Author Reply to Referee 1_Third 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

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Additional and important observations should be added to my previous review of Somaratne and Smettem’s manuscript. These relate to scale and spatial variability, as follows:

Referee 1-C1: The method described by Somaratne and Smettem requires a runoff calculation to obtain the preferential recharge. They abandon the two-part Cl end-member approach contained in their methodology, and simply add Qp to their groundwater-based "diffuse recharge" estimate. Hence, the method is no longer a Cl-based one. The implications of this are explored further below. They most certainly do not apply a generalised CMB method as the title suggests. It is, essentially, a recharge exaggeration tool, because it takes evidence for recharge from a groundwater system and adds poor approximations of bypass recharge to it.

Author Reply: This may be an oversight. In page 320, Lines 13-15, it clearly states that:
“Recharge to the Uley South basin and Mount Gambier in the Blue Lake capture zone are estimated using equation (13c), and for the Poocher Swamp fresh water lens, where $c_s << c_{gd}$, equation (13d) is used.” The Equation 13C is the generalized CMB, and approximation is only in 13d which was applied to the Poocher Swamp freshwater lens.
Therefore first part of the comment is baseless.
The applicability of 13d to Poocher Swamp fresh water l;ens is described below.
For example Poocher Swamp chloride concentration (Cs) is 28 mg/L., and diffuse zone chloride concentration (outside the lens) is (Cgd) 550 mg/L.(see Table 1, in Page 326). Therefore Cs (28mg/L) <<Cgd (550 mg/L) assumption is correct as (Cgd-Cs)/Cgd ≈ 1(=0.95).

For the second part, please see Page 319, Lines 8-13. Qp appears in the Equation 13d is not as a result of ‘just adding’ to the equation. It is as a result of approximation made for brackish water aquifers where Cgd >>Cs as described above. [We noticed there is a missing ‘d’ in the subscript and it is now added to read as:
“A special case occurs where ambient groundwater chloride concentration is much higher than the chloride concentration of surface runoff, $c_{gd} >> c_s$, and then $(c_{gd}-c_s)/c_{gd} \approx 1$, thus equation (13c) yields:

$$\mathrm{R} = \frac{\mathrm{P}c_{\mathrm{p+D}}}{c_{\mathrm{gd}}} + \mathrm{Q_p} \qquad (13d)”$$

As one can see, Q_p is not arbitrarily added for convenience, rather it is derived from the Equation 13 C.]

Referee 1-C2: The Somaratne and Smettem method is written as though it applies to the basin scale, and that the method somehow determines basin-scale diffuse and preferential recharge from two uniform end-member Cl concentrations. However, the aquifers in question show variability in Cl concentrations, reflecting spatial variability in recharge rates, and probably variability in end members. A reasonably minded hydrogeologist would not attempt to develop a single-recharge value across such an area (e.g. around Poocher swamp) in light of these observations, as suggested by Somaratne and Smettem as being standard practice. Rather, there would be some attempt to average or partition the aquifer into recharge zones. Also, it is unimaginable that one would use the highest Cl values to determine the basin-scale recharge, as suggested by Somaratne and Smettem as current contemporary practice. They adopt this malpractice scenario to exaggerate differences between their method and conventional CMB. Rather, a reasonable hydrogeologist would consider each Cl measurement on its merits and consider recharge variability across the system. Certainly, there is no basis to start taking groundwater Cl-based recharge estimates and adding runoff to them. The implications of doing this are discussed below.

Author Reply: Please read the Somaratne et al (2013) "Hydrological function of sinkholes...", where we explain why we cannot apply CMB method. In Page 11434, Lines 12-24 it states:

"Application of conventional CMB to estimate recharge to the Poocher Swamp fresh water lens requires further consideration. Average chloride concentration in the fresh water lens of 91 mg L^{-1} or a recharge value of 14 mm per year are not representative of recharge to the fresh water lens. In fact vertical recharge (2.5 mm $year^{-1}$) that crosses the watertable plane corresponds to a diffuse zone groundwater chloride concentration of 550 mg L^{-1}. The fresh water lens's recharge water is generated outside the fresh water plume area. Low salinity and chloride concentrations found in the fresh water lens results from a lateral flux moving from point source recharge down gradient. Taking chloride measurements from a lateral flux to estimate vertical recharge is essentially estimating 'apparent recharge'. This is because the estimated recharge never crossed the watertable plane at the location. "

Therefore, no matter how many sample points are used for calculations, the vertical recharge calculated at sampling points are not actual recharge rather 'Apparent Recharge'. The actual recharge occurs only at the two sinkholes in the Poocher Swamp (Point Recharge) while the rest of the aquifer receives only 2.5 mm/yr diffuse recharge.

