Author Reply to Referee 1_Fifth 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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The conceptualisation presented by Somaratne and Smettem is a demonstration of the flawed notions they harbour about basic hydrogeological processes. The following describes the key problems.

Referee 1-C1. No sensors used routinely are installed at the water table. The majority of the Uley South piezometers sample all of the unconfined aquifer - from watertable to aquifer basement and represent integral samples thereof. The sampling strategy suggested here is entirely fictional and absurd, invented in an attempt to defend a flawed notion.

Author Reply: No permanent sensors are installed due to the excessive numbers required and their expense. Instead, the lead author's organisation carry out periodical sonding (a down hole geophysical method) to obtain salinity profiles. Sondes are the ideal sensors to identify high/low salinity zones in the profile as they record at closer depth intervals (usually 5 cm intervals). Based on sonded salinity profiles, Somaratne et al (2013) described low salinity water moving in the deeper part of the aquifer, which is the location of the main conduits in Mount Gambier. Two such salinity profiles we have provided for Uley South basin in Author Reply to Referee -1's Fourth Round of Comments.

Referee 1-C2. 50 mg/L is not reflective of rainfall, it exceeds it significantly.

Author Reply: It is given as an example to illustrate and simply explain the context.

Referee 1-C3. 5GL is an enormous volume of water. This volume is 2000 olympic swimming pools, or 10m depth of water across 100 football fields. Adding that (instantaneously it would seem) to a single karst conduit would probably drive water into the matrix through micro-fissures in all but the most voluminous of caverns. Over long timeframes, diffusion will take it into the matrix (e.g. up to 10s of metres in 5000 years, and 100s of metres in 50,000 years, according to a basic Ogatta-Banks estimate), not to mention the role of smaller conduits. The authors use this conceptual model to defend arguments pertaining to Uley South. Uley South has sandy sediments, despite that the authors wish to oppose several well-documented reports by others saying as much. This model doesn't apply, despite the authors suggesting it does. Even if the aquifer was solid concrete, diffusion will still act to mix into/flush the matrix over geological timeframes and over significant distances, especially given the microfractures in concrete and even higher heterogeneity of natural sediments.

Author Reply: The conceptual diagram shown in the article "Why the conventional CMB fails in karst" is only for illustration purpose to explain the text. It has no relation to any of the case studies. A single sinkhole is a representation for "all sinkholes'. It is not possible to draw all the sinkholes, and their sizes etc in a diagram and no need to show every detail to illustrate the points made.
Thank you for giving the Olympic pool size.

We have put the actual volumes of point recharge in three case studies into perspective below. In all three case studies total porosity (not the specific yield) is taken as 0.3 for karst systems to calculate depth of water in the aquifer, which is equal to saturated thickness multiplied by the total porosity.

Basin	Total Point Recharge (GL per year)	Point recharge as Equivalent basin depth (m)	Water depth =Average saturated thickness x porosity (0.3) (m)	Ratio of Point Recharge to Aquifer water volume %
Uley South	8.5	0.075	5 (15 x 0.3)	1.5%
Mount Gambier	6.6	0.39	20 (60 x 0.3)	1.95 %
Poocher Swamp	2.5	0.125	16.5 (55 x 0.3)	0.75 %

As one can see in the above table, point recharge is only a small fraction of the volume of water in the storage. As shown in Referee 1's fourth round of comments, much of the point recharge water occupies conduits and is carried away at a much faster flow rate, mixing with surrounding waters. Because of this advective-dispersive process, 'fresher water pockets' or 'lenses' are formed with a broad spectrum of chloride concentrations.

Referee 1-C4. . The authors suggest that their method assumes constant Cl in the groundwater system, but their method doesn't do any calculations whatsoever for the aquifer system. They do a mass balance across the watertable, and ignore completely the mass balance below the watertable. Doing a mass balance across the water table (which is never actually used in their final equations) does not amount to an aquifer water balance.

Author Reply: This was addressed twice before in detail. We applied chloride mass balance to the saturated storage. When lateral fluxes do not change groundwater chloride in the system (long-term steady state in terms of chloride mass), and when no other chloride sources and sinks are present, changes to saturated zone chloride can only occur across the watertable plane. The watertable plane is the entry or exit 'gate' of the saturated zone chloride. We trust this clarifies the point.

