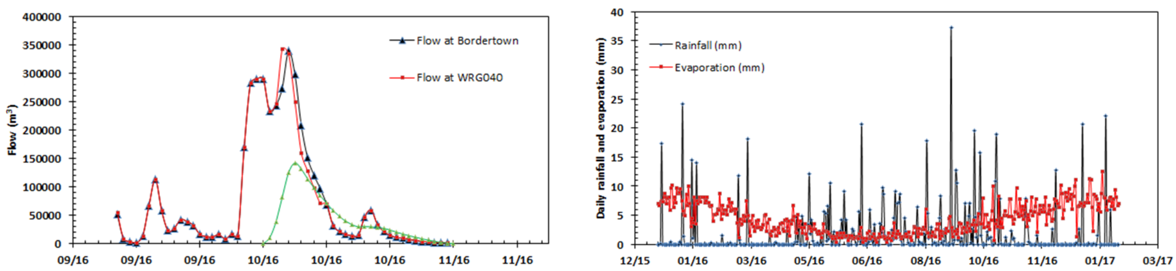
Point recharge to the aquifer was assessed using water balance method; balancing the inflow to and outflow from the Poocher Swamp. Inflow was from the Tatiara Creek while outflow from the Swamp was taken as the point recharge via sinkholes and overflow through the outflow channel. Water losses from the Swamp via evapotranspiration and direct vertical infiltration were considered minor. A thick clayey surface soil prevents any large water losses from the Swamp active storage. However seepage from the eastern and western lagoons may occur, albeit at slow rate, as water is retained for an extended period, up to mid-summer (Herczeg et al., 1997), until completely loss through evaporation.

Inflow to the Poocher Swamp was obtained from the data logger at gauging station WRG040. Surveyed ground level elevations and the Swamp's daily water level records from data loggers were used to obtain storage volumes corresponding to water levels. The overflow level of the eastern lagoon (66 mAHD reached on 15 September 2016) and the overflow level of western lagoon (65.5 m AHD reached on 15 September 2016) were used to calculate dead storage volumes of the eastern and western lagoons 165×10^3 m^3 and 50×10^3 m^3 respectively. Swamp water levels reached the overflow elevation of 67 m AHD on 02 October 2016 giving the Swamp's storage volume up to the overflow level is about 790×10^3 m^3. The maximum water level of the Swamp reached to 67.6 m AHD on 7 October 2016. The storage volume from the overflow level to maximum level is calculated at 390×10^3 m^3.

During the overflow period (2 October 2016 to 1 November 2016), Poocher Swamp water level elevations were used to calculate the outflow volume using Manning' equation for each day. Manning's roughness coefficient of 0.053 for a thick-tall grassed channel of slope of 0.00685 was used to obtain overflow velocity. The calculated outflow rate for 8 October 2016 was 1.49 $m^3.s^{-1}$, which agrees with the measured velocity measurement-based flow rate of 1.53 $m^3.s^{-1}$. The flow velocity was measured using manual current meter. By this way, total overflow volume is estimated at 1300×10^3 m^3 for the overflow period.

The point recharge rate via the sinkholes was assessed during the water level recession period. Inflow from the Tatiara Creek ceased on 31 October 2016. Poocher Swamp's water level dropped from the overflow level (67 m AHD on 1 November 2016) to the dry bed elevation of 65.5 m AHD on 14 December 2016. The only outflow during this period was the recharge via sinkholes. Thus, storage of 790×10^3 m^3 discharged in 43 days, giving a sinkhole recharge rate of 18.3×10^3 $m^3.day^{-1}$. Total point recharge through sinkholes was determined using the recharge rate and total recharge period (90 days from 15 September 2016 to 14 December 2016) to be 1650×10^3 m^3. The total outflow from the overflow channel and recharge via the sinkholes is about 2950×10^3 m^3. Measured flow at the Bordertown gauging station (3900×10^3 m^3) corresponds well with measured flow at the WRG040 (3800×10^3 m^3) gauging station (Figure 8a) as there is no significant catchment contribution to flow between the two stations. A portion of the discrepancy in inflow and outflow to the Swamp (850×10^3 m^3) consist of filling of dead storages in eastern and western lagoons (215×10^3 m^3) and, evaporation losses at 5 $mm.day^{-1}$ (Figure 8b) over the recharge period (220×10^3 m^3). The balance of 415×10^3 m^3 may be attributed to measurement errors, loss of water from the Swamp via direct vertical infiltration and seepage to the western potential conduit zone, all of which are unable to quantify with any degree of accuracy.