Referee 1-C3: Somaratne and Smettem ignore groundwater flow patterns, and are basing their investigation entirely on Cl distributions. Flow in the SE of South Australia, around Blue Lake, is regionally in somewhat of a south-south-westerly direction. Flow at the boundaries of Uley South is driven by inflows from other carbonate basins to the north. Any groundwater bubbles will move with the groundwater flow, and mix with both recharging water and water from elsewhere. Mixing and groundwater flow together violate the notions of diffuse only Cl values suggested by the authors. The only place these can be found will be in lower unsaturated zones, that are free from the flushing effects of preferential flow.

Author Reply: We were very conscious of these issues raised by Referee1 and were very careful in selection of wells for chloride analysis.

Chloride values in wells on the south side of the Blue Lake are absolutely not affected from point recharge through drainage wells or sinkholes for two reasons.

1. The Blue Lake water level is 0.1 m lower than the surrounding aquifer water levels. Therefore the aquifer water flows into the Blue lake (opposite direction to the regional flow) from surrounding. Please see the Figure on Page 5.
2. There is a major displacement of aquifer sub-units across the Blue Lake due to faulting. Therefore there is no continuity of the sub-units across the Blue Lake.

Therefore, in the case of the Blue Lake, all diffuse recharge zone wells only capture ‘chloride from diffuse recharge’.

Regarding the Uley South diffuse recharge wells, all wells were selected closer to landward boundary, to capture only ‘diffuse recharge derived chloride’. The Uley South Limestone aquifer does not receive through flow from the northern lenses because Limestone in the area in-between is dry. Please see the Map (Page 6) and Table in Page 7 (taken from Somaratne 2013, Hydrogeology of the Uley South basin, SA Water internal report). As Referee 1 can see, the Limestone aquifer base is at a higher elevation than the first water cut (water found below the Limestone base, i.e in the Tertiary Clay or Tertiary Sand). Therefore, selected wells are not affected by through flow from northern lenses due to dry Limestne presence in between. The chlorides in selected monitoring wells are purely derived from diffuse recharge.

Referee 1-C4: Looking closely at the Cl distributions shown for Uley South, Figure 1, shows that there are Cl values amongst the "sinkhole region" that are higher than some of the "diffuse only" Cl values. How can this be? It violates every aspect of the methodology and its application.

Author Reply: This is a correct observation. Note that diffuse recharge also occurs in the sinkholes areas and the aquifer water is not fully mixed. This is the very basic reason why we need a generalized CMB. Chloride concentrations in diffuse recharge is purely determined by chloride in surface water and to what degree the infiltrating water had been subjected to evapotranspiration processes. Depending on this, chloride enrichment varies. So it is not unusual to see some high chloride values even in the sinkholes dominant areas, which may not be connected to flowpaths originating from point recharge sources and therefore remains unmixed. Please see the article ‘Why the conventional CMB fails in karst’.

Referee 1-C5: A simple calculation for Uley South can be made to bring the methodology into complete disrepute. According to Somarantne and Smettem: the 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. If the authors apply their own theory (see previous review equations R1 and R2) to obtain Cg, one obtains a value of mixed groundwater of 71 mg/L. There is no groundwater of this salinity in Uley South. Therefore, either their recharge rate is too high, or there is no mixing and every observation of Cl in Uley South is remarkably avoiding the freshwater bubbles. Or perhaps their end member concentrations are wrong. No matter what scenario for groundwater processes one might adopt - mixing or no mixing, there is no way to use the current method to get a reasonable basin-scale recharge. The remarkable no-mixing scenario renders the current method entirely impractical, because there is no manner in which to measure these elusive freshwater bubbles, and the user has no way to discern the proportion of the aquifer that is avoiding Cl measurement.

Author Reply: This is an interesting mixing model and we thank Referee1 for raising this so that we can make some clarifications.

If one adds 56 mm of water of chloride concentration of 147 mg/L to a glass jar and another 75 mm of water of chloride concentration of 14.2 mg/L is added and well mixed, one would find 131 mm of water with a chloride concentration of 71 mg/L. This ideal mixing scenario is not always the case in the real world aquifers, particularly in karstic aquifers.

In diffuse recharge only aquifers through granular porosity, it is assumed that at the watertable plane and saturated zone fairly uniform chloride concentration exits which is a valid assumptions. In these type of aquifers there is no issues on duality of recharge. That is why the conventional CMB works well in diffuse recharge only aquifers.

