Author Reply to Referee 1_Fourth Round

Theory of the generalized chloride mass balance method for recharge estimation in groundwater basins characterised by point and diffuse recharge

By N. Somaratne and K. R. J. Smettem

Anonymous Referee #1

Unfortunately, it appears that no amount of logical reasoning can bring this discussion to a sensible conclusion. I can only appeal to the editors to consider the damning reviews on this and the previous manuscript and ensure that these notions are not allowed to enter the debate and policies around recharge to the water-limited areas of their case studies, and potentially for other areas in the world that have the misfortune to adopt this corrupted methodology and eventually exhaust groundwater resources as a result.

Two points, amongst many others, irrefutably show that this method is entirely indefensible, from both a mass-balance test and a practical sense.

Referee 1-C1: For Uley South, the simple mixing calculation (Cl value for diffuse only recharge is 147 mg/L and diffuse-only recharge is 56 mm/year; Cl for point recharge is 14.2 mg/L and point recharge is 75 mm/year), deemed "interesting" by the authors, is rather an irrefutable mass balance for the water entering Uley South. It is completely inconceivable that the dozens of Cl measurements (none of which are somehow remarkably monitoring at the watertable as indicated by the author's "Why the Conventional CMB Fails in Karst") can be avoiding this huge influx of freshwater (75 mm/yr of Cl 14.2 mg/L) that the authors are suggesting. The piezometers mostly go to the bottom of the unconfined aquifer and there are dozens of them. None of them find water of the average mixed portion (71 mg/L), or fresher. Not a single one. There is no hope that karst passageways are magically weaving their way around the piezometers. If there is 75 mm/y of 14.2 mg/L and 56 mm/yr of 147 mg/L, then half of the aquifer contains water of 71 mg/L or less, apparently. Yet, the lowest Cl is >100 mg/L. The authors have created recharge that they can't defend from the perspective of the aquifer's Cl values. Mass balance is violated, and it has nothing to do with the monitoring strategy, it occurs because the authors eliminate salt mass flux through sinkholes. It is incomprehensible that something so obvious can continue to be a sticking point for the authors.

Author Reply:

The Referee 1 has raised three main issues in the above comment and each of them is addressed below. The issues raised are:
1. Authors eliminate salt mass flux through sinkholes.
2. Why 71 mg/L chloride is not present in the sinkhole area or in the basin.
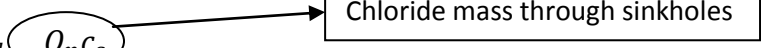3. Why the conventional CMB fails in karst- "karst passageways are magically weaving their way around the piezometers"

1. Authors eliminate salt mass flux through sinkholes.

We disagree with the Referee 1's assertion that salt mass flux through sinkholes is eliminated from the equation. The equation developments are very transparent (based on conservation of mass) and at all steps $Q_p c_s$ (chloride mass through sinkholes) is included. Please see the generalized CMB equation below:

The generalized CMB equation is:

$$R = \frac{(Pc_{p+D}) + Q_p(c_{gd} - c_s)}{c_{gd}}$$

Re-arranging terms:

$$R = \frac{Pc_{p+D}}{c_{gd}} + \frac{Q_p c_{gd}}{c_{gd}} - \frac{Q_p c_s}{c_{gd}}$$

Chloride mass through sinkholes

Only when $c_s \ll c_g$, the term $Q_p c_s / c_{gd}$ becomes very small and eliminated. This is applicable only in recharging into brackish water zones such as in Poocher Swamp fresh water lens (there is no use in keeping near zero $Q_p c_s / c_{gd}$ term in the equation).

Please note that results from the generalized CMB method, which is a physically based model, can not be verified with the Referee 1's mixing model result (71 mg/L).The pitfalls of Referee 1's mixing model are discussed below.

2. Why 71 mg/L chloride is not present in the sinkhole area or in the basin.
It is unfortunate, that Referee 1 keeps repeating his/her 'mixing model' that was used to arrive at 71 mg/L of chloride in the basin. This suggests a lack of understanding of behaviour of karst systems; lack of understanding/experience in the Uley South basin; and lack of

understanding of applying mixing-models to complex hydrogeological settings such as karst systems.

Uley South limestone aquifer water is derived from three main sources: diffuse recharge from the basin, point recharge through sinkholes, and Tertiary Sand water with high salinity/chloride entering the limestone aquifer as a result of limestone aquifer's depth coincident with Tertiary Sand aquifer in the area where Tertiary clay aquitard is not present.