Outflow from the overflow channel adds to the diffuse and point recharge in areas closer to southern boundary of the lens (Figure 1) where water flows into depressions and minor sinkholes in the vicinity of WRG044 well. This recharge elsewhere in the lens is not quantified in this paper.

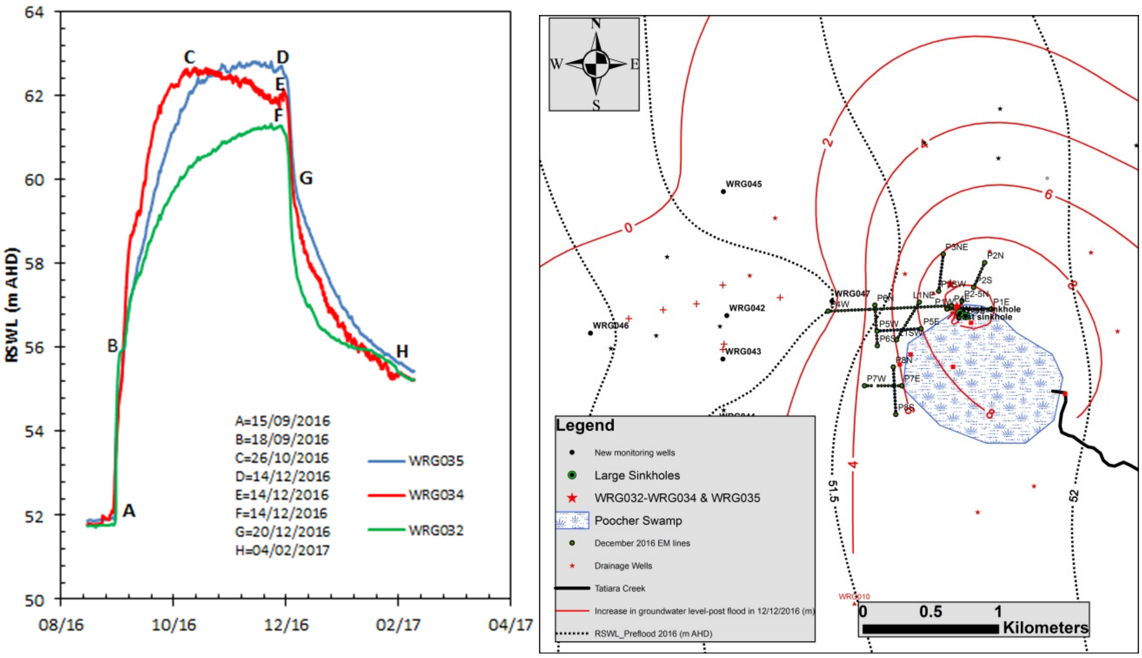


(a) (b)

Figure 8. (a) Major flow components for the Poocher Swamp compared with flow at Bordertown (b) Daily rainfall and evaporation at Bordertown

4.4 Bore Hydrograph Response to Recharge

In general, time series of groundwater levels are used for the identification of storage and transmission processes, and are considered as a prerequisite for the study of the dynamic behaviour of recharge and flow in aquifer systems. Prior to the flood event, water level rise in the monitoring wells WRG032 (0.17 m), WRG034 and WRG035 (0.3 m) are typical of the water level response to winter rainfall. As a result of the flood event on 14 September 2016, recharge into the conduit system dominates the early hydrograph response (Figure 9, point A to B). The first time derivative of the hydrograph or rate of rise and fall (Table 1) is considered as indicative of filling of the conduit system and transmission through the aquifer. A total of 73.3×10^3 m^3 of water discharged into the aquifer via two sinkholes in 4days causing monitoring wells close to the Poocher Swamp (WRG034, WRG035 and WRG032) to rise rapidly by 4 m simultaneously. In a previous study, Herczeg et al. (1997) reported that the more distant well (WRG032) responded quicker than nearby shallow wells (WRG034 and WRG035) to the Poocher Swamp recharge. Based on this observation, Herczeg et al. (1997) concluded that a conduit zone from the sinkhole may be in a deeper part of the aquifer. The different response in this recharge event is due to deepening of both WRG034 and WRG035 wells in June 2016 to 29.9 m (in MGL) from their original depths of 18 m (in the Bridgewater Formation). This confirmed the connection of wells via conduit systems occur in deeper parts of the aquifer in the MGL.



