Author Reply to Referee 1-Second round-Generalized CMB:

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

The authors would like to thank Referee 1 for participating the discussion forum and for second round of comments. The corresponding replies are listed as follows:

Anonymous Referee #1

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General: The manuscript by Somaratne and Smettem attempts to develop a new approach to Cl interpretation from groundwater, and aims to discredit the current use of this method, stating that recharge is under-estimated by factors up to 7 for systems in South Australia. The research follows closely from a recent HESSD submission - Somaratne et al. - which received a largely negative response from referees.

Author Reply: We wish to state that our work is not aimed at discrediting the current chloride mass balance method as used in saturated or unsaturated situations. Rather we are seeking to extend the CMB method by adding a point recharge component to the CMB method.

Results of our study are consistent with Wood et al (1997) findings:

(a) Wood et al. (1997) report macropore recharge flux ranges between 60 and 80 % of total recharge and concluded that if the recharge in playa floors is calculated with only the conventional chloride mass balance method or the tritium method, the recharge is severely underestimated because of the presence of macropores.

(b) In our three case studies, the point recharge flux is estimated to contribute 63%, 85% and 98% of the total recharge for Uley South, Mount Gambier and Poocher Swamp fresh water lens respectively. We concluded that recharge is under-estimated by the conventional CMB, if point recharge occurs in groundwater basins.

With regards to recent HESSD submission of Somaratne et al (2013) we would like to state that most of the comments were directed to the Structure of the paper rather than Contents. No Referee has disputed the salient points of the paper (a) Boundary condition of conventional CMB is not applicable when point recharge is present (b) Preferential groundwater flows exits through interconnected networks (c) Representative groundwater chloride samples cannot be obtained due to incomplete mixing (d) The bi-model approach may be the appropriate CMB method when point recharge is a contributing factor. In fact, some of the reviewers reinforced the above points with their own experience, and stated that the conventional CMB always underestimates groundwater recharge when point recharge is present. The editor and Referees provided valuable guidance to improve the manuscript through revisions.

General: The response from the authors to my first round of review comments was verbose and did not address the basic issues of the manuscript. Hence, I provide here additional comments, given that most of the previous ones were refuted or not properly dealt with. In the interests of providing clarity for readers and the authors, only the most fundamental errors in the manuscript are identified, with a scope to writing in the clearest possible manner:

Author Reply: We thank the Referee 1 for providing additional technical comments. By this way, we may be able to provide further clarification, and revise the manuscript where it is needed.

Referee 1_C1. The background literature on the topic of the paper is misrepresented. It is not the case that previous authors discount saturated zone CMB where preferential flow occurs. Only the authors' prior discredited HESSD manuscript attempts this. It is the unsaturated zone CMB that does not apply where unsaturated zone preferential flow occurs. The authors use one method to undermine a different one.

Author Reply: We consider this is an oversight. We thank the Referee 1 for raising this issue so that we can provide further clarification.

We agree that previous authors such as Wood et al (1997) stated that the unsaturated zone CMB does not apply where preferential flow or point recharge occurs. Apart from Somaratne et al (2013) and this manuscript, to the best of our knowledge, no other papers have considered the validity of saturated zone CMB to groundwater basins where point recharge occurs. We highlighted two problems (1) boundary conditions of the conventional CMB are not applicable when point recharge occurs (2) Representative groundwater chloride samples cannot be obtained when point recharge occurs due to mixing. These aspects were thoroughly discussed in detail to our Author Reply to Prof. Warren Wood and are not repeated here.

Please read the document entitled "Why the Conventional CMB Fails in Karst".

Referee 1_C2: The investigation assumes that there is no mixing in either the unsaturated zone or the saturated zone, between preferential flow and diffuse flow. This assumption must be acknowledged. Regardless, it is entirely indefensible to consider this a valid assumption for all systems with preferential flow, because despite unsaturated zone preferential flow, there may be saturated zone mixing of waters originating from diffuse and bypass flows. The no-mixing assumption is most certainly not applicable to Uley South (calcrete capping underlain by sand). The relatively small variations in Cl from dozens of sample sites across this aquifer are testament to that.

