Groundwater recharge to a sedimentary aquifer in the topographically closed Uley South Basin, South Australia

Carlos M. Ordens · Adrian D. Werner · Vincent E. A. Post · John L. Hutson · Craig T. Simmons · Benjamin M. Irvine

Abstract The chloride mass balance (CMB) and water-table fluctuation (WTF) analysis methods were used to estimate recharge rates in the Uley South Basin, South Australia. Groundwater hydrochemistry and isotope data were used to infer the nature of recharge pathways and evapotranspiration processes. These data indicate that some combination of two plausible processes is occurring: (1) complete evaporation of rainfall occurs, and the precipitated salts are washed down and redissolved when recharge occurs, and (2) transpiration dominates over evaporation. It is surmised that sinkholes predominantly serve to by-pass the shallow soil zone and redistribute infiltration into the deeper unsaturated zone, rather than transferring rainfall directly to the water table. Chlorofluorocarbon measurements were used in approximating recharge origins to account for coastal proximity effects in the CMB method and pumping seasonality was accounted for in the WTF-based recharge estimates. Best estimates of spatially and temporally averaged recharge rates for the basin are 52–63 and 47–129mm/year from the CMB and WTF analyses, respectively. Adaptations of both the CMB and WTF analyses to account for nuances of the system were necessary, demonstrating the need for careful application of these methods.

Keywords Groundwater recharge · Chloride mass balance · Water-table fluctuation · CFC · Australia

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Introduction

Reliable estimates of recharge are often a key prerequisite for the proper management of groundwater resources. The measurement of groundwater recharge and the interpretation of its processes are difficult due to a number of factors, including the complex and multifaceted nature of recharge processes, spatial and temporal variability in recharge rates, and both scarcity and uncertainty in measurements pertaining to recharge estimation. For these reasons, Scanlon et al. (2002) advocate the use and comparison of different methods for quantifying groundwater recharge. The application of multiple methods does not guarantee more reliable outcomes but will highlight errors in the form of inconsistent outcomes (Healy and Cook 2002). These errors may stem from the use of methods beyond their limits of validity or from invalid assumptions about the nature of the recharge processes. A sound conceptual model of the recharge mechanisms is vital to the successful application of recharge estimation techniques.

A wide variety of recharge quantification approaches is available. The accuracy of different methods is dependent on a multitude of factors, including the site conditions (e.g. geology, hydrogeology, climate, etc.) and data availability (Scanlon et al. 2002). Recharge estimates inferred from field measurements apply to various temporal and spatial scales. Point estimates of recharge may be obtained from soil testing (e.g. lysimeter measurements and soil chloride analyses), whereas groundwater-based methods such as the chloride mass balance (CMB) method, chlorofluorocarbon (CFC) dating and water-table fluctuation (WTF) analysis produce spatially averaged estimates (Allison and Hughes 1978; Kitching and Shearer 1982; Gee et al. 1992; Healy and Cook 2002; Scanlon et al. 2002). Lysimeters and the WTF approach offer insight into the temporal variability in recharge, whereas most other methods produce long-

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term averages. Based on a review of 172 recharge studies across Australia, Crosbie et al. (2010) found that WTF estimates were higher than those based on the CMB method. They attributed this to the difference in timeframe over which the methods operate (i.e. whereby CMB represents pre-development recharge) and to the potential contribution of transpiration from the saturated zone.

The focus of the current study is the characterisation of recharge in the Uley South Basin, Eyre Peninsula, South Australia. Abstraction of groundwater from the basin supplies around 70% of the water demand of the Eyre Peninsula's population of 33,500 (Werner et al. 2011), with the remainder being met by surface-water sources or by groundwater from other basins. Both recharge variability and long-term averages rates of recharge are of high importance for water-management decision-making, particularly given historical declines in groundwater levels within the basin (EPNRM 2006; Werner et al. 2011). The limestone terrain of the Uley South Basin forms a recharge environment that is especially challenging to characterise. Spatial variations in land cover, topography, water-table depth and soil type, and, it is hypothesised that, the presence of dissolution features all contribute to create a complicated pattern of recharge pathways. Diffuse recharge is expected to occur in areas with undisturbed calcrete and well-developed soils, whereas sinkholes may potentially act as point sources for recharge.

Previous work in other systems characterised by sinkholes has not resulted in a consistent picture of the contribution of sinkholes to recharge on a regional scale. Allison et al. (1985) determined recharge below undisturbed calcrete containing wide-diameter, old (> 40,000 years) sinkholes and small, young (<100 years) sinkholes based on vertical profiles of chloride (Cl) and isotopes in soil water. They found that the highest recharge rates were associated with the small-diameter sinkholes and that these accounted for most of the regional recharge based on an aerially-weighted average. Wood and Sanford (1995) investigated the recharge processes in a sedimentary aquifer capped by a calcrete layer with sinkholes (referred to as macropores), using Cl and isotopic data in groundwater. One interpretation of the solute and isotopic data indicated that significant sinkhole recharge (i.e. 10% of total aquifer recharge) could be occurring at the regional level. On the other hand, Herczeg et al. (1997) found that localised recharge to a limestone aquifer via sinkholes contributed less than 10% of the total regional recharge and was only important after sustained periods of rainfall. Globally, the role of sinkholes in generating recharge appears to be variable and a general understanding of the influence of sinkholes on recharge remains unresolved.

The primary aim of this study is to develop a conceptual understanding of the recharge mechanisms in Uley South Basin using hydrogeologic and water quality observations, leading to quantification of the basin's recharge using the CMB and WTF approaches. Previous studies have attempted to quantify Uley South recharge using various methods (e.g. WTF, CFC, CMB and water balance analysis), producing a wide range of basin-averaged and time-averaged estimates (i.e. 40–200 mm/year; Harrington et al. 2006; EPNRM 2009). There is a need to seek plausible explanations for the lack of agreement across previous recharge studies, and therefore the focus of this study is to explore recharge and hydrogeological processes and to critically examine CMB and WTF approaches as they apply to the Uley South Basin conditions. Adaptations of both methods are proposed to account for local factors that are deemed to be important.

Study area

The Uley South Basin is located in the southern part of Eyre Peninsula, South Australia (Fig. 1), and is a topographically closed surface drainage basin. The central part of the basin has a flat to undulating land surface at an