Please refer to the Page 382, Fig. 1 of the manuscript. In Figure 1, the Tertiary Clay absent area (about 5 km in length) at the landward boundary of the central basin, is the area where Tertiary Sand water enters into the limestone aquifer. The high salinity water originates from Big Swamp, 18 km north-east of Uley South and flows through the Tertiary Sand (on its path way mixing with other low salinity waters) and enters Uley South where Tertiary Clay is absent (see Figure 1 below).
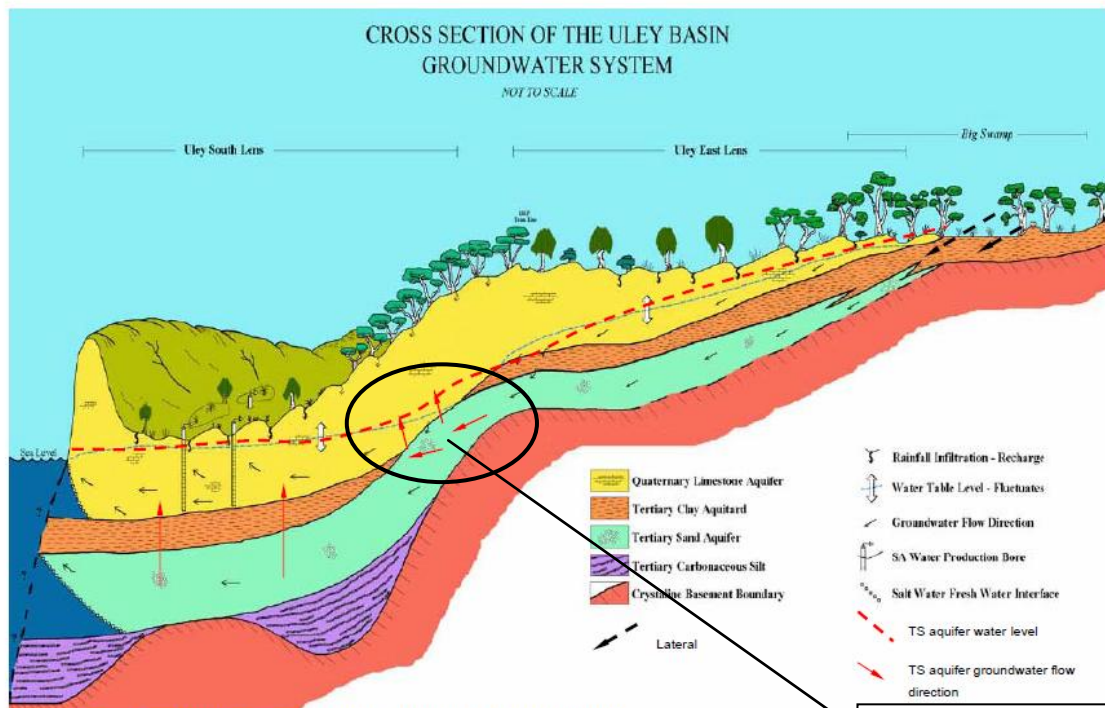

Area where Tertiary Clay not present with depth coincident of Limestone and Tertiary Sand aquifers

Figure 1. Uley south link to Big Swamp (from Zulfic et al, 2007).

This higher salinity water, once it enters the Uley South along its 5 km stretch, mixes with low salinity Limestone water and flows through the entire Central Part of the basin (see Figure 2 below). The nested bores ULE109 and ULE197; and ULE184 and ULE 185 are located approximately 2 km down gradient from the Tertiary Clay absent area and up-gradient to the all production wells. As can be seen from Figure 2,