Referee 1-C5.. The obscure notion of lenses due to karst processes completely violates the authors own conceptual diagram here and the arguments of the sensors missing the freshwater. Lenses would be found floating on the saltier water, not caught in karst features, and if lenses indeed occurred, the sensors are almost perfectly placed to observe them, in complete contradiction to the arguments here.

Author Reply: Sensors recorded low salinity zones in both monitoring and drainage wells in Mount Gambier (please refer to Somaratne et al (2013) Hydrological function of sinkholes..) . We have described in detail in our reply to Referee 1's fourth round of comments how the Tertiary Sand water that enters the Limestone aquifer influences the salinity/chloride in the point recharge zone of Uley South. We do not consider any further explanation is necessary.

Referee 1-C6.. Where are the bimodal water types in Uley South, that are suggested here? There is no evidence of this. Perhaps this is because the aquifer is mixing - but if so, why is it that the current method produces recharge that completely violates mass balance, as I have shown. The current paper's short-comings evolve from the previous one, which there no water at or fresher than the mass-balance estimate of 71mg/L from their ill-conceived estimates. The conceptual model fails when compared to field observations, especially of Uley South.

Author Reply: With all due respect, we request once again from Referee 1 that please refrain from applying a simplistic mixing model to Uley South. That is only suitable for glass jar type experiments.

We have shown very clearly in our reply to Referee 1's fourth round of comments how the 71 mg/L mass balance is flawed. We consider no further explanation is necessary.

Referee 1-C7. The only way a conventional CMB would under-estimate recharge in a karst aquifer is if someone was ill-informed enough to measure in a few places and make sure they missed any of the karst features. Indeed, this would only happen if they were ill-informed enough to use the monitoring strategy proposed by the authors in their diagram, which is an entirely impractical arrangement in any case. It would seem that the authors are unaware of the approaches to monitoring the aquifers that they discuss. Also, there is no evidence that reasonable hydrogeologists are measuring the hard rock Cl values in an area known to be karst and making recharge estimates from these. This is a straw man notion. The authors are creating absurd ideas and then refuting them to try to defend the obscure notions of this research.

Author Reply: The diagram simply illustrates a point regarding resident concentration sampling, it is not a 'proposed sampling strategy'.

Increasing sampling points to apply conventional CMB in karst is a myth. This is mainly because trying to analyse karst aquifer systems with granular porosity mind-set. One of the major problems associated with karst is identifying flow-paths and we have reviewed all major works of international karst hydrologists. Some of these are summarised in the Introduction section of the Somaratne et al (2013) "Hydrological function of sinkholes...". We consider the best answer to above comment is the Introduction section of Somaratne et al (2013) and reproduce it here. We have highlighted the relevant sections to this discussion.

"Karst landscapes are often characterized by the presence of sinkholes, caves and underground conductive zones, formed primarily by dissolution of soluble limestone and dolomite. A distinct recharge feature of karst systems is the duality of flow regimes (Gunn 1983, Taylor and Greene 2001), which can be separated into: point (shaft and conduit dominated), and diffuse (matrix, meso-pore and macropore dominated) infiltration and recharge. In characterizing properties of a karst aquifer, quantitative water tracing tests conducted with fluorescent dyes, are among the most useful types of field methods that can be employed in the investigation of a karst aquifer (Taylor and Greene 2001). Alternatively, naturally occuring tracers such as chloride and stable isotopic signatures (δ^2H and $\delta^{18}O$) can be used for identifying recharge, and groundwater mixing with either low salinity rainwater or surface water entering the aquifer via a point recharge source (Leaney and Herczeg 1995, Herczeg et al., 1997). Knowledge of recharge conditions is important if limestone aquifers are to be developed as water resources (Gunn 1983). Two main forms of recharge to limestone aquifers are recognised (Gunn 1983, White 2003, Goldscheider and Drew, 2007). Allogenic, where recharge water is collected from outside the aquifer area, whereas autogenic input water is derived solely from rainfall within the aquifer area. Hydrologic characteristics of karst aquifers are largely determined by the structures and organization of the conduits (White 2003). Rapid flow through point sources in karst aquifers may create pathways for surface contaminants to enter and degrade groundwater resources (Hallberg and Hoyer 1982, Tihnsky 1999, Gordon 2011, Hyland et al. 2006). These aquifers are highly heterogeneous and anisotropic (White 2003, Bakalowicz 2005) and are susceptible to dissolution by circulating groundwater. The identification of groundwater flow paths in karst aquifers is therefore problematic (Tihnsky 1999). Dissolution cavities have a distinct geomorphology, may have a wide range of sizes and become hydraulically interconnected, enhancing the movement of groundwater.