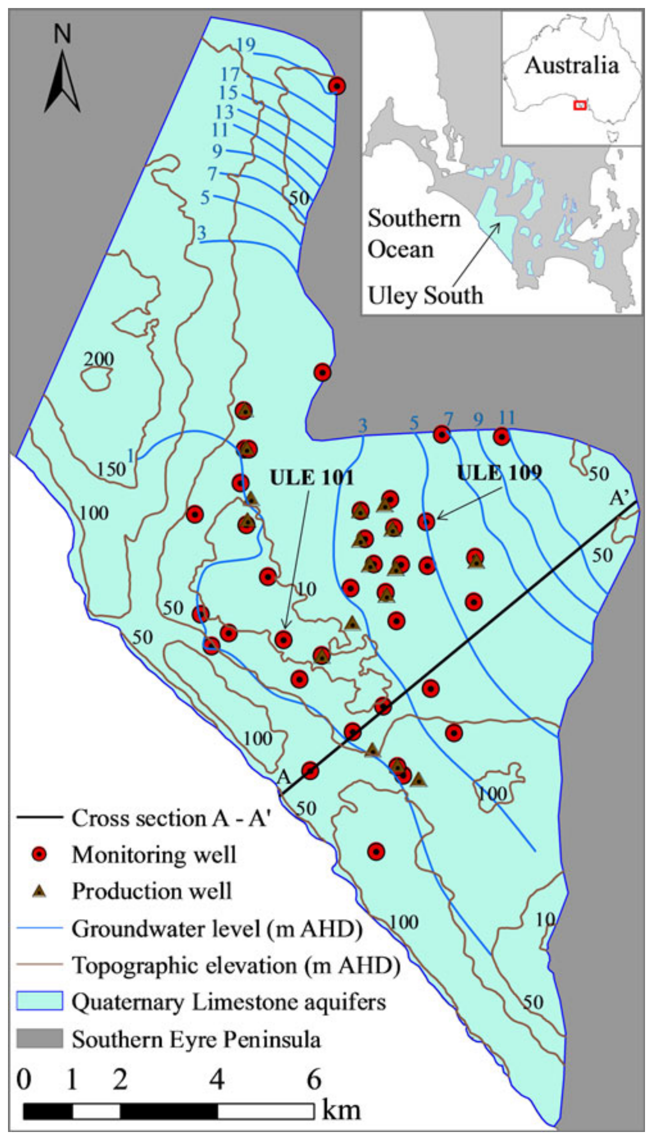

Fig. 1 Extent of the Uley South Basin, showing groundwater levels and surface elevations, and the location of monitoring wells (i.e. those used in recharge calculations) and production wells in the Quaternary Limestone aquifer

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elevation of less than 10 m AHD (Australian Height Datum, roughly equal to mean sea level). The basin is bounded to the northwest, northeast and southeast by topographic rises from 50 m AHD up to 170 m AHD, and to the southwest by coastal cliffs of up to 140 m AHD that border the Southern Ocean. The morphology of the basin is associated with ancient dune systems overlying basement ridges and troughs, with distinct dunal landforms and subtle undulations defining local surface drainage systems (Harrington et al. 2006). Surface-water systems are highly ephemeral, flowing only after moderate-to-heavy rainfall and persisting for tens to hundreds of metres before terminating abruptly at sinkholes within local surface depressions (Harrington et al. 2006). An important feature of the basin is that there are no surface-water outflows to the sea, and therefore at the basin scale, rainfall is partitioned into only evapotranspiration and groundwater recharge. No surface expressions of groundwater are evident in the basin.

The climate is semi-arid, characterised by wet winters and dry summers (Zulfic et al. 2007). Climate data for the study area were obtained from the Bureau of Meteorology (2010) for Big Swamp monitoring station (station no. 18017; located 18 km NE of Uley South Basin), where daily data are available dating back to 1889. The daily minimum temperatures range from 0 to 26°C, averaging 11°C, while the daily maximum temperatures range from 8 to 45°C, averaging 20°C (for the period 1889–2009; Bureau of Meteorology 2010). The average annual rainfall is 560 mm/year, the average pan evaporation is 1,547 mm/year, and the average FAO56 reference evapotranspiration is 1,084 mm/year (Bureau of Meteorology 2010).

Figure 2 shows the groundwater hydrograph from observation well ULE 101, together with monthly rainfall data at Big Swamp monitoring station. Groundwater levels are measured at approximately monthly intervals in some 42 wells across the basin. A clear seasonal fluctuation in groundwater level can be recognised, together with a steady decline in groundwater levels since the middle of the 1980s. This decline is attributed to the combined effects of pumping and below-average rainfall, and there are presently concerns about movements in the freshwater–seawater interface in the coastal aquifer (Werner et al. 2011).

Soils are typically lithosols (calcareous soils or shallow loamy soils), generally less than 3-cm thick or absent in areas of outcropping surface limestone (calcrete). Shallow depressions may contain up to 5 cm of loamy soils (Harrington et al. 2006). No soils have developed in the modern sand dune areas (designated "deep sand" in Fig. 3a). The lack or absence of soils across large areas of the basin causes rapid surface runoff, leading to almost instantaneous infiltration via a vast array of sinkholes, which vary in size from millimetres to several metres in diameter. Sinkholes are especially dense in the calcrete and lightly vegetated regions of Fig. 3a.

Dense stands of mallee vegetation (*Eucalyptus diversifolia* and *E. gracilis*) occur above 30 m AHD. Below this level, only isolated stands occur. Some areas are dominated by drooping she-oak (*Allocasuarina verticillata*) that were probably the predominant vegetation species prior to extensive modification most likely from pastoral activities (Harrington et al. 2006). There are large areas of open, sparse grassland, and some infestations of woody weeds (Way 2006). Remotely sensed multi-spectral images were used to identify the substrate cover (Fig. 3a) and vegetation types (Fig. 3b). Landsat Enhanced Thematic Mapper Plus (ETM+) remotely sensed scenes (multi-image datasets) were obtained from the United States Geological Survey (USGS 2009). Ground-truthing was conducted in February 2009 to link substrate and vegetation types to land cover clusters identified in the multi-spectral images. The substrate types were classified according to: calcrete, soil lightly vegetated, soil highly vegetated, and sand. Likewise, the vegetation types were classified according to: grass on calcrete, grass and shrubs, shrubs and trees, forest, and lightly vegetated/bare sand (in the sand dune area).

The stratigraphy of the Southern Eyre Peninsula comprises Tertiary and Quaternary sediments unconformably overlying an Achaean metamorphic basement composed of gneiss and quartzites (Harrington et al. 2006). A geological cross section is given in Fig. 4. The basement geometry shows troughs and ridges with a general NE–SW direction, and the geometry of the sedimentary units that constitute the aquifers reflect the infilling of the basement troughs by Tertiary and Quaternary sediments (Harrington et al. 2006). The Quaternary sediments extend

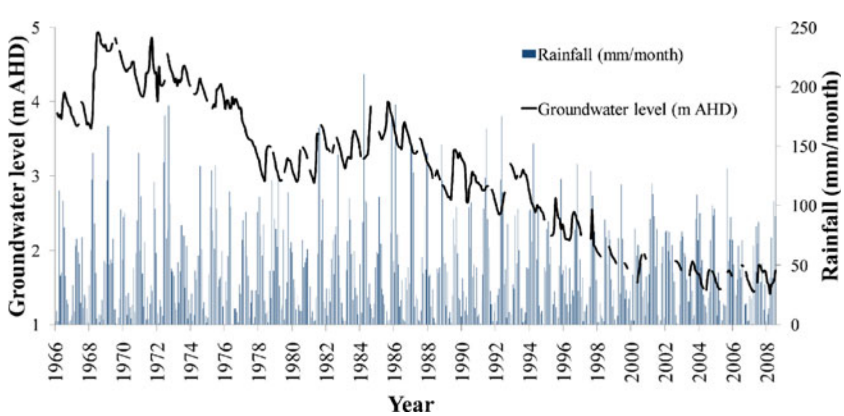

Fig. 2 Hydrograph of monitoring well ULE 101 (see Fig. 1 for its location), and monthly rainfall at Big Swamp monitoring station, modified from Werner et al. (2011)