considerable depth of high salinity Tertiary Sand water is contained in the bottom of the Limestone aquifer, with a mixing zone above.
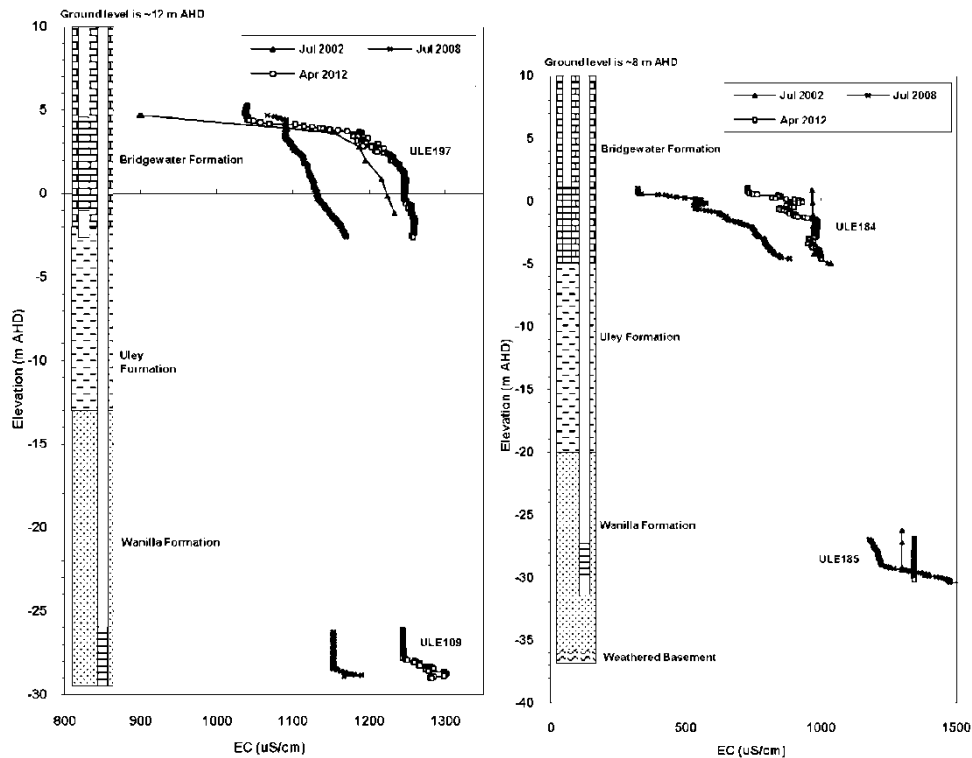

Figure 2. Salinity profiles-down gradient of the Tertiary Clay absence area in the Uley South central basin (Somaratne, 2013)

Unfortunately, the central basin is the high recharge zone and that is where the majority of sinkholes are found (see page 382, Fig. 1). Therefore, low salinity water from point recharge through sinkholes mixes with high salinity diffuse recharge and Tertiary Sand waters.

Therefore, the 'mixing model' of the Referee 1 to produce 71 mg/L chloride in the basin cannot be applied.

3. "karst passageways are magically weaving their way around the piezometers"
    We believe we have partially answered this above (1) and explained why the low salinity water is not found in the point recharge zone (central basin).   Note that in karst systems, conduit flow can dominate and conduits of even a few centimetres diameter can carry large volumes at much faster flow rates than the granular porosity systems (conduits need not be large tunnels).   If point recharge is primarily channelled through these conduits, all one can see are 'fresher water pockets' or 'lenses' as stated in the 'Why the conventional CMB fails in karst'.

Please note that some of these conduits have been intercepted by wells, as pumping tests indicate 13,000 m^2 per day transmissivity and specific yield up to 0.72 (please see Page 315, Lines 7-8). It is not clear how the Referee 1's 'mixing model' handled this. Note that conduits flows are non-Darcian as well.

Points (1) and (2) above violate all the assumptions and boundary conditions that the conventional CMB is based upon. Therefore, application of the conventional CMB method as Ordens et al (2012) have done is invalid, no matter how many groundwater samples are used to get representative chloride values.

This is where the generalized CMB method becomes a handy tool. All one needs are; estimates or measures of Q_p, c_s, and measures of c_g or c_u.

We invite Referee 1 to consider the following section taken from Referee 5's comments on Somaratne et al (2013) and the Author Reply. The sections relevant to this discussion are highlighted.

"*Referee 5-2: However, I would encourage the authors to make the suggested changes so this becomes a worthwhile and significant study.*

Firstly, the authors need to become more familiar with the principles of karst hydrology. In the well-cemented limestones that characterize much of North America and Europe, karst conduits (caves) carry the bulk of groundwater flow. In the porous limestones of SE Australia, groundwater flow is shared between the granular porosity and karst conduits, but the 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 (Waterhouse's study of the Gambier Limestone shows this clearly). In a bore it is easy to intersect groundwater within granular porosity, but very difficult to intersect a conduit, so the former contribution to the overall groundwater flow in the limestone aquifer is emphasised at the expense of the latter (this is the mistake that Ordens et al. have made).

Author Reply 5-2: The Authors thank the Referee for valuable guidance. Manuscript will be re-revised to include work of Waterhouse (1977) in Mount Gambier aquifer and the landmark study of Herczeg et al (1997) in the Poocher Swamp sinkhole associated conduit flow. Outcomes of these studies will be linked to the Results and Discussion of this study to consolidate our findings."