The above assumption is not valid in karstic aquifers as point recharge occurs through relatively small areas (though volume is large) and flow through an interconnected network of conduits/flow paths with little or no opportunity for thorough mixing with aquifer water as in glass jar mixing experiment. We have provided enough evidence from our own data and others in the Somaratne et al (2013) “Hydrological function of sinkholes....’ manuscript, to illustrate the existence of interconnected networksand the difficulties with representative sampling. .

Please read the document on ‘Why the Conventional CMB Fails in Karst’ for further explanation.

Referee 1-C6: Given 1. to 5., it is clear that the method over-estimates basin-scale recharge. However, a modified form of the method might offer some insights into the spatial variability of contributions from sinkhole recharge. If one is somehow able to isolate diffuse and bypass Cl values, a two-end member approach would allow for a "% sinkhole recharge" map to be produced, but ultimately, there is no way to obtain the recharge values of Somaratne and Smettem for Uley South aquifer without violating mass balance constraints, as shown in the simple calculations of comment 5. above.

Author Reply: No further response is required..

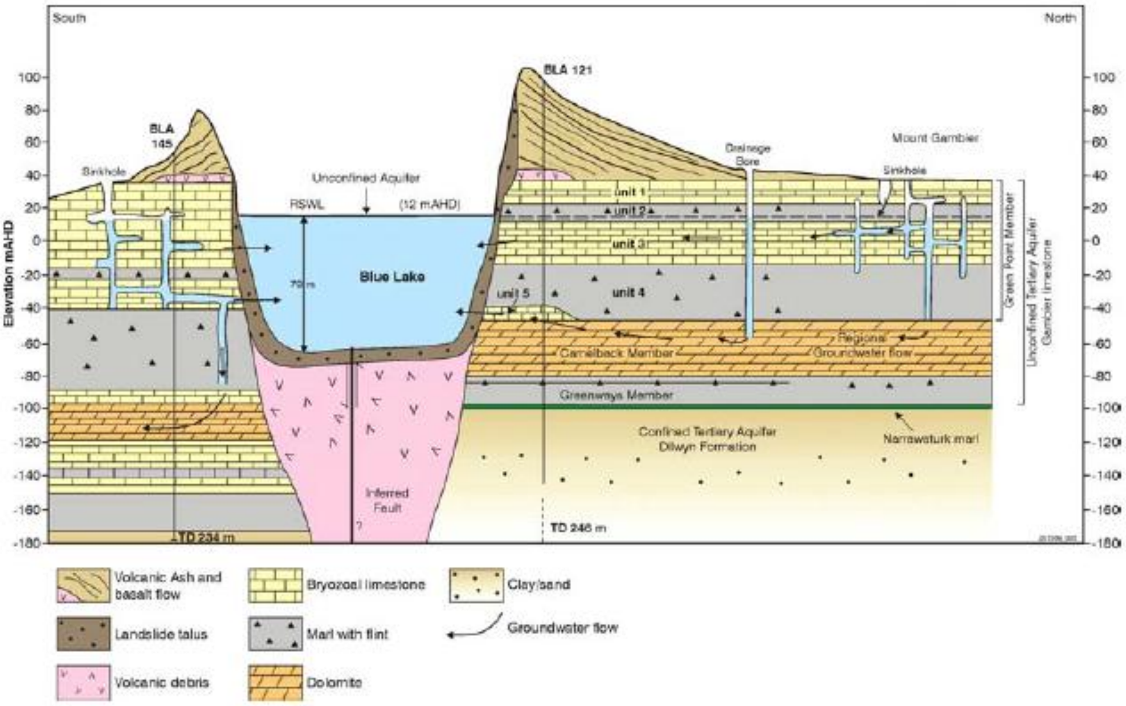

Figure 26. Recent stratigraphic assessment in the vicinity of the Blue Lake (Lawson and Hill, in press).

Taken from:

Vanderzalmm J., Dillon, P., Page, D., Marvaneck, S., Cook, P., King, H., Dighton, J., Sherman, B., Adams, L. 2009. Protecting the Blue Lake from land use impacts. CSIRO:Water for a Healthy Country National Research Flagship.