White (2003), Taylor and Greene (2008), Lerch et al. (2005) and Bakalowicz (2005) recognise the complex nature of flows resulting from the presence of karstic features. Taylor and Greene (2001) and Bakalowicz (2005) hold that conventional study methods used in classical hydrogeology are generally invalid and unsuccessful in karst aquifers, because the results cannot be extended to the whole aquifer nor to some parts, as is often possible in non-karst aquifers. One inherent problems from the presence of karstic features such as sinkholes on the hydrological functions is that recharge estimation using the conventional chloride mass balance (CMB) method does not accurately account for the complex hydrological processes in the system. The fundamental basis of the conventional CMB method is that recharge mass flux crossing the watertable plane can be calculated if the following conditions are met (Wood 1999, Gee et al. 2005):

- chloride in the groundwater originates from precipitation directly on the aquifer, and no unmeasured runoff occurs;
- there is steady influx of water and chloride; and
- chloride is conservative in the system and there are no other sources or sink in the aquifer,

Problems arise holding above assumptions because different recharge processes may operate simultaneously, such as unsteady surface water directly injected into aquifers bypassing the soil zone, and internal runoff. Under these situations, it appears that the basic premise of the conventional CMB method is violated. Sinkholes and other karstic features supply a significant amount of recharge to many carbonate aquifers in temperate and humid regions throughout the world (Herczeg et al. 1997), yet applicability of the conventional CMB to karstic systems has not been studied.

We critically examined the validity of the conventional CMB method for recharge estimation in three karstic groundwater basins with particular reference to chloride distributions in point and diffuse recharge zones, groundwater mixing, preferential flowpaths and prediction of groundwater recharge using the conventional CMB method, and compare this to point recharge estimates. "

Referee 1: The editors have now received uniformly negative feedback from numerous reviewers, including a world-leader on the topic in Prof. Warren Wood. If the journal is indeed adopting a peer review process, then the peer reviewers are recommending rejection. Added to this, my analysis has shown, with painstaking detail and despite almost uniform disagreement from the belligerent authors, that the authors' research is completely flawed, in both this paper and their previous one. I implore the editors to follow the advice of peer-reviewers, but also to consider that the lead author's organisation was at the centre of a parliamentary inquiry on the water resources management of one of the study areas (according to the authors comments), for good reason given historical water level declines. Their ridiculous notions may eventually lead to short-term commercial gain and perhaps the collapse of aquifers due to over-estimation of recharge and allowable pumping, if their method is considered as "peer reviewed" by HESS (despite being unanimously discredited by the peer reviewers). The editors must surely see that any method that produces exceedingly high recharge should be considered with significant scepticism, if a precautionary principle is considered, not to mention that the current method produces recharge that completely violates mass balance, as I have shown. The current paper's short-comings evolve from the previous one, which was equally flawed, and it is distressing to find out from the authors that the journal continues to consider it for peer-reviewed publication, and it has now given rise to this more recent manuscript, which provides more clarity on the fatal and irreconcilable errors in their scientific notions.

Author Reply: The paper is submitted soley for consideration of its scientific merit. Inclusion of attacks on the credibility of the authors reflects poorly on the referee and adds nothing to the debate on the value of the science. It would be very unfortunate if work to advance the general scientific understanding is rejected solely on the basis of a perceived vested interest of the authors. This is akin to the fate of Galileo at the hands of the Roman Inquisition.