(a) (b)

Figure 9. (a) Hydrographs for WRG032, WRG034 and WRG035 wells (b) Pre-flood water level contours and post flooding increased water levels near Poocher Swamp

From the point B in Figure 9a, the rising limbs of the three wells take different paths to reach points C and E (WRG034), D (WRG035) and F (WRG032). This indicates that different flow paths have been activated and discharge may be by both conduit and granular porosity of the aquifer. The wells WRG032 and WRG035 continued to rise up until 14 December 2016, the day the Swamp emptied and no further flow reached the sinkholes. However, WRG034 well reached its maximum on 26 October 2016 coinciding with the day the Tatiara Creek flow ceased but Poocher Swamp remained 0.12 m above overflow level. As the Poocher Swamp emptied on 14 December 2016, rapid recession of the hydrographs started and within six days water levels dropped to about 60 m AHD (point G) in all three wells.

The rapid fall of water level is speculated to be due to pressure drop of the aquifer as the compressed air can escape through exposed sinkholes. With wells WRG034 and WRG035 being closer to the sinkholes, compressed air escape more easily and thus the rate of fall is greater than WRG032. It appears that the saturated or partially saturated clay layer in the Bridgewater Formation provides some local confinement. Water levels take different paths from 60 m AHD elevation (point G) to arrive at 56 m AHD (point H) on the recession limb. This has similarities to the rising limbs of the hydrographs and is an indication of a major conduit system below the elevation of point B, at 56 m AHD. The common confluence point H is an indication that water levels have recede back to the major conduit porosity zone.

Table 1. Rates of rise and fall of hydrographs

Well	Rapid rise ($m.d^{-1}$)	Slow rise ($m.d^{-1}$)	Rapid fall ($m.d^{-1}$)	Slow fall ($m.d^{-1}$)
WRG032	1	0.06	0.195	0.24
WRG034	1	0.17	0.40	0.24
WRG035	1	0.07	0.45	0.24

Figure 9b show the maximum rise in water levels compared to ambient water levels within the lens. The corresponding average aquifer storage increase is about 12.4×10^6 m^3 (after correction for air pressure, the average water level rise of 4 m over 3.1 km^2 area). The volume-balance method is used for determining specific yield:

$S_y = V_r/V_g$ (5)

where V_r is the volume of point recharge (1.65×10^6 m^3) and V_g is the volume of the recharge mound. This gives an approximate S_y value of 0.133. Similarly, the storage parameters of the conduit zone can be assessed, if it is assumed that the simultaneous rise of watertable in WRG032, WRG034 and WRG035 from 52 m AHD (pre-flood) to 56 m AHD (point B in Figure 9a), is due to filling of the northern conduit zone. The scale of the conduit zone determined using TEM sections is considered adequate to assess the storage parameter. The area within the northern conduit zone is 0.114×10^6 m^2, while the volume discharged in 4 days is 73.3×10^3 m^3 giving an approximate specific yield of 0.16. Thus specific yield of the conduit zone on sub-regional basis is about 0.13-0.16 and the method provides an average specific yield for the aquifer (equivalent porous media) but not particularly the karst conduits.

Even though the attractiveness of the WTF method lies in its simplicity and independence from the mechanisms of recharge, this highlights the difficulty in choosing an appropriate specific yield to apply in karst aquifers, even though WTF method is valid for point recharge dominant system.

In 2016, high spring (September-November) rainfall (234 mm) is compared to the rainfall of 201 mm for winter months (June-August). Different levels of response to the high rainfall in September-October, 2016 were observed in well hydrographs of WRG042 to WRG047 (Figure 10). The lowest rise (0.2 m) in water level was observed in WRG045 located near the boundary of the lens, whilst highest rise is in WRG044, located outside the lens near minor sinkholes that receive overflow water from the Poocher Swamp. Water level rise in three wells; WRG042 (0.63 m), WRG043 (0.6 m), and WRG046 (0.5 m) may be due primarily to diffuse recharge in response to high rainfall.