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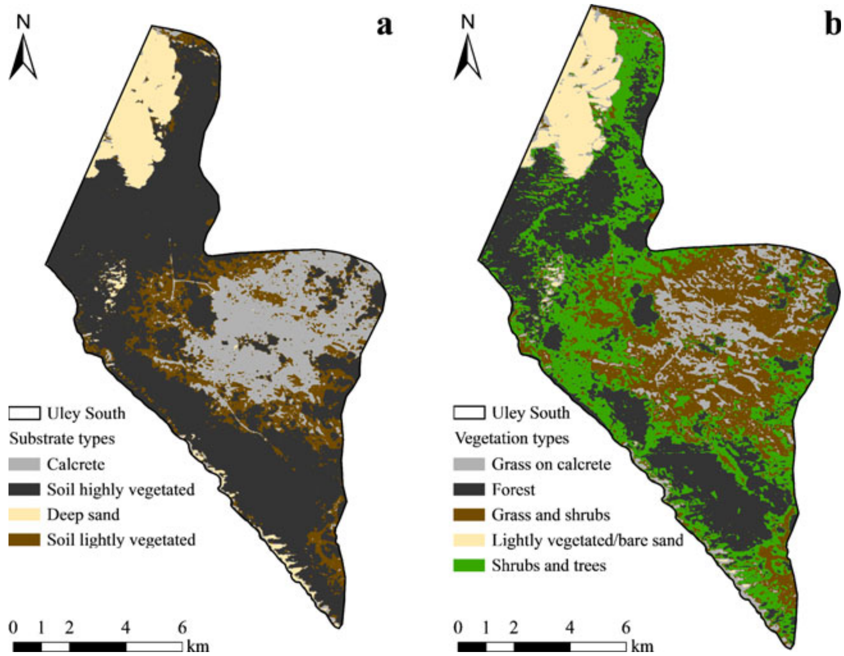

Fig. 3 **a** Substrate and **b** vegetation types of Uley South

from a thin layer covering the underlying units to extensive accumulations of over 130 m of aeolian fine sands and shell fragments (Evans 1997). The lower hydrostratigraphic unit (Tertiary Sand) is known as the Wanilla Formation, which consists of fluvial sands, clays and grits with some lignite lenses in the base. The Tertiary Sand aquifer is referred by Harrington et al. (2006) as confined to unconfined, depending on the presence of a clay layer. This formation has a maximum thickness of 60 m and can be locally absent (Harrington et al. 2006). A lateritic clay sequence (Tertiary Clay) of up to 25 m thick, known as the Uley Formation, is found in the upper Tertiary sediments across much of the basin, although this palaeosol horizon is discontinuous in places (Harrington et al. 2006). Tertiary sediments are overlain by the Quaternary Limestone, also known as the Bridgewater Formation, corresponding to the unconfined Quaternary Limestone aquifer, which is composed of a combination of unconsolidated Aeolian sediments and limestone of varying hardness and porosity, presenting karst features in places (Harrington et al. 2006). The thickness of the Quaternary Limestone sequence is over 130 m in areas of high topographic relief such as the coastal limestone cliffs, and the base of the Quaternary aquifer occurs to elevations of −60 to 50 m AHD (Zulfic et al. 2007; Fitzpatrick et al. 2009). A surface or near-surface calcrete horizon is extensive across the basin, along with secondary porosity in the form of dissolution features (sinkholes; Twidale and Bourne 2000).

Groundwater abstraction from Uley South is undertaken solely by the water utility organisation SA Water Corporation, who extracts roughly 7×10^6 m^3/year of high-quality groundwater from the Quaternary sediments (Werner et al. 2011). The hydraulic conductivity of the Quaternary sequence reaches up to 2,000 m/day locally, reflecting karst aquifer characteristics (Sibenaler 1976). The high permeability of the aquifer produces relatively flat water tables, which fluctuate in response to the annual cycle of wet–dry seasons. Water-table responses to individual rainfall events are of small magnitude (i.e. in the order of a few millimetres), likely due to the coastal proximity and hydraulic connection to the sea, i.e. the coastal head boundary tends to control water levels and high hydraulic conductivities extend this water-level control significant distances inland.

Based on all the available physiographic data, a generalised conceptual model of the recharge processes in the basin was developed. Sinkholes are believed to be

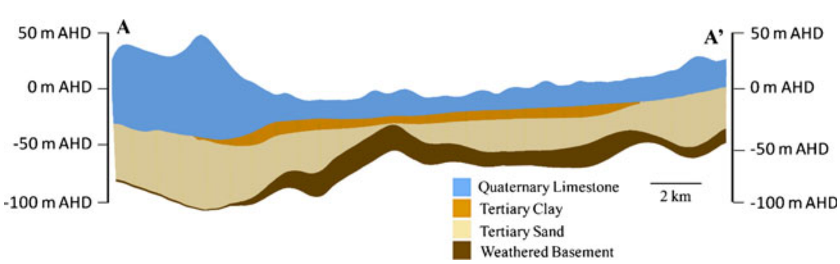

Fig. 4 Cross section stratigraphy through A–A' showing the main geologic strata of the Uley South Basin (modified from Werner et al. 2011). The cross-section alignment is shown in Fig. 1, with a general direction SW–NE

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important infiltration pathways at the land surface, but the contribution of sinkhole infiltration to the basin's total recharge, however, is yet to be understood. Their depths are presently unknown, and so it is not certain whether sinkholes directly recharge the water table or simply conduct water deeper into the unsaturated zone. As such, the influence of evapotranspiration on sinkhole recharge is also unknown. Moreover, the degree to which vegetation assemblages draw from the unsaturated and saturated zones is unclear.

Methodology

Water-table fluctuation analysis

The WTF method uses rainfall-induced water-table rise and the aquifer's specific yield to estimate recharge q_R [LT^{-1}], calculated as (Healy and Cook 2002):

$$q_R = S_y \frac{\Delta h}{\Delta t} \qquad (1)$$

where S_y [−] is the specific yield, h [L] is the water-table height and t is time [T]. Water-table rise (Δh) is taken from the extended hydrograph recession to the water-level peak of the recharge event (Healy and Cook 2002). The WTF method has the advantage over some other methods in that it provides insight into transient recharge trends. The existence of preferential flow paths is not a restriction in its application, although the WTF method is limited by difficulties in accurately determining S_y, and additionally, such factors as the presence of entrapped air, changes in barometric pressure and evapotranspiration can influence water-table fluctuations (Healy and Cook 2002).

The WTF method was applied using monthly groundwater levels of fifteen observation wells with records of varying continuity, spanning the period 1961 to 2007 (DWLBC 2010). Recharge was estimated for discrete water-table rise-and-decline events (typically spanning several months) from time series data, and these were then summed to produce annual recharge estimates. Values of S_y for the Quaternary Limestone aquifer are reported by Sibenaler (1976), Zulfic et al. (2007) and in Werner et al. (2011). Sibenaler (1976) estimated S_y from eight pumping tests, obtaining an average of 0.13 (with values ranging from 0.03 to 0.35). Zulfic et al. (2007) used a range of 0.10–0.30 as possible input S_y values in a groundwater model of Uley South's Quaternary Limestone aquifer, and through calibration of the model they established S_y zones of 0.20 and 0.30, giving a basin average of about 0.25. Recently, Werner et al. (2011) calibrated a lumped water balance model of Uley South and arrived at S_y values ranging from 0.14 to 0.20. A plausible S_y range for the purposes of this study was taken as 0.12–0.25.

