Water **2015**, *7*, 464-479; doi:10.3390/w7020464

OPEN ACCESS

water

ISSN 2073-4441
www.mdpi.com/journal/water

Reply

Karst Aquifer Recharge: A Case History of over Simplification from the Uley South Basin, South Australia

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Academic Editor: Miklas Scholz

Received: 22 December 2014 / Accepted: 22 January 2015 / Published: 4 February 2015

Abstract: The article "Karst aquifer recharge: Comments on 'Characteristics of Point Recharge in Karst Aquifers', by Adrian D. Werner, 2014, *Water* 6, doi:10.3390/w6123727" provides misrepresentation in some parts of Somaratne [1]. The description of Uley South Quaternary Limestone (QL) as unconsolidated or poorly consolidated aeolianite sediments with the presence of well-mixed groundwater in Uley South [2] appears unsubstantiated. Examination of 98 lithological descriptions with corresponding drillers' logs show only two wells containing bands of unconsolidated sediments. In Uley South basin, about 70% of salinity profiles obtained by electrical conductivity (EC) logging from monitoring wells show stratification. The central and north central areas of the basin receive leakage from the Tertiary Sand (TS) aquifer thereby influencing QL groundwater characteristics, such as chemistry, age and isotope composition. The presence of conduit pathways is evident in salinity profiles taken away from TS water affected areas. Pumping tests derived aquifer parameters show strong heterogeneity, a typical characteristic of karst aquifers. Uley South QL aquifer recharge is derived from three sources; diffuse recharge, point recharge from sinkholes and continuous leakage of TS water. This limits application of recharge estimation methods, such as the conventional chloride mass balance (CMB) as the basic premise of the CMB is violated. The conventional CMB is not suitable for accounting chloride mass balance in groundwater systems displaying extreme range of chloride concentrations and complex mixing [3]. Over simplification of karst aquifer systems to suit application of the conventional CMB or 1-D unsaturated modelling as described in Werner [2], is not suitable use of these recharge estimation methods.

Keywords: karst aquifers; point recharge; sinkholes; recharge in semi-arid; Australia

1. Introduction

The article of Werner [2], "Karst Aquifer Recharge: Comments on Characteristics of Point Recharge in Karst Aquifers", contains inappropriate over-simplifications of the hydrogeology and recharge processes in Uley South basin. Werner [2], using the conventional chloride mass balance method (CMB) and one-dimensional unsaturated flow modelling, arrives at distorted characteristics of the Uley South QL aquifer. The simplistic conceptual model in Werner [2], appears "fit-for-purpose" for demonstrating the general application of the conventional CMB and 1-D unsaturated flow modelling, but is far removed from the reality of the basin. Werner [2] describes the conceptual model and well-mixed groundwater system in the QL aquifer without providing supporting evidence, although substantial lithological, hydrogeological, hydrochemical and salinity profile data are available. For reader convenience, this reply is sub-divided into two sections as in Werner [2]: (1) Uley South Recharge Processes; and (2) Uley South Recharge: Methods and Estimates.