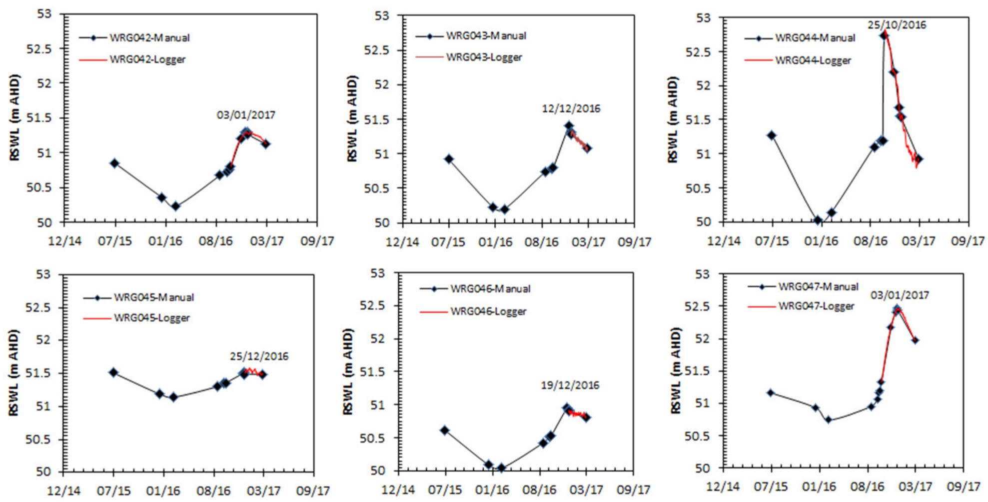
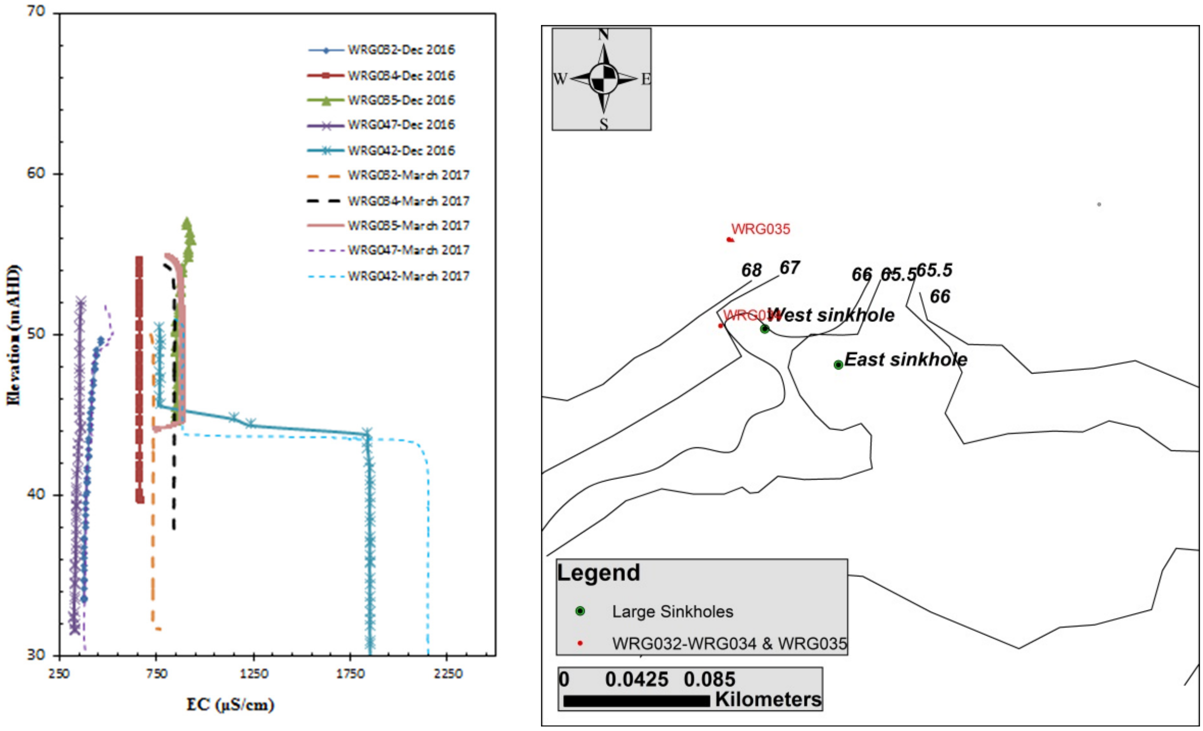