The WTF method relies on water–table fluctuations, which can reflect phenomena other than groundwater recharge, for example pumping (e.g. Healy and Cook 2002). As such, time variant pumping rates can impact the application of the WTF approach to estimate recharge (Cuthbert 2010). For example, water–table rise is expected during periods of decreased pumping, leading to a potential overestimation of recharge (Cuthbert 2010). Further, accuracy of the method depends on the diffusivity of the aquifer, the location of the borehole in question, and the distribution in time and space of the abstraction wells. The Uley South Basin has been subject to considerable groundwater abstraction since November 1976, and Werner et al. (2011) estimated that pumping was a significant component (26%) of the cumulative outflow from the Quaternary Limestone aquifer during the period of 1967–2007. Modifications of the WTF method to account for specific site characteristics or to meet particular objectives have been proposed before (e.g. Crosbie et al. 2005; Moon et al. 2004; Cuthbert 2010). Here, a modification of the WTF approach to account for the effect of pumping seasonality on WTF recharge estimations is proposed, where the objective is to evaluate the potential overestimation of recharge arising from neglecting the effect of pumping in Uley South.

The abstraction of groundwater is well monitored (Werner et al. 2011) and there is a general inverse relationship between pumping and rainfall, whereby pumping decreases during periods of sustained rainfall (and recharge). An overestimation of recharge is expected if Eq. 1 is applied without accounting for the influence of pumping. A modified version of the WTF method was subsequently adopted in which a correction to account for pumping-induced water-table rise, q_{R*} [LT^{-1}], is calculated as:

$$q_{R*} = \frac{Q_{PRP} - Q_{DPR}}{ASy} \qquad (2)$$

where Q_{PRP} [L^3T^{-1}] is the average pumping rate during successive months of no recharge (i.e. when groundwater levels are falling), Q_{DRP} [L^3T^{-1}] is the average pumping rate during successive months of recharge (i.e. when groundwater levels are rising) and A [L^2] is the planar area of the basin. The corrected recharge is then given as $q_R - q_{R*}$, if q_R is obtained using Eq. 1.

Chloride mass balance approach

The CMB method has been widely used to estimate groundwater recharge in semi-arid regions (e.g. Wood and Sanford 1995; Scanlon et al. 2006), i.e. of similar climate to Uley South. The method exploits the fact that Cl in precipitation becomes concentrated by evapotranspiration, such that the increase of the Cl concentration in groundwater relative to rainwater is then a measure of the proportion of rainfall that has evaporated. This assumes that: (1) the only source of groundwater Cl is atmospheric deposition (i.e. dry deposition and rainfall Cl combined), (2) there is no surface runoff from the recharge area, and (3) the atmospheric Cl deposition is in steady

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state. The mean annual recharge flux, q_R [LT^{-1}], is calculated by (e.g. Wood and Sanford 1995):

$$q_R = \frac{PC_{P+D}}{C_{GW}} \tag{3}$$

where P [LT^{-1}] is the long-term average rainfall, C_{P+D} [ML^{-3}] is the representative mean Cl concentration in rainwater including contributions from dry deposition, and C_{GW} [ML^{-3}] is the Cl concentration of groundwater in the recharge area. The assumptions required in the application of the CMB method are considered to be satisfied in the Uley South Basin. That is, it is assumed that there are no sinks or sources of Cl in the rock matrix, the atmospheric deposition is the only source of Cl to the system, and rainfall is partitioned into only infiltration and evapotranspiration at the basin scale.

As Uley South is bordered by the ocean, a strong dependency of C_{P+D} on the distance from the coast is expected. To take this dependency into account, the empirical formula developed by Hutton (1976) was used:

$$C_{P+D} = 35.45\left(\frac{0.99}{d^{0.25}} - 0.23\right) \tag{4}$$

where d [L] is the distance from the coastline in km. This relationship was obtained for an area in Southeast Australia with an average annual precipitation of >500 mm/year, and where the distance from the coast was between 0.5 and 300 km (Hutton 1976). Cl concentrations calculated using Eq. 4 differed by no more than 5% from measured values in rainfall samples near ULE 109 (d=6.1 km, Fig. 1), obtained during July 1988 to March 1992 (Evans 1997) and rainfall samples next to ULE 101 (d=2.3 km, Fig. 1), obtained during May 2008 to March 2009.

The CMB method can be applied using values for C_{GW} that represent either: (1) averaged Cl concentrations over a number of samples in an aquifer (Wood and Sanford 1995), or (2) Cl concentrations from individual wells (Sibanda et al. 2009). The first approach yields a basin-wide average but it cannot be readily applied to Uley South as the Cl deposition rate varies spatially due to the vicinity of the sea. Therefore, the second approach was adopted. The difficulty with this method is that the calculated recharge value applies to an area located somewhere up-gradient of the observation well, i.e. the sampled groundwater has travelled a certain distance through the aquifer since it was recharged. In an attempt to correct for this effect, the following steps were taken to estimate the position of the recharge area corresponding to an observation well. First, the age of the groundwater sample was determined based on its CFC concentration (see the following). Then, using typical values of the hydraulic conductivity (100–500 m/day) and porosity (0.15–0.3) of the aquifer, and the local hydraulic head gradient, the groundwater flow velocity was estimated based on Darcy's law. The length of the flow path up-gradient of the observation well was found by multiplying the flow velocity by the CFC-derived groundwater age. Finally the up-gradient direction from the sampled well to the recharge area was determined by using groundwater pathways derived from hydraulic head contours. Values of C_{GW} were taken from Evans (1997) (sampled in 1993 and 1994), and from DWLBC (2010) (sampled from 1961 to 2004).

Groundwater dating using CFCs

Groundwater CFC concentrations can be used to calculate the time that has elapsed since a water parcel crossed the water table and thus became isolated from the atmosphere (Plummer and Busenberg 2000). Atmospheric concentrations of CFC-11, CFC-12 and CFC-113 increased continuously between 1945 and 1990 (Plummer and Busenberg 2006), so that the moment of recharge can be determined by matching the equilibrium partial pressure of a particular CFC in a groundwater sample with its historical concentration in the atmosphere. The basic assumptions underlying this method are that the historical CFC composition of air in the recharge area is known and that the composition of unsaturated zone air resembles that of the atmosphere. Details of the method are given in Plummer et al. (2006).

The application of CFCs to date groundwater was based on data collected by Evans (1997), who sampled seven wells for CFC-11 and CFC-12 in 1995. The CFC's Southern Hemisphere historical air concentration curve (USGS 2010) was used in the groundwater dating calculations. Preliminary results showed that groundwater ages obtained using CFC-11 are older relative to groundwater ages dated with CFC-12, which indicates that CFC-11 has been subject to degradation (Cook et al. 1995; Plummer and Busenberg 2000). For this reason only the apparent ages calculated from CFC-12 were used.

Under idealised conditions, such as a constant thickness aquifer receiving uniform recharge and with homogeneous hydraulic properties, an exponential increase in the groundwater age would, theoretically, be observed with depth below the water table, and the groundwater age can be used to infer the recharge rate (Solomon et al. 2006). Such conditions are thought not to apply in Uley South, and rather there is little evidence of vertical stratification in water-quality parameters. This is likely due to various factors, including the highly heterogeneous nature of the aquifer, and the variability in recharge. The long screen lengths of the majority of monitoring wells would further mask any vertical stratification, if present. The calculated ages were used in approximating groundwater flow lengths and expected locations of upstream recharge areas attributable to the groundwater obtained from wells used in applying the CMB method. That is, simple Darcy's law calculations were undertaken to approximate the groundwater travel distance using estimates of hydraulic conductivity, hydraulic gradient, porosity and the groundwater age.