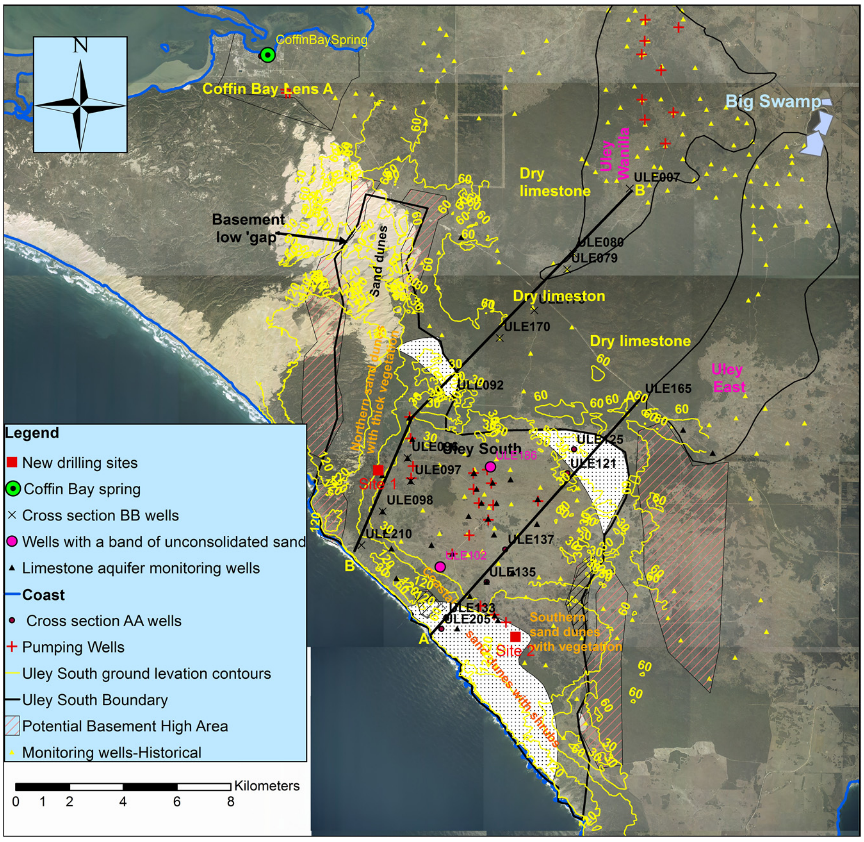
2. Uley South Recharge Processes

2.1. Basin Features: Sand Dunes, Vegetation Cover and Groundwater Flow Direction in Uley South

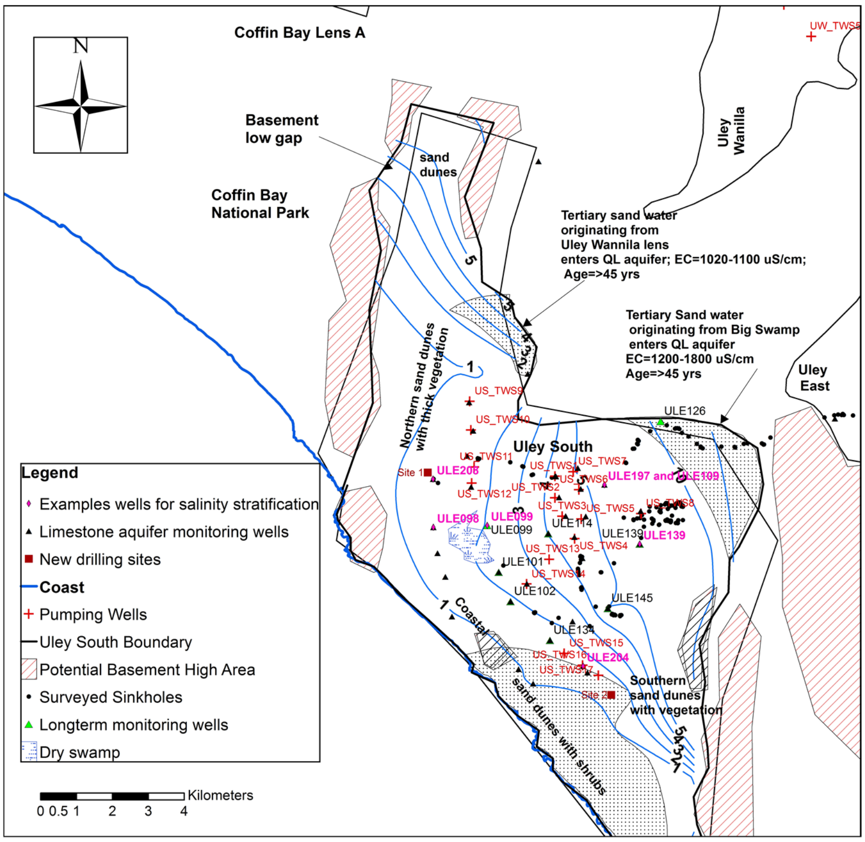
Since a more detailed description of Uley South basin features is given in Somaratne [1], Somaratne *et al.* [4] and Somaratne and Frizenschaf [5], only a succinct summary is provided here, focusing in features relevant to the points of contention [2]. The basin is topographically closed due to surrounding sand dunes and basement high areas except in the landward direction where dry limestone is found (Figure 1a). Vegetation is sparse in Uley South central basin, except on dunes, which generally occur 30 m above mean sea level (Figure 1a). Groundwater flow direction is from north-east to south-west (Figure 1b), as the basement high area between Coffin Bay and Uley South restricts groundwater movement to the west. There is a basement low area of 700 m length (gap) near the north-western corner of the basin (Figure 1a), however, no investigation well has been drilled in this area. Groundwater flow towards the "gap" is restricted due to basement high areas and dry limestone in the landward direction. During intense rain events, runoff of neighboring limestone dry areas and basement high areas drain to karstic features in Uley South that recharge the aquifer. Thus the area beyond the Uley South landward boundary forms an allogenic recharge zone.

2.2. Characteristics of QL Aquifer

Werner [2] describes the Uley South Quaternary Limestone as mainly comprising aeolian sediments, which are generally either unconsolidated or loosely aggregated [2]. Unconsolidated sediments are nonlithified having no mineral cement or matrix binding such as $CaCO_3$ in their grains. Technically, an aquifer comprised of such sediments would not be called "Quaternary Limestone" because limestone is one type of sediment that has undergone lithification and formed into a sedimentary rock.



(a)



(b)

Figure 1. Uley South basin features (**a**) Topographic features (**b**) Groundwater elevations contours.

The description of the basin geology in Werner [2] is based on a previous work [6] rather than examination of available geological information. In their study, McKee and Ward [7] survey the pertinent literature, and show that no "one term" has had exclusive adoption and that approximately 20 names or variants have been applied to the calcareous dune deposits and consolidated rock derived from them. The feature of $CaCO_3$ composition has been variously indicated in the sediment name or rock name by use of such terms as calcareous, carbonate, calcarinite, sandstone or limestone [7]. The agent of deposition is mostly indicated by the name aeolian, wind-blown, dune sand or dune rock. Only modern dunes are generally unconsolidated, mostly active, and becoming cemented and stabilized over time, even though there is a great variation in the amount of time required for lithification [7]. Thus QL lithology in Uley South is variously described over the 1960 to 2014 period of well drilling, but the primary composition is calcarenite-albeit with varying degrees of cementation.

With the above background, and in an effort to more accurately describe basin characteristics, 98 available lithological descriptions with corresponding drillers' logs spanning the period 1961–2003 were re-examined. Two lithological descriptions contain "Aeolian unconsolidated bands" (ULE186 at 6–11.5 m depth and, ULE102 at 4–13 m depth in Figure 1a), three lithological descriptions of historical wells show "Aeolinite-Hard" (ULE115, ULE117, ULE113) and one well describes the lithology as "Aeolinite-buff, fine to medium consolidated" (ULE101). The remaining wells' lithological logs describe either Limestone (LST) or Sandstone (SST) with common descriptions such as: "LST: cream, buff, fine, chalky, hard; LST: grey boulders, SAND at places strongly cemented (or moderately and places with weakly cemented) bars; LST: off white, chalky indurated; LST: off white moderately cemented; LST: sand hard bars; SST cream, dense (or fine) calcarenite". The lithology of wells adjacent to sand dunes mostly fitted the description as shown in ULE202 "Calcrete: aeolinite, medium grained, very strongly cemented, whitish brown".

The occurrence of near-vertical cliffs over 100 m height, along the entire coastline (about 18 km) (Figure 2) suggests that the QL aquifer comprise of consolidated sediment. All of the above evidence appears to contradict the conception, as shown in the schematic diagram of Werner [2] of upper subsurface conditions with unconsolidated or poorly consolidated sediments. This schematic diagram also shows a continuous subsurface calcrete horizon [2]. Not all wells show a calcrete layer in the lithological descriptions. Whilst some wells show the presence of a calcrete layer in vadose zone, in some other wells, the calcrete layer only appears in the saturated zone. It is also common that limestone or sandstone "hard bars" occur at multiple horizons in the profile even in a single well. However, no evidence is found in the lithological descriptions, that such horizons form continuous layers.

During drilling, it is noticeable when intersecting a large cavity, but not so noticeable if intersecting a small conduit, unless core samples are collected. No core samples have been collected from Uley South drillholes making it difficult to identify conduit porosity zones, particularly of small-pipe conduits. However, in several wells "lost circulation" (no drill cutting returns to surface) has been reported, indicating the presence of large cavities. For example in ULE208 well (Figure 1b) drilled in 2003, at 24–42 m depth interval, "lost circulation, no returns, no samples, hard bar at 38 m" is reported. Depth to water of ULE208 is about 28 m and therefore "lost circulation" begins in the unsaturated zone indicating the presence of conduit porosity in both saturated and unsaturated zones. The new investigation well drilled in 2014 at Site 1 (Figure 1a) which is about 240 m west of ULE208 and 15.5 m higher elevation shows the presence of lost circulation and hard bars at the same elevation as that in ULE208 (Figure 3). The well at Site 1 is 0.1 m diameter with an open hole production zone from 54.9 to 63 m. The depth to standing water level is about 44 m. The occurrence of conduit porosity at about the same elevation in the Site 1 well and ULE208 is an indication of possible inter-linking of conduit porosity in both unsaturated and saturated zones. The lithological description of the well at Site 1 (Figure 3a) shows the occurrence of calcarenite with varying degrees of cementation.