Author Reply: Thank you for comments. We highlight the assumption that **'no mixing occurs in either the unsaturated zone or at the watertable plane'.** If there is mixing in the unsaturated zone prior to reaching the watertable plane or mixing at the watertable plane there is no need for a bi-model approach as derived in this paper or bi-model presented in Wood et al (1997). Below is an extract from our reply to Prof. Warren Wood:

"Of course, there is an area of uncertainty if the two streams (point recharge and diffuse recharge) mix well before arriving at the watertable, OR mix well in the watertable. If this happens no distinguishable point or diffuse recharge crosses the watertable plane. Therefore, the recharge flux arriving at the watertable plane may have the chloride concentration as in saturated zone (at least approximately) and the conventional CMB is still applicable. This may apply to the case of point recharge through root channels, burrows, cracks and minor fissures or in large regional aquifers, such as the case reported by

Herczeg et al (2003) where point recharge is 10% of the total recharge in the regional Tatiara catchment (>500 km^2)."

The mixing is considered in the saturated zone and that is why groundwater chloride c_g is expressed within the range: $c_s \leq c_g \leq c_{gd}$..

With regards to the comment on 'calcrete underlain by sand', this is an assumption based on an erroneous conceptual model. Calcrete is limestone formed by the cementation of soil, sand, gravel and shells, by calcium carbonate deposited primarily by evaporation. Apart from the recent coastal monitoring well drilling programmes, all historical investigation/monitoring/production wells have been drilled by the percussion drilling technique. As a result of this drilling process, some of the wells' returned drill cuttings may look like 'unconsolidated sand' due to pulverisation of the calcrete (of cemented sand). Drillers logged these wells as 'sand', but they are carbonaceous sand and subject to dissolution and therefore in general, highly porous flow paths or cavities exist

Referee 1_C3: Equation 10 is in direct contradiction to the conceptual model. Equation 10's Cg is clearly the mixed groundwater Cl concentration, whereas Figure 5 (and much of the case study descriptions) refer to distinct and separate high Cl-low Cl water bodies ("bubbles") that somehow defy dispersion processes. Which case is it - mixing or no mixing in the groundwater?

Author Reply: This is best understood as a gradation between the two extremes of all diffuse to all point recharge. As such there will be a gradation of mixing between these two extremes. As Referee 1 stated, we agree that Cg is the mixed groundwater. The conceptual model is a general presentation and as such not specific to any case studies. For example, see Figure 4, where Cs is directly recharging the groundwater and mixing with ambient groundwater chloride. We have used the words 'fresh water pockets', 'bubbles' and 'plumes' to describe the wide spectrum of chloride values possible between the two end members; that is chloride associated with point recharge and ambient groundwater in the plume. The dispersion process is not ignored.

Referee 1_C4: Eq 10 is wrong. A "flow across the watertable" would need inflows of RuCu + QpCs, and groundwater outflows of (Ru+Qp)Cg. This is not withstanding the lack of lateral groundwater flows here, which is equally problematic for the analysis. There is simply no way that the different water inflows at a point are somehow able to remain isolated as they discharge below the watertable.

Author Reply: The Equation 10 is correct. Firstly please refer to Page 317, Line 21 to Page 318, Line 5. It states:

"This implies that groundwater chloride in the saturated zone is derived only from recharge and that there is no chloride loss from the saturated zone through evapotranspiration. It is also assumed that lateral fluxes, and upward and downward leakages do not result in changes in chloride concentration, and there is no irrigation water recycling or waste water irrigation. Using the above assumptions, groundwater chloride in the saturated zone is determined only by the diffuse and point recharge fluxes crossing the watertable."

Now consider two streams of chloride arriving at the watertable plane. The chloride mass arriving at the watertable plane as a result of diffuse recharge R_u is $(R_u c_u)$. Similarly, chloride mass flux arriving at the watertable plane as a result of point recharge (Q_p) is $Q_p c_s$. Therefore, total chloride mass about to cross the watertable plane is ($(R_u c_u + Q_p c_s)$.

Unless two streams mix at the watertable plane, Ru and Qp crosses the watertable plane with their respective chloride concentration. At the watertable plane (where saturated zone starts), there is no need to use C_u, (which is chloride concentration just above the watertable plane) any more as it has been defined as the C_{gd} (which is basically C_u in the watertable plane). In between, there is no mixing and no chloride loss or gain. Therefore, on reaching the watertable plane unmixed, both point and diffuse recharge fluxes cross the watertable plane still unmixed with total chloride mass of $(R_u c_{gd} + Q_p c_s)$. **No mixing at the watertable plane is an important assumption and we have highlighted this in the revised manuscript**.