Referee 5-3: Point recharge (at sinkholes) feeds karst conduits with very rapid groundwater flow; it is important to realize that sinkholes almost always feed conduits (otherwise the sinkholes would not exist). Some of the recharge around sinkholes will also seep slowly into the granular porosity around the recharge point. However, most of the recharge to the granular porosity of the aquifer is through surface recharge across the entire surface of the aquifer; recharge to the granular porosity from the point recharge areas would be a relatively minor contribution restricted to those areas. The authors need to reinterpret their data with this in mind; studying the recharge to the granular porosity around

point recharge areas is useful, <mark>*but remember that most groundwater flow is through the conduit that is fed by the sinkhole.*</mark>

Author Reply 5-3: *Authors agree with the view of Referee 5. In the revised manuscript, we have highlighted the fact that in the point recharge dominant zone in Uley South, 10 mg/L reduction of chloride concentration is a result of mixing of point recharge water with diffuse recharge and ambient groundwater.* <mark>*Referring to Fig. 6 & 7, we have described that low salinity water in upper part of BLA 107 and BLA 164 are the results of both diffuse recharge and point recharge mixing;*</mark> *and low salinity in the profile at depth in BLA 164, is the interception of conduits carrying low salinity water from point recharge source (drainage wells) These observations are supported with Herczeg et al (1997) observations at Poocher Swamp monitoring wells.*

The findings regarding calcrete surface generated runoff and that flow to sinkholes, as well as calcrete surface contributes to diffuse recharge, is supported by a presentation made by the first author two years ago to a group of local hydrogeologists. We present the relevant slide below, which is self explanatory. This photo shows the typical landscape of the Uley South basin."
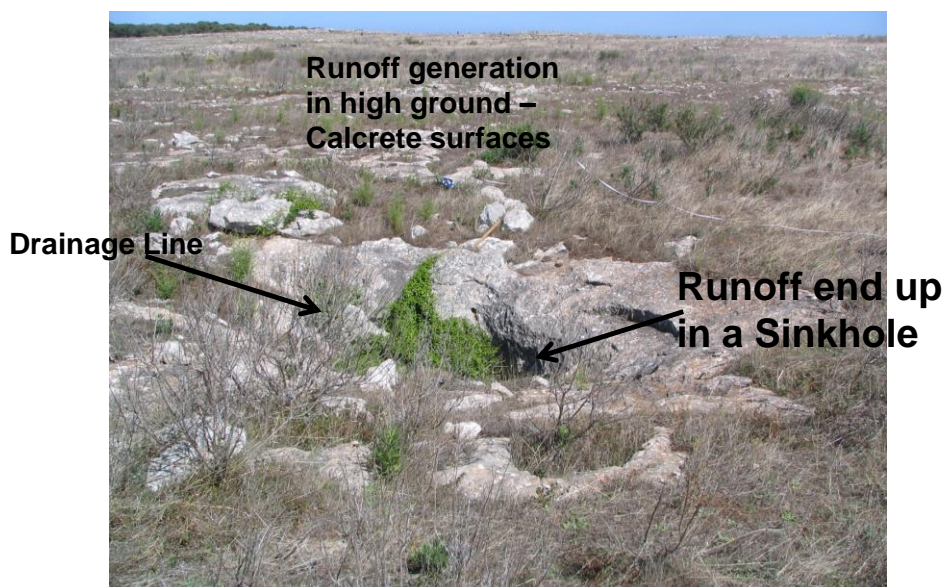

Figure 3. Uley South typical sinkhole-Runoff terminates in a sink hole

Referee 1-C2: The method is NOT a generalised Cl method. It requires an estimation of catchment Runoff, which according to the authors ALL ends up as recharge. This is a ridiculous notion. All catchment runoff can never become sinkhole recharge, unless the catchment is, literally, a bathtub. What's more, the method requires a characterisation of diffuse recharge Cl and sinkhole Cl, neither of which is obtained for the cases they present. In Uley South, there is no clay between the upper and lower aquifers in places - mixing occurs between upper and lower aquifers, and the lower aquifer is connected to basins to the north. There is simply no way that their diffuse Cl values can be taken from Cl measurements around the basin's perimeter. Without unsaturated zone Cl values, the method is entirely indefensible, and therefore impractical without considerably more measurements. Runoff (becoming sinkhole recharge) and diffuse recharge Cl are beyond the capacity of the authors to obtain, and hence they have invented values that, intentionally in my view, produce recharge to Uley South that is excessive for the purposes of commercial gain.

Author Reply: We divide the above comment into following:

1. All catchment runoff can never become sinkhole recharge.
2. the method requires a characterisation of diffuse recharge Cl and sinkhole Cl, neither of which is obtained for the cases they present.
3. In Uley South, there is simply no way that their diffuse Cl values can be taken from Cl measurements around the basin's perimeter.