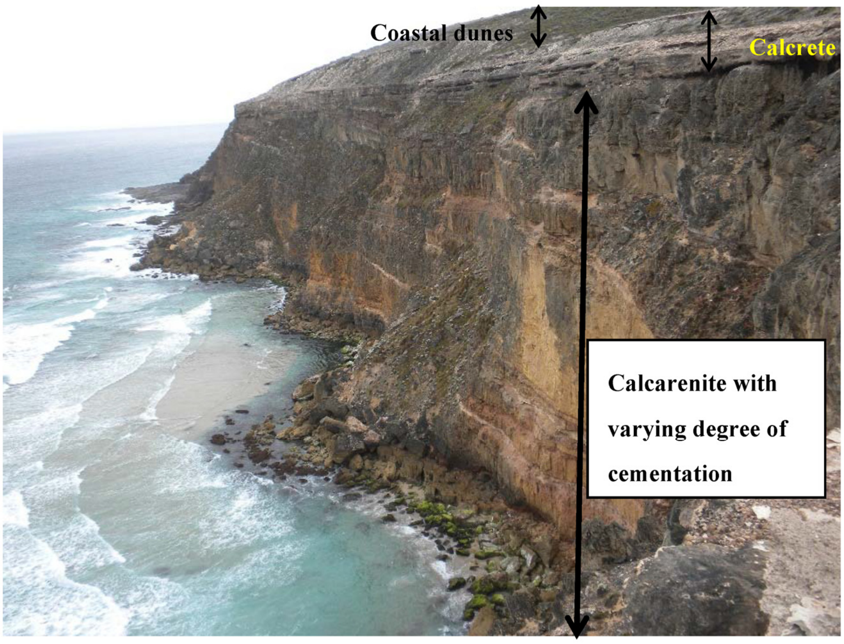
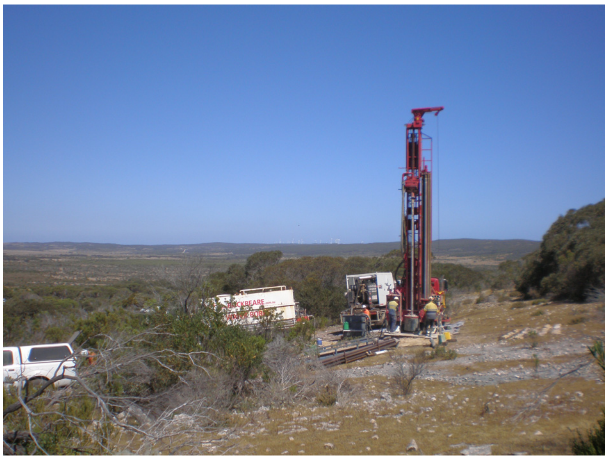


Figure 2. Section of the coastal cliff.

Depth (m)	Description
0–4	Calcarenite; light brown off white
4–14	Calcarenite, buff, very weakly cementing
14–16	Calcarenite;no returns; injecting form
16–63	Calcarenite; very weak cementing to moderate cementing and mostly no returns; water at 44 m depth. At 41 m, 51 m, and 52–53.5 m very hard bars; Cavity from 53.5–55 m; Hard from 58–60 m

(**a**)



(**b**)

Figure 3. Geology and topographic features at Site 1 (**a**) Summary of lithological description (**b**) Drilling at Site 1 (note the surface calcrete in foreground and coastal dunes with vegetation cover in the background).

Investigation drilling at Site 2 (Figure 1a), located at the foot of the coastal dunes reveal similar lithological facies. At 28–30 m depth, a cavity is encountered and at 79–93.5 m depth "lost circulation" is reported. The well is 0.25 m diameter and cased to 69 m with an open hole production zone from 69 to 84 m. Depth to water is about 60 m from ground level.

Further evidence of the presence of conduit porosity emerges from the hydraulic parameters of the QL aquifer. Pump tested hydraulic conductivity of water supply wells in Uley South basin is 300–1300 md^{-1} and specific yield is 0.03–0.72 indicating large heterogeneity. This is typical of karstic aquifer but not of unconsolidated sediments. For example, town water supply well number 1, TWS 1, (Figure 1b) had been pump tested at 126 Ls^{-1} for 16 h and produced only 2.1 m drawdown. The saturated thickness of the QL aquifer at TWS 1 well is about 10 m. The TWS 1 was constructed in 1964; TWS 2-8 constructed during 1969–1975 and TWS 9-17 constructed in 1999. There have been no reports of collapse or instability since their construction and are still functioning as water supply wells. The TWS wells are 0.25 m diameter, apart from TWS 9, 11 and 12, all the other 14 water supply wells are constructed with open hole production zones indicating stable saturated zones. This would not be possible in unconsolidated or poorly consolidated sediments.

Similar to the Uley South basin, Werner [2] describes the Coffin Bay aquifer as "surface calcrete overlying unconsolidated sediment". Located adjacent to Uley South basin, the Coffin Bay Lens A aquifer is geologically similar to Uley South, comprised of calcarenite. However, there are no sinkholes evident in Coffin Bay and therefore no point recharge sources as in Uley South. Despite this, conduit porosity does exist as evidenced in spring discharges along the coastline (Figure 1a). It is thus concluded that the primary recharge mechanism in the Coffin Bay Lens A aquifer is diffuse recharge.

2.3. Solution Sinkholes in Uley South

In Werner [2], sinkholes are described as "predominantly solution features within the calcrete capping" and "the limited depth of sinkholes over the majority of Uley South is such that there are no known dissolution features that reach the watertable within the basin". In order to guide the reader on recharge through sinkholes, a brief description of sinkhole classification and recharge process is provided below. Out of six sinkhole types (solution, collapse, caprock, dropout, suffosion and buried) [8], solution (Figure 4a) and buried (Figure 4b) sinkholes are evidenced in Uley South. Solution sinkholes occur in areas where limestone is exposed at land surface or is covered by thin layers of soil [8]. Solution of carbonate rock is most active along joints, fractures, cavities, bedding planes or other openings in the limestone that permit water to move easily into the subsurface. Thus solution sinkholes develop along these openings. Dissolved limestone and insoluble residue are carried downward by percolating water along enlarged openings as solution of limestone progresses.