The mixing occurs in the saturated zone below the watertable, after penetrating the watertable, driven by lateral flow and solution equilibrium. We agree that different water flows do not remain isolated but rather that mixing occurs giving the broad spectrum of chloride between the two end members. This we have indicated in page 318, line 7 as: $c_s \leq c_g \leq c_{gd}$. .

Referee 1 suggests that groundwater outflows can be expressed by $(R_u + Q_p)\ c_g$. after crossing the watertable plane. To write the above expression, both point recharge and diffuse recharge need to mix at the watertable plane. The above concept, $(R_u + Q_p)\ c_g$, is the fundamental basis of the conventional CMB.

We provide the relevant section from Author Reply to Prof. Wood below:

"Of course, there is an area of uncertainty if the two streams (point recharge and diffuse recharge) mix well before arriving at the watertable, OR mix well in the watertable. If this happens no distinguishable point or diffuse recharge crosses the watertable plane. Therefore, the recharge flux arriving at the watertable plane may have the chloride concentration as in saturated zone (at least approximately) and the conventional CMB is still applicable. This may apply to the case of point recharge through root channels, burrows, cracks and minor fissures or in large regional aquifers, such as the case reported by Herczeg et al (2003) where point recharge is 10% of the total recharge in the regional Tatiara catchment (>500 km^2). "

Referee 1-C5: There is considerable confusion expressed by the authors regarding equation 10. For example, "initial" and "at the end of delta-t" don't apply to a steady-state analysis. They are trying to do a mass balance across a plane (the watertable), and hence the LHS derivative term has no meaning, because a plane has no volume. That is, Cgd = Cu, and the RHS is obviously zero, which one would expect. The inference from equation 10 is that diffuse and point recharge crossing the watertable are somehow able to remain immiscible, and remain in the aquifer with their unsaturated zone concentrations. This is entirely non-physical.

Author Reply: Thank you for the comment. Initial and at the end of delta t was removed from the text. First part of the comments addressed after Referee 1's first round of comments**.**

We do not attempt to obtain mass balance across a plane but rather in the groundwater storage. Any changes to groundwater chloride in the storage occurs only through recharge fluxes crossing the watertable plane. That is why in Equation 10 chloride mass balance was taken as the difference between just before arriving watertable plane and at the watertable plane. As mentioned before, fundamental assumption is the no mixing occurs (between diffuse and point recharge) in the unsaturated zone or at the watertable plane. Apart from chloride associated with recharge fluxes, nothing else can change the chloride mass in storage (What we have stated in the manuscript is: "groundwater chloride in the saturated zone is determined only by the diffuse and point recharge fluxes crossing the watertable).

Referee 1-C6: Regardless of point 5. above, equation 10 is not needed to continue through the authors' mathematics. Equation 11 is simply PCp+D = RuCgd + QpCs (Equation R1) and does not require Eq. 10 as suggested. Hence, despite what the authors say, there is no groundwater mass balance included in their investigation. It is misleading to suggest this. To obtain Eq. 11, they simply drop the Qo term from eq. 9.

Author Reply: This is the authors' earliest approach and a short cut. Equation (9) contains C_u and the Equation 11 contains C_{gd} . The relation of c_u=c_{gd} from Equation 10 is necessary to highlight all the related assumptions, particularly **No Mixing of Two Streams (point and diffuse recharge) at the Watertable plane.** With respect to dropping Q_o, it is stated that: "for closed basins where Q_o=0." (see page 318 Line 14).

Referee 1-C7: Following from this, equation R1 above is rearranged to Ru=(PCp+D – QpCs)/Cgd (Equation R2), which requires that the Cgd or Cu (which are the same) be known – i.e. that the Cl in the unsaturated zone immediately above the watertable is characterised. Hence, the once-simply and elegant saturated-zone CMB method now requires un- saturated zone measurements, not to mention some estimate of Qp (point recharge). Equation 13c is then simply the RHS of equation R2 plus Qp.

Author Reply: We highly appreciate Referee 1's great interest and enthusiasm with respect the Equations and CMB method. The very advantage of having C_u or C_{gd} in the equation with Q_p is explained below, taking relevant sections from our reply to Prof. Wood.

As mentioned in the Somaratne et al (2013) manuscript (Hydrological functions of sinkholes...), one of the main disadvantage of applying conventional CMB to point recharge dominant groundwater basins is the difficulty of getting representative groundwater chloride.