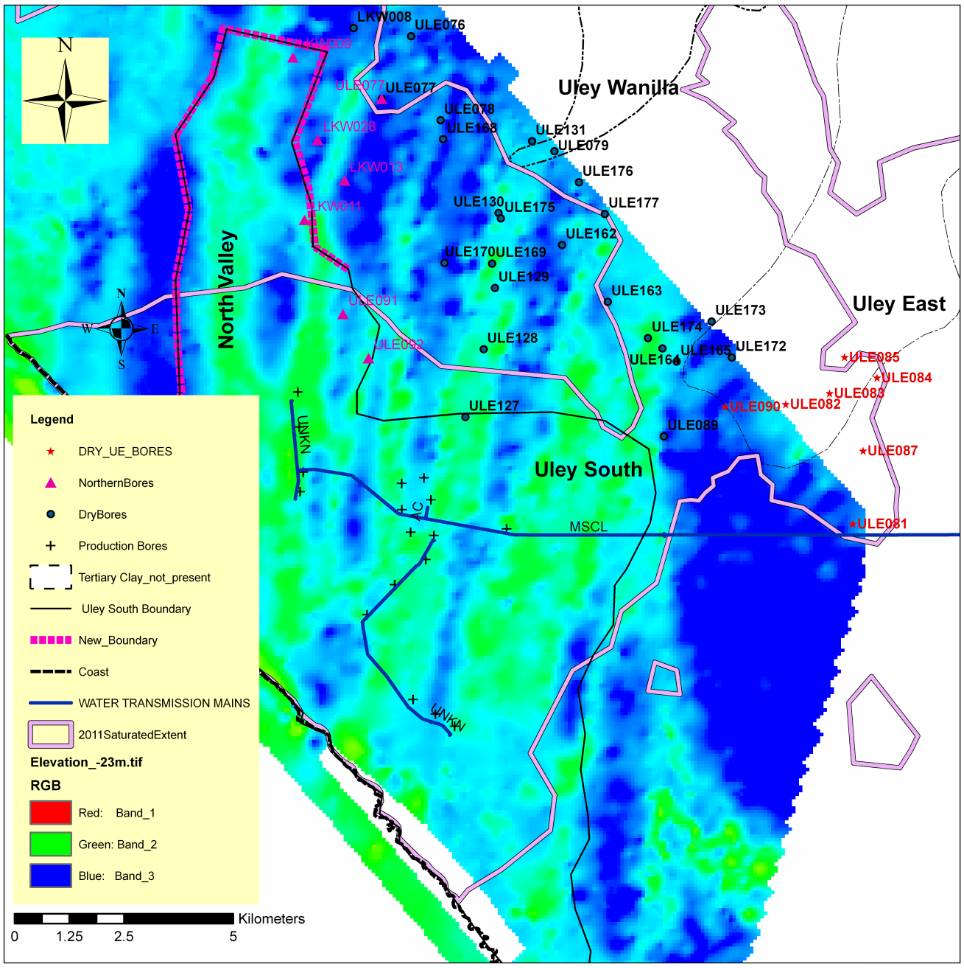

Figure 1. Location of Bores between Uley Wanilla-Uley South and Uley East with AEM survey highlighting Quaternary Limestone dry areas, (Band_2: Aquifer, Band_3: Basement rock).

Table 1. First water cut details for the bores drilled between Uley Wanilla, Uley South and Uley East :Quaternary Limestone dry areas.

Bore name	**Depth to Quaternary Limestone Base (m)**	**Depth of First water Cut (m)**	**Limestone Wet/Dry condition**	**Remarks**
LKW008	14	21.95	Dry	Basement high
ULE 76	21.64	29.87	Dry	Basement high
ULE 77	27.12	27.17	Just wet at the base	Uley South Original Boundary
ULE 78	7.6	10.3	Dry	Basement high
ULE 79	17.3	11.15	Wet	At the Edge of the Uley Wanilla lens
ULE162	5.0	17.22	Dry	Basement high
ULE163	24.0	29.0	Dry	Tertiary clay
ULE168	12	16	Dry	Tertiary clay seepage, No TS-Basement High
ULE131	17.9	12	Wet	Uley Wanilla Boundary
ULE130	9.7	15.2	Dry	At edge of a Basement high
ULE175	9.6	11.9	Dry	At edge of a Basement high
ULE170	25	26.3	Dry	Basement high
ULE169	13.5	17	Dry	
ULE127	16.4	15.8	Wet	Uley South Boundary
ULE128	22.05	26.2	Dry	
ULE129	11.9	16.76	Dry	
ULE176	9	13	Dry	At edge of a Basement high
ULE177	11	11.2	Dry	At edge of a Basement high
ULE173	12	25	Dry	Uley East edge
ULE172	29.5	24	Wet	In Uley East Lens
ULE164	20	24.5	Dry	
ULE165	28	24.5	Wet	Should belongs to Uley East edge
ULE174	22	29	Dry	
ULE 89	25.9	37.5	Dry	