Circulation of water through karstified rocks is affected by three concentration mechanisms [9]: Overland flow; through flow, that is, flow through a layer of soil above limestone; and subcutaneous flow. Each of the above flows differs depending on the level of development of the karst process. Similarly, the input mechanism from sinkhole to groundwater can also be divided into three mechanisms [9]: Shaft flow from predominantly vertical shafts (connected sinkholes, Somaratne [1]); flow through enlarged joints, cavities and fractures of the vadose zone (connected sinkholes, Somaratne [1]); and vadose seepage or slow sinking through small fissures (macro pores in unconnected sinkholes, Somaratne [1]). Point recharge at sinkholes feeds karst conduits to the saturated zone, bypassing the surrounding matrix and thus largely escaping evapotranspiration. It is expected that a small component of recharge around sinkholes also seeps slowly into the granular porosity around the recharge point.

(**a**) (**b**)

Figure 4. Sinkhole types in Uley South (**a**) Large active solution sinkhole showing upper calcrete layer and below consolidated sediment (calcarenite); (**b**) Large buried sinkhole showing upper calcrete layer and infill materials.

Groundwater flow in karst aquifers is shared between the granular porosity and karst conduits, but groundwater flow through even a porous limestone aquifer is generally mostly through the conduits, because groundwater in the conduits flows several orders of magnitude more quickly than in the granular porosity. In contrast to solution sinkholes, buried sinkholes are formed due to subsequent deposition of material washed into sinkholes from sides. However, these sinkholes become active once the new lateral dissolution of limestone occurs as shown in Figure 4b.

2.4. Sources of Groundwater Mixing in the QL Aquifer and Salinity Stratifications

Werner [2] and Ordens *et al.* [10] posit diffuse recharge as the primary recharge mechanism in Uley South. The different recharge mechanisms and their influence on salinity stratification and hydrochemical changes, evident in Uley South QL aquifer is described below. The reader is directed to Somaratne and Frizenschaf [5] for more detailed description of the different water types and mixing in the Uley South basin.

Rainfall in Uley South is seasonal, occurring predominantly during winter months. Uley South QL aquifer groundwater is derived from three sources, two of which are rainfall driven. Diffuse recharge from rainfall takes place through surface exposed epikarst, buried and unconnected sinkholes and pockets of soil that occur in the basin; point recharge of runoff through connected solution sinkholes which is intermittent and highly transient; and finally, leakage of TS water into QL aquifer at the landward boundary where Tertiary Clay is absent (Figures 1b and 5). This leakage is independent of rainfall and occurs throughout the year. The TS water quality has influenced salinity stratification, hydrochemical and isotope composition of QL aquifer.

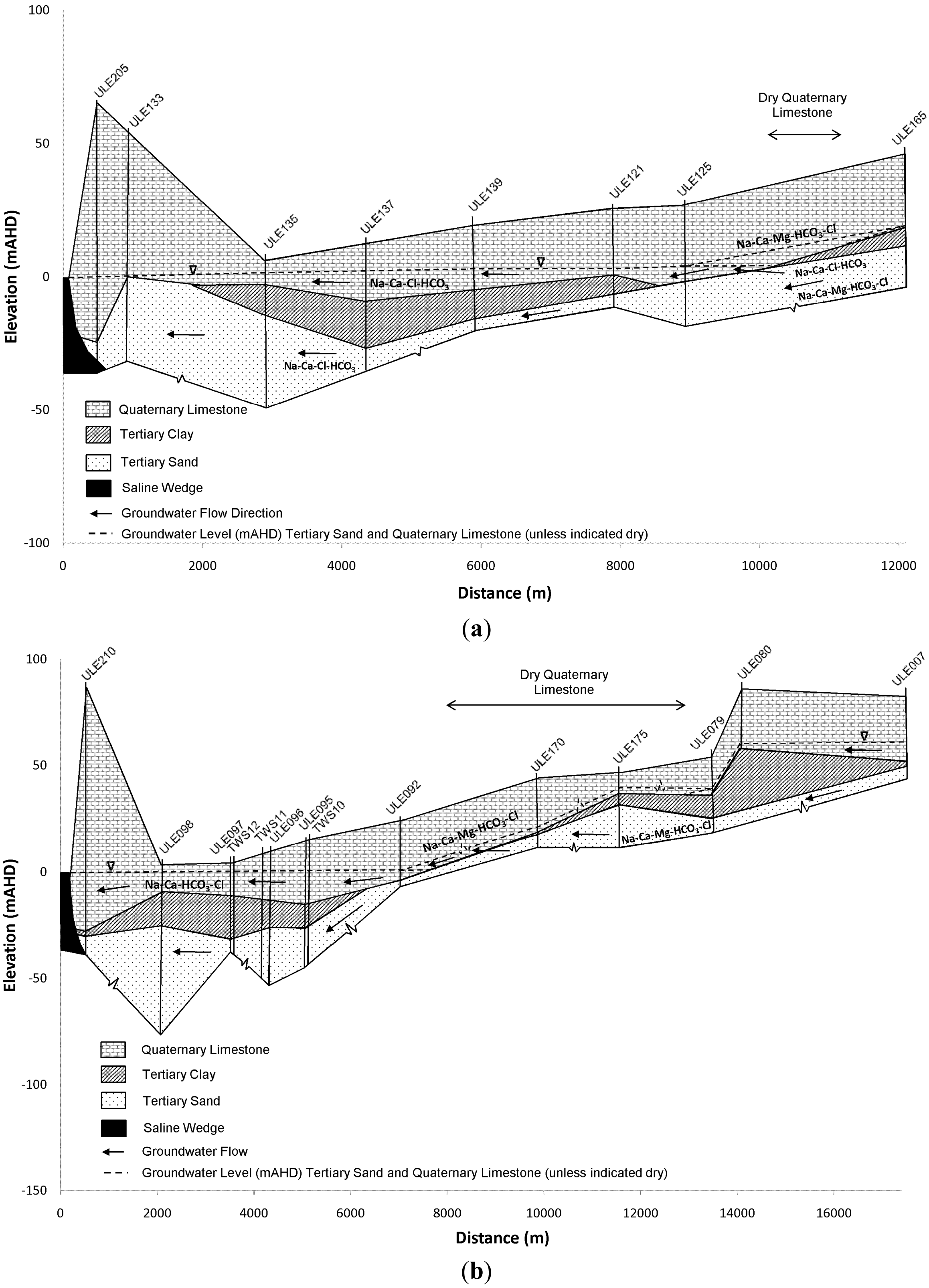
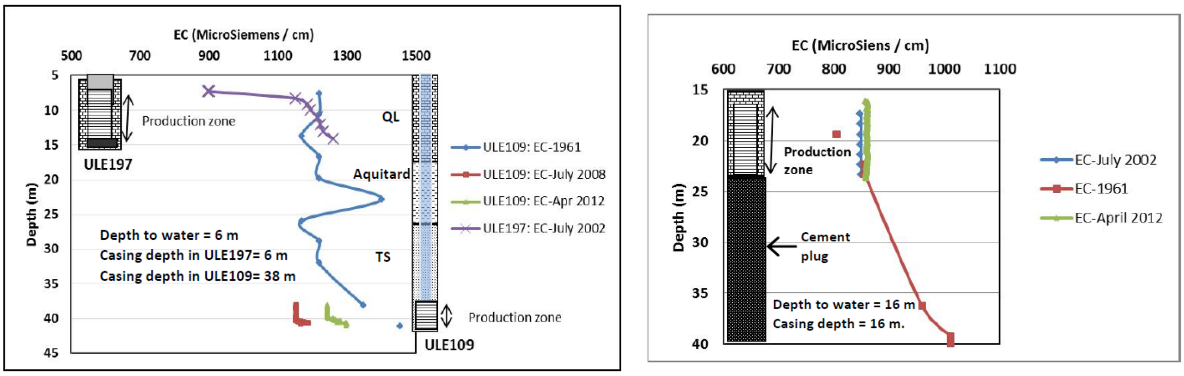