1. When groundwater compartment (mixing) occurs, it is not possible to obtain representative samples due to a wide spectrum of chloride values that are possible between two end members; that is chloride associated with point recharge and ambient groundwater in the plume. This is similar to Aquifer Storage and Recovery (ASR) wells, where different concentrations of groundwater chloride exist, radiating from the point of recharge location outwards to ambient groundwater chloride concentrations. This is true no matter how small or large the volume of point recharge is. For example in Fig. 4 (see page 331), groundwater chloride for a drainage well (which is point recharge source) is (21.1 ± 21.6 mg/L) and for a monitoring well, (which is a sampling point) is (63 ±26 mg/L). In the Poocher Swamp fresh water lens, the surface water chloride concentration is 28 mg/L in the Swamp, 40 mg/L in nearby wells, and outside the lens in the diffuse recharge zone the chloride concentration is greater than 550 mg/L. When such extreme variation in groundwater chloride occurs due to extreme point recharge, the very definition of 'representative samples' becomes questionable. Even if one increased the sampling density, in the hope of getting average chloride values, it could still grossly underestimate the recharge.

2. In real world situations, when the aquifer is not fully mixed there are difficulties in obtaining average representative chloride samples from heterogeneous (karstic aquifers). We have shown in an earlier manuscript, doi:10.5194/hessd-10-11423-2013 (Hydrological functions of sinkholes..), that it is not possible to measure representative samples due to the unknown extent of both the plume and the spread of conduits. We have shown using salinity profiles that low salinity freshly recharged water from point sources move at varying depths in the Blue Lake capture zone, Mount Gambier. We have cited an example from Herczeg et al (1997) in their study on Poocher Swamp sinkhole recharge. Herczeg et al (1997) established three monitoring wells at 10 m, 50 m and 150 m down-gradient of the two sinkholes to study the water level behaviour during recharge. The first two (shallow) wells terminated at 6 m below water level, and the third well (at 150 m) terminated at 50 m depth and about 35 m below the water level. The maximum water level rise was observed at the well 150 m from the sinkhole indicating a direct sub-surface connectivity to the sinkhole.

3. An attractive feature of the generalized CMB equation is that it is not necessary measure groundwater chloride (c_g or Cl_{gw} in Wood, 1999) as it is not required in the equation. Instead generalized CMB uses only c_{gd} (OR C_{uz} in Wood, 1999) which can be obtained from soil water extraction described above or measuring diffuse zone chloride concentrations. Therefore, uncertainty associated with extreme variability of groundwater chloride concentrations due to extreme point recharge is not affected on calculated recharge (see page 319, Eq. 13c).

   Please read the document entitled “Why the Conventional CMB Fails in Karst”.

Referee 1-C8: The approximation to produce eq. 13d from eq. 13c is both unnecessary and has important implications. It assumes that all the Cl load to the aquifer occurs via diffuse flow, despite preferential flow occurring. That is, it is eliminating the QpCs term from the mass balance RuCgd = PCp+D – QpCs. Note that, despite what is suggested by the authors, eq. 13d and eq. 3 are not the same, because firstly eq. 3 is a water balance and eq. 13d is a salt balance, but also one would assume that an extension to eq. 3 would involve properly diverting salt into its constituent pathways. Dropping QpCs from the mass balance will have only small implications in some cases only.

Author Reply: This is a gross misunderstanding and misreading of the equation. The simplification means the RHS second term (Q_p) is mathematically correct. Please re-read the Page 319, Lines 8-13.

Please note that the Equation 13d is also a water balance, derived from chloride mass balance. In Equation 13 d, R is the total recharge (not the Total Salt) as in Q_{tb} in Equation 3; the first term of the RHS is the diffuse recharge estimated using unsaturated zone CMB using c_{gd} (which is c_u) and equivalent to Q_{ib} (which is also estimated using unsaturated CMB using C_u), and the second term Q_p is point recharge in 13d) is equivalent to Q_{mb} (which is recharge through macropore in Equation 3). Please re-read the Page 319, Lines 12-13. Units are given in brackets.

Referee 1_C9: Notwithstanding the problems with the theoretical development and the conceptual model, plus the misrepresentation of previous literature, arguably the most important errors are introduced into the manuscript by the manner of applying equation 13d. The problem here is two-fold.

Firstly, runoff Cl is not known - it is likely higher than rainfall Cl. Secondly, Somaratne et al. do not know Cgd - especially for Uley South, but probably this is almost impossible or prohibitively expensive to properly characterise in most systems. The average of monitoring wells near the inland boundary is certainly not adequate. For the case of Uley South, limestone aquifers occur to the north of the inland boundary, across which there is inflow from these. Hence, the Cgd used by Somaratne and Smettem is a value that reflects preferential and diffuse flows into other aquifers, and in no way will reflect diffuse flow only. By using this lower value, they are grossly over-estimating "diffuse recharge" - by their definition of this process.