Figure 10. Well hydrographs for WRG042 to WRG047 (new wells)

The water level rise in WRG047 well is about 1.43 m from September 2016 to 03 January 2017, continuing to rise about a month after the cessation of Poocher Swamp recharge. The time lag between peak water level in WRG032 and WRG047 is about three weeks. The identical salinity profiles of WRG032 and WRG047 (Figure 11a) suggest the wells are inter-connected and there is a minimal mixing with ambient groundwater. The WRG042 well also continued to rise up to 03 January 2017, and it is possible that some lateral flow from the Sinkhole recharge may have contributed but it is unable to be confirmed as the EC correlation is poor.

Identification of spatial and temporal distribution of recharge to karst aquifers is a challenge (Geyer et al., 2008) owing to the different recharge mechanisms. Even though point recharge is highly localized, the lateral distribution across the lens over time makes it difficult to apportion the contribution of diffuse and point recharge to the hydrograph of a monitoring well. A lack of a clear hydrograph deflection point in WRG042 and WRG047 means other parameters such as variation of groundwater chemistry, isotope and groundwater age monitoring may be required to identify the contribution of point recharge.

EC profiles of monitoring wells were taken on 21 December 2016 and 6-7 March 2017. Even though monitoring wells WRG034 and WRG035 are located 50 m apart and close to sinkholes, the EC profile of WRG034 was 200 $\mu S\ cm^{-1}$ lower than WRG035 in December (Figure 11a).



(a) (b)

Figure 11. (a) Salinity profiles for WRG032, WRG034, WRG035, WRG042 and WRG047 wells (b) Ground elevation contours (m AHD) near east and west sinkholes

The east and west sinkholes are located at two different elevations (Figure 11b), the west (about 66.5 m AHD) being about 1 m higher than the east sinkhole (elevation <65.5 m AHD). The simultaneous water level responses observed in WRG032, WRG034 and WRG035 are a clear indication of the arrival of recharge water from sinkholes. This eliminates the hypothesis of different waters in WRG032, WRG034 and WRG035. A more plausible reason for the different EC profiles may be presence of regional groundwater with higher EC (see Figure 1 for salinity contours) near the WRG034 and WRG035 wells. In addition, evaporation of the dead storages in the east and west lagoons for an extended period into the summer months (December-February) increases the salinity. Seepage from the lagoons, albeit at slow rates, may have contributed to higher EC groundwater under the Poocher Swamp. This is evident in grab sampled EC data presented in Table 2. During the recharge period in October 2016, WRG032 well which is about 200 m north of the sinkhole (170 m from the WRG035) recorded an EC value of 305 $\mu S.cm^{-1}$ which is reflective of Poocher Swamp water with EC 283 $\mu S.cm^{-1}$. The EC of WRG035 water is about 817 $\mu S.cm^{-1}$ which is 534 $\mu S.cm^{-1}$ higher than the EC of Poocher Swamp water. This is an indication of freshly recharged water mixing with higher EC ambient groundwater.

The impact of mixing with ambient water is demonstrated in the EC profiles of December 2016 and March 2017. The EC of groundwater in WRG035 well remains at 870 $\mu S\ cm^{-1}$, which may equate to the EC of groundwater under the Poocher Swamp, whereas the EC of WRG034 increased from 660 $\mu S.cm^{-1}$ to 840 $\mu S\ cm^{-1}$. In March 2017, the EC of WRG032 well increase by 330 $\mu S.cm^{-1}$ while WRG047 increased by only 75 $\mu S.cm^{-1}$ indicating larger residence times for the EC front to reach the well. Data indicate that low salinity water may not necessarily occur near the point recharge source, but is dependent on the elapsed time following recharge, interconnection of conduits linking the monitoring points and quality of ambient groundwater in the vicinity. Below 43 mAHD, the EC of WRG042 increase dramatically reaching almost to the level of EC at the lens boundary. The source of higher EC groundwater in WRG042 was not identified in the study.