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^{18}O, Cl and Br data analysis

The Cl and ^{18}O data were used in this study to infer the evapotranspiration processes, and in which way they impact the groundwater recharge. The Cl/Br ratios were used to confirm the origin of the recharging water, and to underpin the use of the CMB method.

The Cl and Br concentrations and $\delta^{18}O$ values were adopted from Evans (1997) (25 groundwater samples collected in 1993 and 1994). Evans (1997) collected five samples of rainwater for determination of $\delta^{18}O$. These were compared with the rainfall isotopic data provided for Adelaide by the International Atomic Energy Agency (IAEA) Global Network of Isotopes in Precipitation (GNIP) service (IAEA and WMO 2005); only complete annual data sets from the GNIP database were used.

Results and discussion

Conceptual model of groundwater recharge mechanisms

The available chemical and isotope data provide important insights into the processes that contribute to groundwater recharge. The Cl concentrations in groundwater samples from the Quaternary Limestone aquifer range from 100 to 220 mg/L. No spatial trends in Cl concentrations are apparent, and despite the Cl concentrations in the underlying Tertiary Sand aquifer being generally higher (ranging from 137 to 524 mg/L; data from Evans 1997), no increase of Cl concentrations with depth within the Quaternary aquifer is observed. It is therefore assumed that any mixing of waters from these two aquifers is insufficient to preclude application of the CMB method to estimate recharge.

Figure 5 shows the $\delta^{18}O$ values versus Cl concentrations in groundwater. This plot shows that: (1) there appears to be a minute increase of $\delta^{18}O$ over the observed range of Cl concentrations, and (2) no groundwater samples exhibit Cl concentrations below 100 mg/L. Ranges in $\delta^{18}O$ values (IAEA and WMO 2005) and Cl concentrations for precipitation are also indicated in Fig. 5. The averages of bulk rainfall $\delta^{18}O$ from IAEA and WMO (2005) and from Evans (1997) compare well, being −4.3‰ and −4.2‰ respectively.

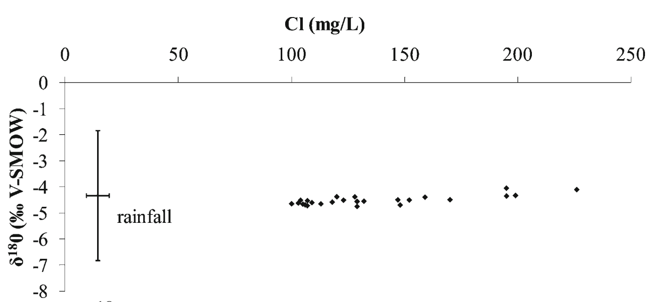

Fig. 5 $\delta^{18}O$ (‰ V-SMOW; Vienna-Standard Mean Ocean Water) values versus Cl concentrations of groundwater samples (data from Evans 1997). Ranges from bulk rainfall samples have also been indicated. *Error bars* indicate the standard deviation, crossing at the mean values

Cl/Br ratios in both the rainfall and the groundwater samples are all very close to the Cl/Br ratio of seawater of 288 (using concentrations expressed in mg/L), indicating that dissolved salts in rainwater and groundwater are marine derived. This observation is consistent with the vicinity of the ocean, the land use (no application of fertilizers and pesticides) and the lithology of the basin (i.e. absence of Cl-bearing rocks). It rules out the contribution of Cl from sources other than both rainfall and dry deposition of marine aerosols, thereby fulfilling one of the key assumptions for the application of the CMB method.

It should be noted that the Cl concentrations of bulk rainfall integrate both wet and dry deposition, so that the observed Cl concentration gap between groundwater samples and rainwater (Fig. 5) cannot be attributed to the dry deposition and subsequent dissolution of Cl-bearing particles from the atmosphere. This, and the absence of other sources of dissolved Cl as inferred from the Cl/Br ratio, implies that the increases in groundwater Cl relative to bulk rainfall are due to evapotranspiration. Moreover, the observed lack of significant enrichment of ^{18}O as Cl increases (Fig. 5), is interpreted to reflect one or a combination of two processes, namely: (1) transpiration dominates over evaporation (plant root water uptake is not accompanied by isotopic fractionation; e.g. Wood and Sanford 1995; Ingraham et al. 1998; Geyh 2001), and (2) at times, complete evaporation of rainfall occurs and the precipitated salts are washed down and redissolved during wet phases when recharge occurs. The latter process may occur at the land surface during overland flow of rainfall or within the sinkholes themselves after infiltration. What remains unclear is whether the vegetation, the mallee trees in particular, draw their water from the unsaturated zone or whether their roots have access to groundwater. No information exists on rooting depths of these trees in Uley South.

The absence of intermediate data points between the rainfall and groundwater data points in Fig. 5 is interpreted to reflect the fact that any rainfall that results in recharge first undergoes either or both of these processes (complete evaporation and transpiration) before reaching the water table (or the screens of the monitoring wells). Most recharge occurs in winter, as can be inferred from the water-level observations (Fig. 2). The observed gap between Cl concentration of rainfall and groundwater should be taken as an indication that the contribution of sinkhole-channelled rainfall that escapes evapotranspiration contributes only little to the total recharge amount, as otherwise more intermediate data points would be observed in Fig. 5. This does not preclude that recharge rates below individual sinkholes are higher than below the undisturbed calcrete, as suggested by Allison et al. (1985) for the Murray Group marine limestone aquifer (Murray River Basin, South Australia), or that there are some localised occurrences of sinkhole recharge directly to the water table.

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Recharge estimates based on the WTF and CMB methods

The mean annual recharge obtained by averaging the results of the WTF analysis of the 15 wells varies between: (1) 66 and 138 mm/year if the pumping correction is not applied, and (2) 47 and 129 mm/year if the pumping correction is applied. Recharge ranges reflect the adopted range in S_y, which imparts a significant uncertainty on WTF-estimated recharge. A further source of uncertainty stems from the potential effects of other components of the basin water balance, including groundwater outflow to the sea and any inflows through the basin boundaries. Although these are in principle considered in the WTF method by extrapolating the hydrograph recession to the groundwater level peak of the recharge event (and using that water level as the minimum in the calculation of Δh; as per Healy and Cook 2002), this is a rather crude approach that may not accurately take into account the response of the groundwater system to other stresses. While some attempt has been made to modify the WTF approach to account for pumping seasonality, only a rough approximation of the correction is obtained from the simple representation of the pumping effects. Nonetheless, it is clear that the pumping impact is significant and cannot be ignored in the WTF methodology.