Figure 5. Geological cross section: (**a**) Cross section AA-Uley South to Uley East lens [1,5]; and (**b**) Cross section BB-Uley South to Uley Wanilla lens.

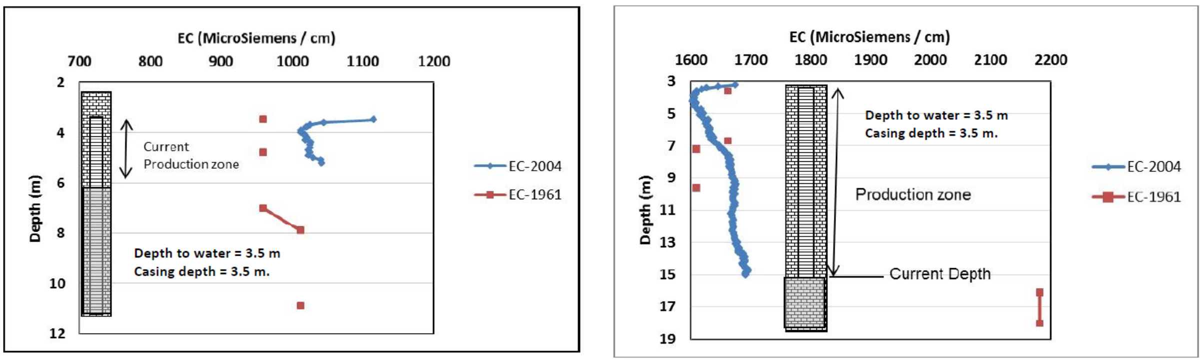
Harrington *et al.* [11] and Somaratne and Frizenschaf [5] show that the high-salinity plume of groundwater in the TS aquifer enters Uley South at the central part of the landward boundary where Tertiary Clay is absent (Figures 1b and 5a). The plume originates from the Big Swamp (Figure 1b) area located 18 km north-east of Uley South as a result of downward leakage of Big Swamp's surface water through the clay aquitard [5]. As the plume moves down gradient along its main flow path, the western edge of the Uley East basin, it is diluted from electrical conductivity (EC) 9000–10,000 µS/cm at Big Swamp to EC approximately 1800 µS/cm at the southern boundary of the Uley East basin. In Uley South in the area where the aquitard is absent, the TS aquifer receives direct recharge, resulting in further dilution of EC to about 1200 µS/cm [5]. Similarly, Tertiary sand water originating from Uley Wanilla lens with EC up to 1100 µS/cm enters the north-central part of the basin where Tertiary Clay is absent at the landward boundary (Figures 1b and 5b).

In order to track the possible pathway of freshwater from point recharge sources, salinity profiles were obtained according to the method described by Somaratne [1]. Salinity profiles are considered to be superior to water sampling as the sonde records EC of water at 0.05 m interval, thus enabling identification of EC changes at short depth intervals. Out of 32 monitoring wells in QL aquifer, 22 were sonded and about 70% of sonded wells showed salinity stratification. Where EC measurements were available from drilling undertaken in 1961, these were presented for comparison (Figures 6–8).



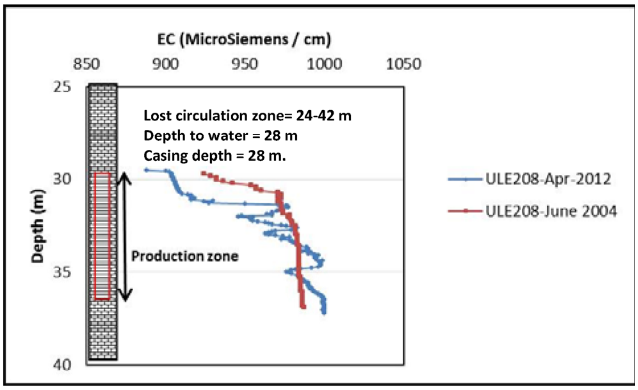
(**a**) (**b**)

Figure 6. Effect of Tertiary Sand water leaking into QL aquifer on salinity stratification (**a**) ULE109 and ULE 197; (**b**) ULE139.

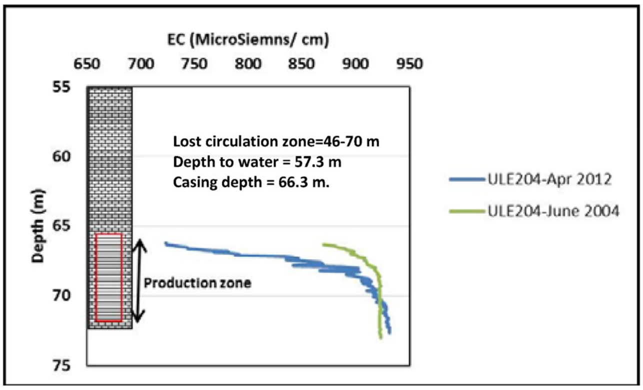


(**a**) (**b**)

Figure 7. Salinity Stratification influenced by evaporation in QL aquifer (**a**) ULE099 and (**b**) ULE098.