Table 2. EC from water sources by grab sampling

Source	Pre-flood-May 2016	During recharge-10 October 2016	End of recharge-13 December 2016
Tatiara Creek at Bordertown	dry	397	Dry
Poocher Swamp/Sinkhole	dry	283	395
WRG034	Dry-well deepen in June 2016	Not sampled	559
WRG035	Dry-well deepen in June 2016	817	851
WRG032	612	305	391
WRG047	670	395	-
WRG042	888	931	-

4.5 Implications on Recharge Estimation Methods and Management of Karst Aquifers

The ambiguous definition of sustainable yield of aquifers is debated (Kalf and Wooley, 2005), but from the concept of safe yield (Bredehoeft, 1997; Sophocleous, 1997; Kalf and Wooley, 2005) to the development and use of the resource in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley and Leake, 2004), assessment of groundwater recharge is a prerequisite. Groundwater depletion is the inevitable and natural consequences of withdrawing significant amounts of water from an aquifer (Bredehoeft 1997, 2002; Sophocleous, 1997). Accurate estimation of groundwater recharge is extremely important for proper management of groundwater systems (Healy and Cook, 2002) and hence appraisal of multiple recharge processes and estimation methods will continue to develop. Various techniques are available to quantify recharge; however, choosing appropriate techniques is often difficult (Scanlon et al., 2002 and references therein). Scanlon et al., (2002) highlight important considerations in choosing a technique include space/time scales, range, and reliability of recharge estimates based on different techniques. Other factors may also limit the application of particular techniques. One inherent problem in recharge estimation is the presence of karstic features resulting in a duality of recharge mechanism. In karst aquifers, modification to the common recharge estimation methods may be required to include both point and diffuse recharge components (Somaratne, 2014). In this study, three techniques; WTF method, generalised CMB and groundwater modelling are compared (Table 3).

For application of the WTF method, a departure from the traditional approach was followed, as the point recharge has been independently assessed, and the groundwater storage volume associated with point recharge mound is used to obtain the specific yield of the aquifer. Water level rise due to diffuse recharge was taken from wells, WRG042, WRG043, WRG045 and WRG046 which are considered outside the influence of the point recharge. The lowest water level occurred in these wells in March 2016 and the maximum water level observed was considered to results from diffuse vertical recharge. The average water level rise, 0.575 m, was taken for the entire lens.

Table 3. Comparison of groundwater recharge to the fresh water lens with the reliability category (Somaratne et al., 2014) given in brackets

Method	Diffuse Recharge		Point Recharge	
	Volume ($\times10^6$ m^3)	Year	Volume ($\times10^6$ m^3)	Year
WTF	0.95 (low to moderate)	2016	1.65 (moderate)	2016
Generalised CMB	0.05 (low)	Long-term	1.65 (moderate)	2016
Groundwater modelling	0.11 (low to moderate)	1975-2016	1.97 (low to moderate)	1975-2015

Four wells, WRG032, WRG034, WRG035 and WRG047 were excluded as the wells are influenced by point recharge. For the application of the generalised CMB, average chloride concentrations from monitoring wells closer to the boundary; WRG044 (487 mg.L^{-1}) and WRG045 (242 mg.L^{-1}) was taken as c_{gd} (365 mg.L^{-1}). The lack of well-defined diffuse recharge zones prevents use of groundwater chloride from other wells. The other variables in equation (4); P (450 mm.year^{-1}) and c_{p+d} (3.1 mg.L^{-1}) was taken from Somaratne (2015b). This results in long-term diffuse recharge within the lens of 3.85 mm.year^{-1}, equivalent to a total diffuse recharge volume of 0.05 $\times10^3$ m^3.year^{-1}. Recharge estimation using groundwater models rely on calibration to long-term observed water levels monitoring. In the groundwater model (Wood, 2016), a range of diffuse recharge 0-24 mm.year^{-1} with mean value of 9.5 mm.year^{-1} has been applied and the point recharge was taken as the monthly stream flow of Tatiara

Creek. As the overflow volume has not been considered, the estimate of point recharge is biased towards the high end, particularly during high flow years. The model has been calibrated to observed water levels in monitoring wells using a hydraulic conductivity of 86 $m.d^{-1}$ and specific yield value of 0.15. This could be further improved by using surface nuclear magnetic resonance survey (sNMR), as the method can separate total porosity into free water (drainable) and bound (retention) porosities (Davis et al. 2013). Combined TEM and sNMR could improve groundwater modelling and recharge assessment using WTF method in karst aquifers by determining porosity zones as a basis for evidenced-based parameter distribution zones while sNMR could provide alternative specific yield values across the basin.