Figures 6 and 7 show the relationship between annual rainfall and annual recharge calculated using the WTF method. Negative recharge values are due to the pumping correction factor applied to the lower S_y case, which for some periods is higher than recharge; this occurred in the years of 1991, 2005 and 2007. Despite there being significant scatter in the data points, correlations are apparent, as expected. Figure 6 shows that recharge and rainfall correlate well in some years (e.g. 1964, 1968, 1971, 1977, 1978, 1992), while poor correlation occurs in other years (e.g. 1966, 1972 to 1976, 1983, 1984, 1988, 1995, 1996). Figure 7 demonstrates that the same annual rainfall total can produce very different recharge rates (e.g. a rainfall rate of ~650 mm/year is associated with recharge rates of 40–112 mm/year, using S_y=0.12) or that the same recharge rate can be produced by different rainfall rates (e.g. a recharge rate of ~40 mm/year can be produced by rainfall rates of 420–50 mm/year). This indicates that the annual rainfall total is not the only factor controlling recharge. Other factors expected to play an important role in the temporal recharge trends include temporal and spatial variability in evapotranspiration, soil-water content, and rainfall pattern (i.e. rainfall intensity, duration and location). This is commensurate with the indication from chemical and isotope data that either low-intensity, short-lived rainfall events do not generate recharge due to complete evaporation and/or that the vegetation consumes a significant proportion of the infiltrated rainwater.

The spatial variations in time-averaged recharge values from the CMB approach (modified to account for the location of recharge and the distribution of atmospheric Cl deposition) are given in Fig. 8. There is a general tendency of higher recharge inferred from wells in the central and southern part of the basin. This general tendency is also observed in the recharge results from the WTF method, although it should be kept in mind that these results rely on the assumption of a spatially constant value of S_y. Regions of calcrete and limited vegetation (see Fig. 3) are by-and-large situated north-east of wells showing higher recharge rates.

Uncertainties in CMB recharge estimates are linearly dependent on Cl deposition (Scanlon et al. 2006). To account for this uncertainty, a range of possible chloride deposition values was tested in the CMB calculations. CFC-based groundwater ages from seven bores averaged 11–14 years, ranging from 9 to 17 years (depending on recharge temperature), equating to infiltrating dates ranging from 1978 to 1986 considering that CFC measurements were taken in 1995 (Evans 1997). This translates to minimum and maximum distance offsets between wells and recharge areas equal to 0.9–17.3 km, averaging 1.1–13.9 km (depending on the groundwater ages and hydraulic properties adopted in the calculations). The CMB method was applied to these seven wells using Cl atmospheric deposition rates: (1) at each well location, (2)

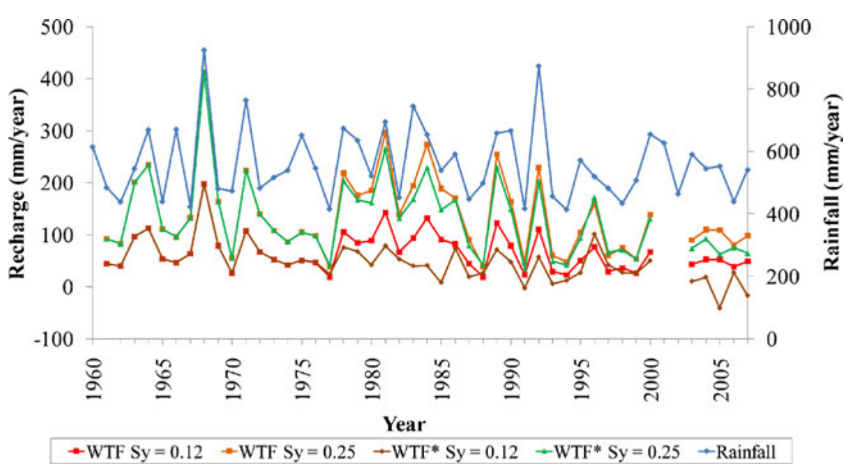

Fig. 6 Temporal variability of rainfall and recharge using the standard WTF approach and the approach taking into account the pumping effect in the *WTF* analysis, symbolised by *WTF**. Insufficient data are available for 2001 and 2002

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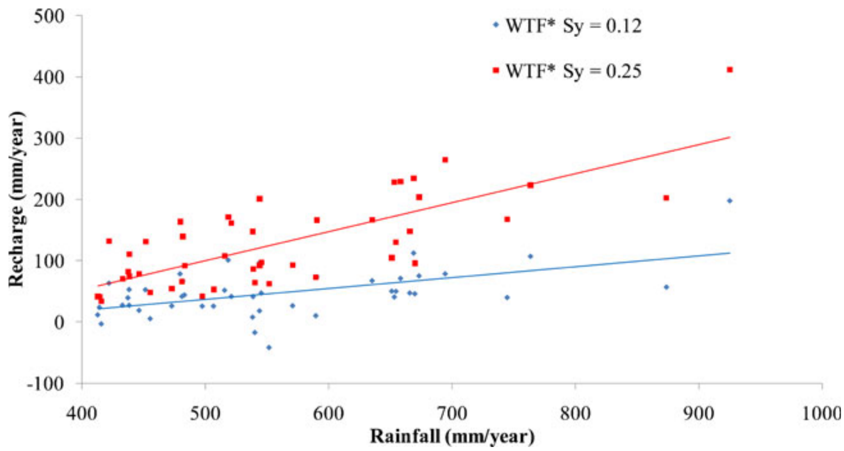

Fig. 7 Relationship between annual recharge using the modified *WTF* approach (*WTF**), and rainfall in Uley South

at the minimum offset distance upstream of each well, and (3) at the upstream aquifer boundary (i.e. the maximum offset distances cross the upstream aquifer boundary). The basin-averaged CMB recharge estimates taking atmospheric Cl deposition at the well location is 68 mm/year. If consideration is given to the upstream distance-offset in Cl deposition, CMB recharge estimates reduce by 9–32% (accounting for spatial variabilities in parameters and associated uncertainties). These percentages were then applied to all the wells (including those with no CFC data), allowing for testing of the influence of spatial Cl distribution in the CMB recharge estimates across the basin. This produced best-estimate values of basin-averaged recharge of 52–63 mm/year, which falls towards the lower end of the pumping-corrected WTF range of 47–129 mm/year. Figure 8 illustrates distributions of CMB recharge estimates for the lower (52 mm/year) and upper (63 mm/year) bounds.

Contrary to the findings of Crosbie et al. (2010), for some 172 recharge studies across Australia, that estimates based on the WTF method were in general much greater than those based on the CMB method, in this particular case it was found that both approaches produce overlapping recharge estimates. Crosbie et al. (2010) justify the WTF-CMB discrepancy to timeframe differences and to the potential contribution of transpiration from the saturated zone (accounted for in the CMB method, but not in the WTF approach). In this study, both methods were applied in a consistent timeframe (i.e. groundwater in Uley South is young (11–14 years old) and both Cl concentrations and groundwater fluctuations were analysed for the period 1960s to 2000s). Furthermore, Uley South is influenced by factors which modify the water-table behaviour (and therefore WTF estimates of recharge) such as pumping and groundwater discharge to the sea, and these may impose stronger controls than transpiration