1. Catchment runoff can never become sinkhole recharge.

Obviously, not all runoff becomes sinkhole recharge. A proportion of the runoff becomes defuse recharge and a portion is lost to ET. It is the issue of how the rainfall-runoff models are parameterised, including the setting up of initial and continuous losses. For the three case studies, the following descriptions are given in Somaratne et al (2013) and summarised in this paper.

Uley South is a topographically closed basin. Runoff is highly ephemeral, occurring only after moderate to high intensity rainfall and persisting only tens to hundreds of meters before entering a sinkhole (Evans, 1997; Harrington et al., 2006; Ordens et al., 2012)- see page 312, Lines 15-17. As such, the assumption of total runoff becoming recharge is reasonable.

In Mount Gambier, there is no surface drainage and no runoff leaves the city as the storm water derived from the central 16.8 km^2 of the city area (26.5 km^2) is discharged to the unconfined aquifer through three sinkholes and 400 storm water drainage wells (see page 312 Line 26, and Page 313 Lines 1-2). Therefore, total estimated runoff becomes point recharge.

Poocher Swamp's fresh water lens, which is the largest of these fresh water plumes that float on brackish water, is a result of flows from Tatiara Creek which enter Poocher Swamp. The major recharge is through two sinkholes located in the north-west section of the swamp

(Herczeg et al. 1997). Average annual flow calculated from daily flow data of Tatiara Creek measured at Bordertown, about 6 km upstream, is taken as the annual recharge.

2. the method requires a characterisation of diffuse recharge Cl and sinkhole Cl, neither of which is obtained for the cases they present.

It is not clear how the Referee 1 arrived at this conclusion. We have described diffuse recharge zone chloride and surface chloride measurement under Methods in detail in the revised manuscript of Somaratne et al (2013). Important relevant sections are given below:

"Groundwater chloride and stable isotope (δ^2H and δ^{18}O) for the Uley South basin is from Evans (1997), with further groundwater samples collected in 2008. Data gaps were filled by linear regression of TDS to chloride (R^2=0.98) for monitoring wells where TDS are available but no chloride measurements have been undertaken. Selected monitoring wells are away from brackish water upward leakage areas and salinity stratified wells (Somaratne 2013), the swamp and coastal monitoring wells to avoid chloride contamination from other sources. For the Blue Lake capture zone, existing groundwater chloride data were supplemented with samples taken from unconfined aquifer monitoring wells within and outside the city. Selected sampling wells are away from historically known contaminated sites. In addition to the monitoring wells, groundwater samples were taken from drainage wells and surface runoff for major ion and stable isotope analyses. Salinity profiles taken by sonding in 2011 and 2012 for selected monitoring and drainage wells were used to study vertical distribution. Water samples were collected from Tatiara Creek, Poocher Swamp, aquifer monitoring wells and town water supply wells in 2012.

Groundwater samples for major ion and stable isotope analysis were collected using micro-purge (low-flow) sampling procedure (Vail 2011) and grab sampling technique. The micro sampling is employed to gain representative groundwater samples within open hole of monitoring and drainage wells. Low-flow purging is considered (Vail 2011) superior to bailing and high-rate pumping and results in a more representative sample than the typical well purge methodology. The assumption in the grab sampling is that the hydrostratigraphy in the well is in hydraulic equilibrium prior to sampling. To collect the sample by this method, an electronic depth sampler connected to a geophysical logging line is advanced to the target sampling depth and the unit is electronically opened, allowing groundwater to enter the sampler. Salinity profiles of monitoring and drainage wells were obtained using Hydrolab sonde (Eco Environmental, 2013) connected to a logging truck cable and lowered down the well from surface to the well base, recording electrical conductivity (EC) data along the way"

3. In Uley South, there is simply no way that their diffuse Cl values can be taken from Cl measurements around the basin's perimeter.

Please refer to the Page 382, Fig. 1. We have shown in the figure, diffuse zone chloride measurement sites with respect to basin boundary and Tertiary Clay absent areas. There are no sinkholes around these areas and no through flow coming into the Limestone aquifer from outside the boundary as outside is dry limestone. There are sinkholes in the Tertiary Clay absence area in the central part but no sinkhole in the small area where Tertiary Clay is not present to the north. As such, chloride in the limestone aquifer landward perimeter is purely derived from diffuse recharge.

If the Referee 1's concern is that the lower Tertiary Sand aquifer water enters the Limestone aquifer, then we like to offer following. The lower aquifer has higher salinity and chloride than the upper aquifer and this results in a lower recharge estimate rather than a higher recharge.