(**a**)



(**b**)

Figure 8. Salinity stratification influenced by conduit porosity in QL aquifer (**a**) ULE208 and (**b**) ULE 204.

As a result of higher salinity water leaking to QL aquifer, pronounced salinity stratification is found in QL aquifer monitoring well ULE197, located 2 km down-gradient to the Tertiary Clay absence area (Figure 6a). In the ULE197 well, salinity of the QL base is identical to that in TS aquifer monitoring well ULE109, located at the same site. In contrast, the southern half of the QL aquifer has no link to the Big Swamp area through either QL or TS aquifers due to the occurrence of the basement high at the Uley South boundary (Figure 1). Therefore, QL water in the southern part of Uley South is derived primarily from direct rainfall recharge within Uley South. ULE139 (Figure 6b) drilled as an investigation well in 1961 and completed as a QL aquifer monitoring well shows no evidence of salinity stratification suggesting no influence by TS water or connection to sinkholes through conduit. Comparing ULE197 and ULE139 salinity profiles of QL aquifer, leakage of Tertiary Sand water has increased EC of ULE197 by 400 µS/cm at the base of the QL aquifer and this disperse upward towards the piezometric surface (Figure 6a) creating a non-uniform mixing zone.

The influence of TS water entering Uley South is evidenced in all monitoring wells in the central northern parts of the basin. In shallow wells ULE099 and ULE098 (Figure 7), the upper part of the EC profile is slightly higher, possibly due to the effect of evaporation. The difference of EC in the upper and lower parts of the QL aquifer has declined due to dispersion of higher salinity water. ULE098 is located downgradient to a dry swamp (Figure 1b), and EC is higher than upgradient well ULE099 due to evaporation enriched swamp water leaking into groundwater that is possibly intercept by ULE098.

EC stratification due to point recharge is evident in monitoring wells located away from the influence of TS water in the QL aquifer. ULE208 drilled in 2003, is located at the northern end of the central basin (Figure 1b) with a depth to water of about 28 m. The well is located at the foot of a limestone slope. Since the surface is calcretised, it is expected that little direct recharge is received from the surface. The low EC zone (Figure 8a) corresponds to the "lost circulation zone" described previously. The nearest known sinkhole is located down-slope approximately 200 m to the east. It is therefore possible that conduit carrying point recharge from the sinkholes is intercepted by the "lost circulation" zone of ULE208.

Drilled in 1999, monitoring well ULE204 is located on limestone slopes in the southern side of the basin (Figure 1b). Depth to water is about 57.3 m and the well is cased up to 66.3 m. During drilling, circulation was lost between 46 and 70 m depths. The well is constructed as "open hole" in the production zone. Similar to ULE208, low salinity in the upper "lost circulation" area is due to conduit porosity containing low salinity water (Figure 8b) which is thought to originate from cluster of sinkholes in an up-gradient valley, about 1 km to the north-east. This suggests that in Uley South, high flow pathways are evident. This evidence is removed from wells in the central basin by the input of higher salinity water continuously received from the TS.

In similar settings, Allison *et al.* [12] investigated rates and mechanisms of recharge beneath two major landscape settings in the Murray Basin in South Australia; these are calcrete flats with sinkholes and sand dunes in an adjacent landscape. Allison *et al.* [12] suggest that recharge varies from in excess of 100 mm·year^{-1} for sinkhole areas to less than 0.1 mm·year^{-1} beneath sand dunes with native vegetation.

The groundwater age in Big Swamp and Uley Wanilla is >45 years [11]. Mixing of old waters originating from Uley Wanilla and Big Swamp with younger water (<20 years) in Uley South has important ramifications on applicable recharge estimation methods. When mixing occurs between different groundwater systems of different ages and different chlorides concentrations, this results in unreliable recharge estimates using groundwater age and the conventional CMB method [4]. The combination of aquifer heterogeneity, salinity stratification, recharge through solution features, leakage of Tertiary Sand water and non-uniform mixing of different water types and modification along flow paths, results in Uley South being more hydrochemically complex than Werner [2] suggests.

3. Uley South Recharge: Methods and Estimates

Werner [2] discusses various approaches and data limitations on application of recharge estimate methods in karst aquifer systems, and in particular for the Uley South basin. Numerous studies on recharge estimation methods and their limitations are available. For details, the reader is directed to: Simmers [13], Sharma [14], Healy and Cook [15], Scanlon *et al.* [16], and a summary of selected methods in Somaratne *et al.* [4].

With regard to obtaining consistent results and greater reliability of recharge, Scanlon *et al.* [16] hold the view that it is highly beneficial to apply multiple methods but Healey and Cook [15] consider that consistency by itself should not be taken as an indication of accuracy [4]. Concurring both with Scanlon *et al.* [16] and Healey and Cook [15], Somaratne *et al.* [4] introduce a simple technique to assess reliability of recharge based on three distinct criteria: applicability of the method, reliability of data, and spatial coverage of the basin. Somaratne *et al.* [4] show that if the theory or method of recharge estimation is not valid, it always produces a "Low" reliable recharge value. This "Low" level will stand unless the theory or method is improved. Reliability of data and spatial coverage can be improved, if the method is applicable [4].

With this background, underpinning assumptions of the conventional CMB method are provided below. Following Ericksson and Khunakasen [17], the CMB equation can be expressed as:

$$\mathrm{R} = \frac{\mathrm{P}c_{\mathrm{p+D}}}{c_{\mathrm{R}}} \quad (1)$$

where R is recharge (LT^{-1}); c_{p+D} (ML^{-3}) is the representative mean chloride concentration in rainwater including contributions from dry deposition; and c_R is chloride concentration in recharge (ML^{-3}). For Equation (1) to hold after replacing c_R with groundwater chloride (c_g), c_R must be in equilibrium with c_g (saturated version of CMB) [3]. This is not the case with point recharge through sinkholes as Werner [2] anticipates, as point recharge occupies mostly conduit porosity areas. Zhu *et al.* [18] highlights that for the saturated version of CMB to be applicable; groundwater movement in both unsaturated and saturated zones should be approximated as one-dimensional piston flow. This essentially means that chloride concentration of the mass flux crossing the piezometric surface (c_R) is at equilibrium with groundwater chloride (c_g) [3]. When chloride concentrations of groundwater samples (c_g) are used as c_R values in Equation (1) for saturated zone application, the recharge rates determined from the conventional CMB apply to locations in the catchment where the samples are recharged, not where the samples are collected [3]. This requires that hydrodynamic dispersion of chloride between the recharge point and sampling location be small, which essentially requires the piston flow requirement in the unsaturated and saturated zones of Zhu *et al.* [18]; and the necessity of minimal mixing for less variability within the aquifer (valid under steady-state condition), otherwise the conventional CMB equation must be viewed as a gross simplification as indicated by Subyani and Sen [19]. Clearly, when point recharge is a contributing recharge source, fundamental assumptions of the conventional CMB are violated [3]. It is noted here that the conventional CMB is the simplest form of the mass balance equation in hydrology, and is not applicable to account for mass balance in systems displaying complex groundwater mixing caused by point recharge [3]. In particular, groundwater basins, such as Uley South, where the chloride in the aquifer originates from several sources and not just from precipitation directly on the aquifer, such application of the conventional CMB method is likely to provide a distorted recharge value. This is why Somaratne [1] suggest incorporating duality of the recharge mechanism into the conventional CMB, as in the generalised CMB method [3], if it is to be used for karst aquifers. The method must be valid in the first instance, and then parameterisation of the model is a different issue.

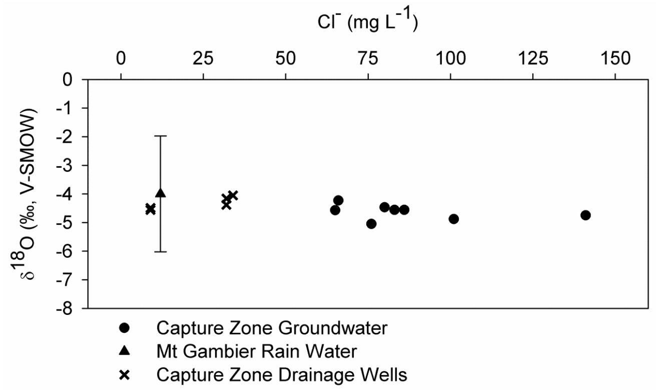
In the article of Somaratne [1], point recharge is described as "highly transient and may occur in relatively short-time periods, yet is capable of recharging large volume of water, even from a single extreme rainfall event. Preferential groundwater flows are observed in karst aquifers with local fresher water pockets of low salinity that develop around point recharge sources". Werner [2] comments that "hence, the seemingly stable freshwater pockets in the vicinity of point recharge" but the word "stable" is not given in Somaratne [1] nor is it implied.

Referring to Herczeg *et al.* [20], Werner [2] states water chemistry and isotope interpretations indicated that point sources contribute less than 10% of total recharge, with diffuse recharge providing the remainder. This is used to justify a diffuse recharge estimate using the conventional CMB method in Uley South basin. For a valid comparison, it is prudent to consider the catchment area and number of sinkholes considered in the Herczeg *et al.* [20] study. Herczeg *et al.* [20] considered three large sinkholes (including the Poocher Swamp sinkholes), one swamp and a drainage bore in the > 500 km^2 Tatiara catchment, whereas hundreds of sinkholes (surveyed 161) are present in the Uley South basin (113 km^2), and 400 drainage wells and three sinkholes are present in the Mount Gambier capture zone (26.5 km^2). The diffuse recharge rate of the Tatiara catchment is 1–15 mm per year [20] and in Uley South is 52.7 mm per year [1].

Werner [2] and Ordens *et al.* [10] interpret the gap in the chloride *vs.* $\delta^{18}O$ relation as evidence that the sinkhole is not directly recharging the aquifer. Somaratne contests [1] that the gap is a sampling bias because of the inability to obtain water samples under solution sinkholes due to their complex architecture and inaccessibility. Sampling to reduce this bias is possible in drainage wells in Mount Gambier as Herczeg *et al.* [20] use a drainage well for their study. Average catchment areas contributing to a sinkhole in Uley South (0.07 km^2) [1] and the drainage well in Mount Gambier (0.03–0.12 km^2) are similar. These small catchments generate small runoff volumes that occur mostly in conduit porosity.

Even though 400 drainage wells are spread across the capture zone in Mount Gambier, a gap of 43 mg·L^{-1} exits between rainfall and monitoring well chlorides in the chloride *vs.* δ^{18}O relation (Figure 9). Any water samples taken from a well is generally considered to be mixture of waters from all flow lines reaching the well. The gap in chloride *vs.* δ^{18}O relation does not mean drainage wells are not directly recharging the aquifer. This gap could only be filled by taking water samples from drainage wells themselves.

In previous recharge estimation efforts, Ward *et al.* [21] adopt a conceptual model of recharge for the Uley South basin that comprised the addition of runoff to the watertable via numerous sinkholes. This produced an average annual total recharge of 75 mm, whereas Ordens *et al.* [10] apply the conventional CMB method to the Uley South basin resulting in an average annual total recharge of 52–63 mm. The three criteria reliability analysis of Somaratne *et al.* [4] results in the total recharge to the basin calculations of both Ward *et al.* [21] and Ordens *et al.* [10] as "Low" reliability estimates [4] as Ward *et al.* [21] ignored the diffuse recharge and Ordens *et al.* [10] ignored the effects of point recharge and leakage of TS water into the QL aquifer. However, the estimation of Ward *et al.* [21] of point recharge and that of Ordens *et al.* [10] of diffuse recharge yield moderately reliable recharge.



(**a**)

(**b**)

Figure 9. Characteristics of chloride *vs.* δ^{18}O relation, Mount Gambier Blue Lake capture zone (**a**) Chloride *vs.* δ^{18}O relation [1]; (**b**) Direct recharge through a drainage well.

The implications of reliance on the conventional CMB estimated recharge in Uley South basin is clear in the long-term water level trends. Average annual pumping from the basin over the past 14 years (2000–2014) is about 60 mm per year (6.8 × 10^6 m^3 over 113 km^2), which is equivalent to the CMB estimated recharge range of Ordens *et al.*[10]. Based on extraction of 100% of estimated recharge, groundwater levels should be falling. However, the water level trend observed in the basin since 1999, is characterized by stable or slight water level rise (Figure 10); the coastal saline wedge is stable [5] and as shown before, groundwater salinities in both QL and TS aquifers are equivalent to 1961 levels. The rise and fall of basin water levels is primarily climate driven as indicated in cumulative rainfall deviation from the mean. Declining water levels from 1968 to 1977 have no relation to groundwater extraction as the extraction began in 1977. The year 1968 recorded the highest rainfall (917.4 mm) at the Big Swamp station (Station: 18017) in the last century and 1977 recorded the lowest rainfall of 414 mm during 1960–2014 period. With the average groundwater extraction during the 1977–1992 period of 5 × 10^6 m^3 (basin equivalent depth of 44.2 mm), water levels generally increased due to average annual rainfall being slightly higher (592.4 mm) than the mean annual average of 550 mm. The period from 1993 to 1999 is mostly dry, with an average 15% reduction in rainfall compared to the mean annual average. During this period water levels declined even though extraction remained unchanged. Years 2000 and 2001 featured up to about 20% higher annual rainfall and since then there has been generally average annual rainfall. During this period, the basin water levels were stable and steadily rising even though the average annual extraction increased to 6.8 × 10^6 m^3 (basin equivalent depth of 60 mm).