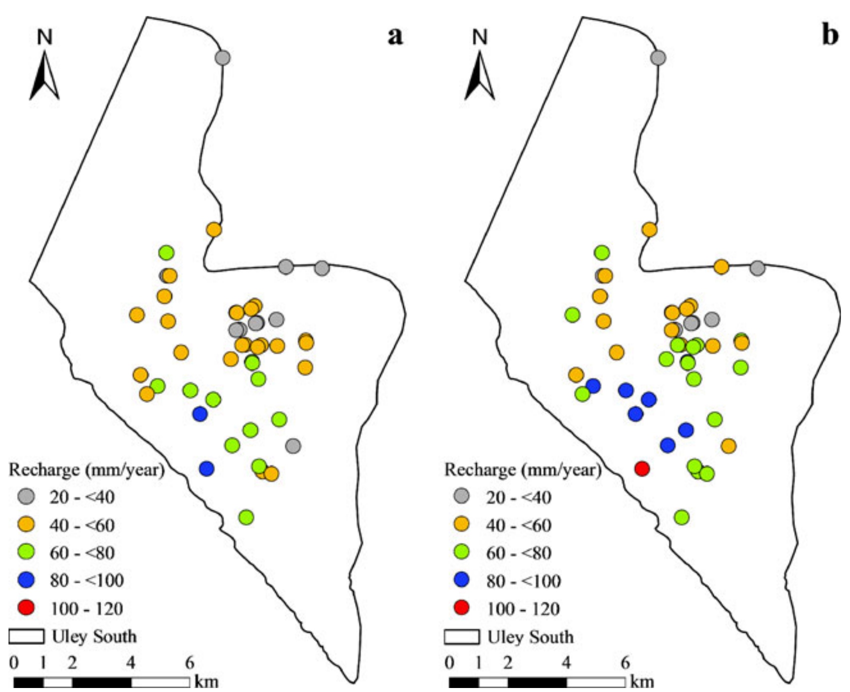

Fig. 8 Spatial distribution of CMB recharge averaging **a** 52 mm/year (lower bound estimate) and **b** 63 mm/year (upper bound estimate)

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effects, given the Uley South specific conditions. Also, the uncertainty in S_y is clearly a major factor in applying the WTF method that potentially masks some of these other uncertain impacts.

There are several additional sources of uncertainty that may bias the CMB method as applied to the Uley South Basin. For example, Cl deposition rates (the term PC_{P+D} in Eq. 3) based on Cl concentrations measured in bulk precipitation from open (un-vegetated) sites are known to underestimate Cl deposition rates under vegetated sites (Beier and Gundersen 1989; Moreno et al. 2001; Neary and Gizyn 1994; Knulst 2004), thereby underestimating CMB recharge. The magnitude of this effect is dependent on the climate, vegetation type, the extent of the vegetated area, and distance to the coast. For example, in coastal dunes in Holland covered by shrubs, the effect was found to be only 10% (Stuyfzand 1993). Casartelli et al. (2008) found that the increase in Cl deposition in subtropical forested areas with *Eucalyptus spp*. was 50% in a site away from the coast and over 100% in a site close to the coast. On the other hand, vegetation will reduce the rate of rainfall reaching the land surface through canopy interception and enhanced transpiration is expected in vegetated areas, and these both serve to decrease the CMB recharge estimates (e.g. by reducing P in Eq. 3). The majority of the wells and/or respective recharge areas are located in lightly or un-vegetated sites (i.e. the distribution of monitoring does not reflect the basin's distribution in soil-vegetation), thereby not being influenced by the vegetation effect in Cl atmospheric deposition. Further research is warranted to assess the extent to which vegetation causes CMB-estimates of recharge to be biased. Hypothetically, if a 50% influence of vegetation in C_{P+D} occurs over 57% of the basin (i.e. under highly vegetated areas; see Fig. 3b), this would result in CMB estimates being higher by 28%.

The seasonality in the groundwater salinity of production bores was also considered as a potential source of error in applying the CMB approach—the salinity of abstracted groundwater is between 8 and 15% higher on average in summer than in winter. That is, recharge estimates based on Cl concentrations of groundwater samples taking during the summer may be lower than those taken during winter months, given C_{GW} variations between the seasons. Also, C_{GW} in Eq. 3 strictly represents the Cl concentration at the water table. The temporal and spatial variability in recharge and Cl deposition rate is expected to create some amount of vertical stratification in groundwater Cl concentrations, albeit vertical variations in groundwater salinity within the Quaternary Limestone were not apparent in the available water chemistry data. To test the likely scale of temporal groundwater salinity effects, the CMB method was applied by separately considering samples collected at different depths below the water table (i.e. <3 m, <10 m, and all the samples). The effect of the sampling depth appears to be negligible (<3%) in the recharge estimates using the CMB method.

Conclusions

In this study, a conceptual model of groundwater recharge to a heterogeneous coastal aquifer subject to pumping, seasonal rainfall and evaporation stresses was developed. A plausible description of recharge processes arising from the available data is given as: (1) Cl in the system is essentially from atmospheric origins and influenced by proximity to the ocean; (2) a substantial proportion of rainfall occurring in dryer months is probably subjected to complete evaporation, with precipitated salts carried into the aquifer during wetter months; (3) the primary function of sinkholes at the basin scale is to redistribute water into the unsaturated zone rather than cause direct recharge to the aquifer; (4) soil water originating from (3) is subject to transpiration more so than evaporation.

The WTF and CMB methods applied in this paper are modified forms of previous applications. Modification to the WTF method involved a simple correction for water-table rise caused by pumping reductions, producing a basin-averaged and time-averaged (1967–2007) WTF recharge estimate that was lower by up to 30% than the "traditional" WTF method. The CMB approach was adapted to consider the location of the recharge relative to the position of the well, based on CFC ages and groundwater flow distances and directions, resulting in a basin-averaged recharge 9 to 32% lower than if the Cl deposition was considered at the well location. Although the accuracy of the alternative recharge estimations cannot be validated, it was demonstrated the importance of considering local site conditions in applying these common approaches to recharge estimation. The results indicate that, potentially for this basin, an overestimate in WTF-based recharge may arise from neglecting pumping effects, and over- or underestimates in CMB-based recharge may occur if Cl deposition factors are ignored.

Estimates of the long-term and spatially averaged recharge to the Uley South Quaternary Limestone were: (1) 52–63 mm/year from the CMB approach, and (2) 47–129 mm/year from the WTF approach. Ranges reflect uncertainty in input parameters, although the assumptions regarding vegetation effects and salinity seasonality were not considered as they were not able to be quantified. The observed decrease in the water levels, especially in areas of shallow water tables, may have altered the groundwater recharge pattern due to associated changes in evapotranspiration. This effect requires additional investigation. The range in possible WTF recharge values is a function of the uncertainty in S_y. Although this method provides a large range of possible recharge values (i.e. larger than the CMB method), it has the advantage of providing information about the time variability of recharge, which cannot be obtained with the CMB method. The range of recharge results presented here is smaller than previous recharge estimations for the basin (i.e. 40–200 mm/year), which is indicative of the contribution from extending the recharge conceptual model beyond pre-existing versions. Furthermore, the current recharge value of 140 mm/year adopted in setting groundwater management policies for

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the basin is likely an overestimate of recharge. The uncertainty in recharge estimates could be reduced through further work, aimed at providing a better understanding of the influence of vegetation on atmospheric Cl deposition, a better characterisation of Cl concentration in groundwater across the basin and an improved characterisation of specific yield, which would collectively provide more accurate and reliable data for the application of the CMB and WTF approaches. Likewise, a more detailed characterisation of spatial and temporal variations of hydrochemistry and hydraulic parameters, both in saturated and in unsaturated zones, would enhance the understanding of the processes affecting recharge in Uley South.