Diffuse recharge estimates using the WTF method suffer from a lack of both monitoring wells immediately south of the Poocher Swamp and long-term observations. Except for WRG046 well, all other wells are located on a north-south transect through the centre of the lens (Figure 1). With 2016 being a particularly wet year, the estimated diffuse recharge is biased towards the high end. For the application of the generalised CMB, it is vital to obtain reliable long-term chloride concentrations from the diffuse recharge zone yet the current data relies on a one-time measurement of two wells. Measurement of as c_{gd} could further improved by taking chloride concentration from unsaturated zone above the watertable and below the root zone of the profile (Somaratne, 2015b). The mean chloride concentration of rainwater ($mg.L^{-1}$), $c_{(p+D)}$, is not measured anywhere in the catchment but rather estimated based on the distance from the coast using the expression given by Hutton (1976). Even though good model calibration to long-term observed hydrographs has been achieved, WRG032 well was the only well within the fresh water lens (Figure 1) having long-term observed water level data. Overall, the paucity of long-term observed data within the lens and the spatial distribution of observations are the main constraints to diffuse recharge estimate in this case study. Hence, reliability of the recharge estimate (Somaratne et al., 2014) falls into low to moderate category. However, in this case study sustainability of the entire freshwater lens depends on the reliability of the point recharge estimates, and the method illustrated here for 2016 recharge is considered adequate to develop a management plan for the lens.

According to Ke et al. (2013), the estimation of the groundwater recharge in a karstic system becomes an important challenge due to the great hydrodynamic variability in both time and space. Rapid filling and emptying of karst conduits means extensive monitoring of water levels are required for the application of the WTF method. This implies a greater number and wider distribution of monitoring wells and a high frequency of monitoring to capture the dynamic behavior of recharge. The duality of the recharge processes (Lerch et al., 2005; Geyer et al., 2008), discrete and turbulent point recharge, complex conduit distribution and uncertainty of the hydraulic parameters create a great challenge to apply numerical groundwater flow models in a karst environment. Nevertheless, Scanlon et al. (2003) applied both lumped parameter and distributed parameter models to karst aquifers and showed the ability of using equivalent porous media model to simulate regional groundwater flow in karstic settings. TEM method offer wide spatial coverage of measured resistivity/potential porosity zones which are typically not easily acquired by other methods. The TEM based porosity zones can be used in developing conceptual model for karst aquifers where zonal distribution of aquifer parameters could be assigned for distributed parameter models that uses equivalent porous medium approach.

5. Conclusion

The present study was undertaken to characterize dynamic nature of recharge through large sinkholes in a karst aquifer and associated networks of conduits. The specific objectives of this study were; use of transient electromagnetic survey (TEM) to identify high potential porosity zones of the aquifer, downhole geophysics, quantifying recharge through the sinkhole using the water balance method, the dynamic nature of recharge and flow by interpreting continuous water level data during the recharge and recession period. Estimated porosity varies from 0.07-0.7 giving a wide range of porosity zones. The use of the volume-balance method for determining specific yield results in approximate values for conduit zones of 0.12-0.13. This could be improved by using magnetic resonance surveys, as the method can separate total porosity into free water (drainable) and bound water (retention) porosities. Combined TEM and sNMR could improve groundwater modelling and recharge assessment in karst aquifers as the porosity zones provides a basis of evidence-based parameter distribution zones and sNMR could provide alternative specific yield values across the basin.

Opposed to typical diffuse recharge processes, the highly dynamic nature of the point recharge and associated rapid water quality changes limit the applicability of recharge estimation methods. For example, point recharge water that mixes with ambient groundwater changes groundwater chloride concentrations and age, invalidating the basic assumptions of using tracer based or groundwater age based recharge estimation. In this case study, point recharge to sinkholes was assessed using the water balance method. However, in groundwater basins having many sinkholes, it is not practical to obtain inflow to sinkholes using surface water flow measurement devices.

Alternative methods such as the use of rainfall-runoff simulation models may be useful to estimate flow into sinkholes. Thus, future studies should consider improving parameter estimates for WTF, generalised CMB and groundwater-surface water modelling or new pragmatic approaches to improve recharge estimation in karst aquifers.

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