Monitoring wells ULE101 and ULE126 are not considered representative wells for the main limestone aquifer, even though they have long-term data sets. ULE101 is located at the edge of a swamp and terminates 5 m into the Tertiary Clay layer, and ULE126 is at the basin's outer margin (Figure 1b) of wet and dry limestone [4]. The current water level of the most up-gradient well within the basin, ULE139, is the same as the pre-development water level of 1961. The most down gradient well, ULE102 is about 0.7 m lower than the 1961 level but steadily rising towards a new equilibrium level. Therefore, recharge estimates based on a conventional CMB are unrealistically low in this karstic setting. Similarly, the minimum average annual recharge value, 47 mm, reported by Ordens *et al.* [10] using the watertable fluctuation method (47–129 mm) is well below the annual extraction. This highlights the danger of presenting recharge values without assessing reliability levels of estimations.

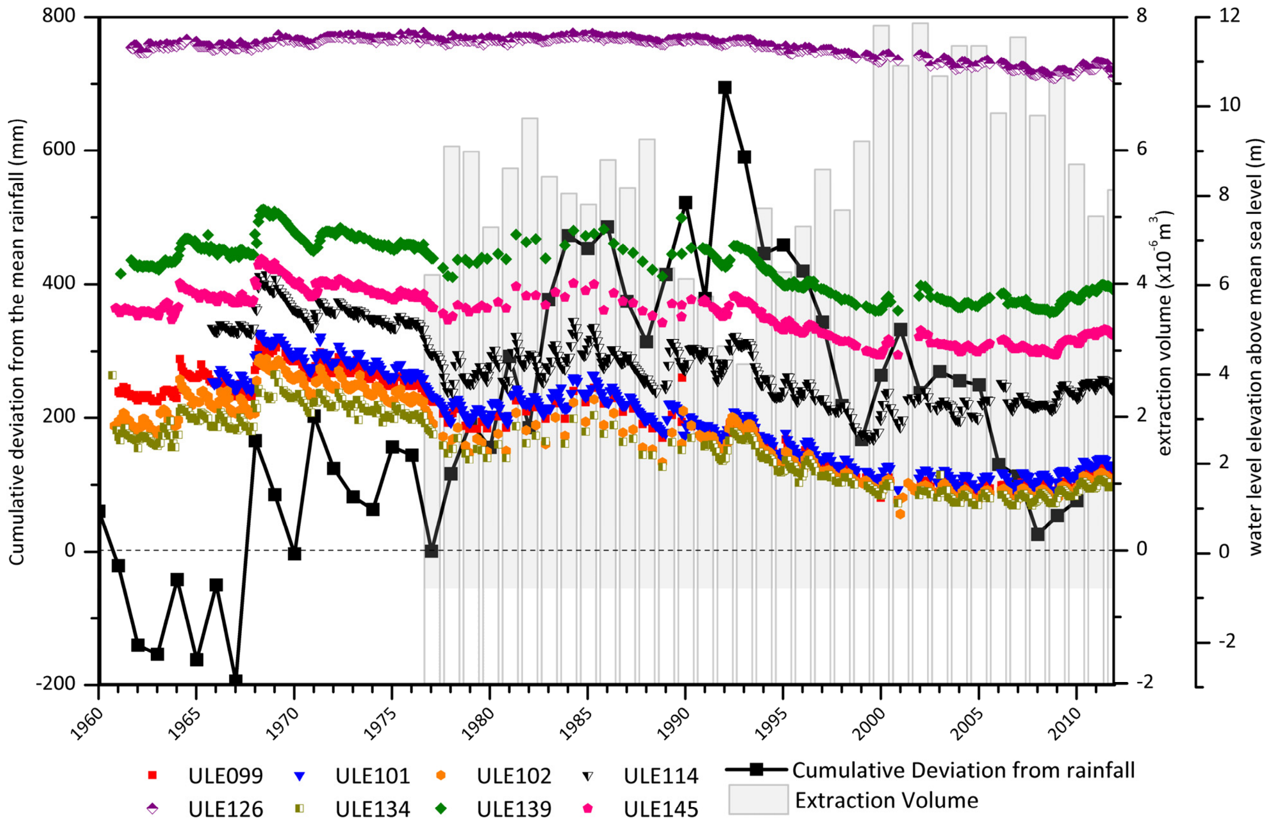


Figure 10. Water level trends in long-term monitoring wells, cumulative deviation from mean rainfall and groundwater extraction in Uley South basin.

4. Conclusions

Understanding recharge mechanisms and reliable recharge estimates is critical to evaluation and management of water resources. An accurate estimate of recharge to aquifers in arid and semi-arid areas still remains a challenge; especially where point recharge (recharge from discrete locations) dominate. The effectiveness of a groundwater basin management plan depends largely on the reliability of estimated recharge and the monitoring to assess the basin's status. Recognising all recharge estimation methods have some degree of uncertainty, a precautionary approach is recommended as one of the guiding principles in utilising groundwater resources. Groundwater allocation based on over-estimated recharge leads to depletion of the resource, damaging the aquifer and the environment that supports it [4]. Similarly management plans based on under estimated recharge result in economic and social costs to the community in the form of development of alternative resources or limitation on development [4].

Reliability of estimated recharge depends on applicability of the particular method employed, availability of reliable data and adequate spatial coverage of data for the basin [4]. This reliability can be compromised by overly simplifying the characteristics of the karst aquifers, recharge processes or the use of invalid methods for recharge estimation; thus contradicting the precautionary principle. The recharge estimation of karst aquifers demands a significant research effort. This could be achieved through prudent analyses and interpretation of data along with modification and development of new methods to capture the recharge processes. As Somaratne [1] suggests, one area of further development of karst aquifer recharge estimation is the incorporation of duality of recharge regimes into the CMB as featured in the generalized CMB method [3].

Acknowledgments

The helpful comments of two anonymous reviewers are gratefully acknowledged. Glyn Ashman is thanked for review of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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