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References

Allison GB, Hughes MW (1978) The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Aust J Soil Res 16:181–195

Allison GB, Stone WJ, Hughes MW (1985) Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride. J Hydrol 76:1–25

Beier C, Gundersen P (1989) Atmospheric Deposition to the edge of a Spruce Forest in Denmark. Environ Pollut 60:257–271

Bureau of Meteorology (2010) SILO database. http://www.bom.gov.au/silo/. Cited 1 February 2010

Casartelli MR, Mirlean N, Peralba MC, Barrionuevo S, Gómez-Rey MX, Madeira M (2008) An assessment of the chemical composition of precipitation and throughfall in rural-industrial gradient in wet subtropics (southern Brazil). Environ Monit Assess 144:105–116

Cook PG, Solomon DK, Plummer LN (1995) Chlorofluorocarbons as tracers of groundwater transport process in a shallow, silty sand aquifer. Water Resour Res 31:425–434

Crosbie RS, Binning P, Kalma JD (2005) A time series approach to inferring groundwater recharge using the water table fluctuation method. Water Resour Res 41:W01008

Crosbie RS, Jolly ID, Leaney FD, Petheram C (2010) Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? Hydrol Earth Syst Sci 14:2023–2038

Cuthbert MO (2010) An improved time series approach for estimating groundwater recharge from groundwater level fluctuations. Water Resour Res 46:W09515. doi:10.1029/2009WR008572

DWLBC (2010) Online groundwater data from the Department for Water. https://obswell.pir.sa.gov.au/new/obsWell/MainMenu/menu. Cited 20 May 2010

Evans SL (1997) Estimating long term recharge to thin, unconfined carbonate aquifers using conventional and environmental isotope techniques: Eyre Peninsula, South Australia, Incomplete MSc Thesis, Flinders University, Adelaide, Australia, 176 pp

Eyre Peninsula Natural Resources Management Board (EPNRM) (2006) Eyre Peninsula Water Allocation Plans. http://epnrm.sa.gov.au/. Cited 19 February 2009

Eyre Peninsula Natural Resources Management Board (EPNRM) (2009) A modelling framework for assessing recharge processes and climate change: Eyre Peninsula. http://epnrm.sa.gov.au/. Cited 5 July 2010

Fitzpatrick A, Cahill K, Munday T (2009) Informing the hydrogeology of Coffin Bay, South Australia, through the Constrained Inversion of TEMPEST AEM Data. CSIRO, Bentley WA, 159 pp

Gee GW, Fayer MJ, Rockhold ML, Campbell MD (1992) Variations in recharge at the Hanford Site. Northwest Sci 66:237–250

Geyh M (2001) Environmental isotopes in the hydrological cycle principles and applications, vol IV: groundwater—saturated and unsaturated zone. IAEA, Vienna, Austria

Harrington N, Evans S, Zulfic D (2006) Uley Basin Groundwater Modelling Project, vol 1: project overview and conceptual model development. Report DWLBC 2006/01, Department of Water, Land and Biodiversity Conservation, Adelaide, Australia

Healy RW, Cook PG (2002) Using ground-water levels to estimate recharge. Hydrogeol J 10:91–109

Herczeg AL, Leaney FWJ, Stadler MF, Allan GL, Fifield LK (1997) Chemical and isotopic indicators of point-source recharge to a karst aquifer, South Australia. J Hydrol 192:271–299

Hutton JT (1976) Chloride in rainwater in relation to distance from the ocean. Search 7:207–208

IAEA and WMO (2005) Global Network of Isotopes in Precipitation (GNIP) Database. IAEA and World Meteorological Organisation. http://isohis.iaea.org. Cited August 2006

Ingraham NL, Caldwell EA, Verhagen BTh (1998) Arid catchments. In: Kendall C, McDonnell J (eds) Isotope tracers in catchment hydrology. Elsevier, Amsterdam, pp 435–465

Kitching R, Shearer TR (1982) Construction and operation of a large undisturbed lysimeter to measure recharge to the chalk aquifer, England. J Hydrol 56:267–277

Knulst JC (2004) Ratio between throughfall and open-field bulk precipitation used for quality control in deposition monitoring. Atmos Environ 38:4869–4878

Moon SK, Woo NC, Lee KS (2004) Statistical analysis of hydrographs and water-table fluctuation to estimate groundwater recharge. J Hydrol 292:198–209

Moreno G, Gallardo JF, Bussotti F (2001) Canopy modification of atmospheric deposition in oligotrophic *Quercus pyrenaica* forests of an unpolluted region (central-western Spain). For Ecol Manage 149:47–60

Neary AJ, Gizyn WI (1994) Throughfall and stemflow chemistry under deciduous and coniferous forest canopies in southern central Ontario. Can J For Res 24:1089–1100

Plummer LN, Busenberg E (2000) Chlorofluorocarbons. In: Cook P, Herczeg AL (eds) Environmental tracers in subsurface hydrology. Kluwer, Boston, pp 441–478

Plummer LN, Busenberg E (2006) Chlorofluorocarbons in the atmosphere. In: Use of chlorofluorocarbons in hydrology: a guide book. IAEA, Vienna, Austria, pp 9–15

Plummer LN, Busenberg E, Cook PG (2006) Principles of chlorofluorocarbon dating. In: Use of chlorofluorocarbons in hydrology: a guide book. IAEA, Vienna, Austria, pp 17–29

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol J 10:18–39

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Proc 20:3335–3370

Sibanda T, Nonner JC, Uhlenbrook S (2009) Comparison of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe. Hydrogeol J 17:1427–1441

Sibenaler XP (1976) Eyre Peninsula groundwater survey: Uley South basin. Report 76/30, Department of Mines, Government of South Australia, Adelaide

Solomon DK, Plummer LN, Busenberg E, Cook PG (2006) Practical applications of CFCs in hydrological investigations. In: Use of chlorofluorocarbons in hydrology: a guide book. IAEA, Vienna, Austria, pp 88–103

Stuyfzand PJ (1993) Hydrochemistry and hydrology of the coastal dune area of the Western Netherlands. PhD Thesis. Vrije Universiteit, Amsterdam, The Netherlands, 366 pp

Twidale CR, Bourne JA (2000) Dolines of the Pleistocene dune calcarenite terrain of western Eyre Peninsula, South Australia: a reflection of underprinting? Geomorphology 33:89–105

USGS (2009) Landsat Enhanced Thematic Mapper Plus (ETM+). http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/ETM. Cited 12 January 2009

USGS (2010) The Reston Chlorofluorocarbon Laboratory. http://water.usgs.gov/lab/software/air_curve/. Cited 20 May 2010

Way S (2006) Strategic management of Aleppo Pines on Lower Eyre Peninsula to maximise biodiversity conservation outcomes. Department for Environment and Heritage, Adelaide, Australia, 54 pp

Werner AD, Alcoe DW, Ordens CM, Hutson JL, Ward JD, Simmons CT (2011) Current practice and future challenges in coastal aquifer management: flux-based and trigger-level approaches with application to an Australian case study. Water Resour Manage 25:1831–1853

Wood WW, Sanford WE (1995) Chemical and isotopic methods for quantifying groundwater recharge in a regional, semiarid environment. Ground Water 33:458–468

Zulfic D, Harrington N, Evans S (2007) Uley basin groundwater modelling project, vol 2: groundwater flow model. Report DWLBC 2007/04, Department of Water, Land and Biodiversity Conservation, Government of South Australia, Adelaide, 128 pp