Author Reply: We agree that runoff chloride is not known in Uley South. However, in Uley South runoff is short lived and there is less opportunity for enrichment via evapotranspiration processes. Therefore C_{p+D} , which contains rainfall chloride and chloride from dry deposition, obtained from Hutton's (1976) equation was used.

With regards to C_{gd} in Uley South, please note that groundwater flow direction is from north-east to south-west (coast line). Limestone outside the landward boundary is dry and therefore no through flow enters the basin via limestone. Selected monitoring wells are completed only in the Limestone aquifer and therefore with no mixing of Tertiary Clay or Teriary Sand waters. The groundwater chloride of these wells are therefore derived only from diffuse recharge.

We acknowledge the disadvantages of not having soil cores, as the percussion drilling had been the technique that had been used. Selected wells are in high ground, as they are in the periphery of the basin. The basin's lowest depth to water occurs at the central part (10-12 m) and all around the basin, depth to water is much higher (20 m>).

Referee 1_C10: In no way should gross basin-scale runoff estimates, intended for other applications, be used to calculate Qp. The southeast of South Australia is littered with wetlands that are underlain by clay, and serve to contain runoff much of which eventually evaporates. Even the layered nature of Uley South sediments will act to retain, mix and diffuse runoff infiltration.

Author Reply: This is not directly relevant to the content of the paper. However, we offer the following information. There are a plethora of surface water models available nowadays, both event based and continuous rainfall runoff process. Current surface water quantification models range from simple Rational Formula to fully process based St Venant equations (such as in MIKE-SHE), and there is no issue in quantifying runoff. Their choice is a matter of time and how much money one would like to spend. Wood et al (1997) used a runoff model to quantify recharge.

Referee 1_C11: Combining the over-estimate of diffuse recharge, and the over-estimate of preferential recharge (i.e. making the assumption that all runoff becomes recharge and neglecting any surface retention, unsaturated zone perching, the evaporation of smaller rainfall events, etc), can only lead to the highest possible estimate of recharge by the authors, at least for the Uley South case. Whereas other authors prefer to offer plausible ranges, using various methods, the current paper is producing an upper bound and a single value. The biased nature of this research cannot be understated. It is especially worrying that the research described here might influence management practices, to the commercial benefit (at least in the short term; notwithstanding the collapse of other basins on the Eyre Peninsula due to over-estimation of recharge and over-extraction) of the lead author's organisation.

Author Reply: After replying to Referee 1's first round of comments, we have decided not to answer any comments based on perceptions, opinion or any allegations etc. Please refer to Author Reply to Referee 2 for our response on this matter.

Referee 1_C12: It is worth considering some additional evidence in regards to the basic claim by the authors that Uley South recharge ought to be doubled. Uley South has been pumped at rates between about 4 and 7 GL/yr in the recent decade or so. Across the area of the basin (113 km2), this is the same as 35 to 62 mm/year of outflow. Despite claims to the contrary, the groundwater storage has most certainly declined (from 1970s to early 2000's - see attached figure from an honours thesis by D. Alcoe showing the average watertable response from several observation wells), then stabilised, and then shown signs of recovery (after 2010), and these stages correspond to periods of higher pumping and then reduced pumping. At its lowest, the water levels in Uley South were marginally higher near the coast to density-corrected sea level, and hence if we consider that discharge to the sea at that time was perhaps small, it seems unreasonable to accept a recharge estimate of 120 mm/year (i.e. twice the high-pumping rate during a period of watertable decline) across the basin, in this semi-arid environment and considering the significant proportion of this uninhabited basin that is thick with vegetation cover. It simply doesn't add up. We can at least infer that recharge has exceeded the lower pumping rate of 35 mm/year, given evidence of watertable recovery.

Author Reply: These comments do not directly relate to the paper being reviewed and should be directed to the South Australian Department of Environment, Water and Natural Resources, who administer the Natural Resources Management Act 2004.

Referee 1_C13:. The ability to correctly apply this method is essentially precluded by the need for separate preferential flow (from the total recharge) and a characterisation of lower unsaturated zone Cl concentrations. This is complexifying the CMB (saturated zone) approach, which otherwise integrates catchment processes. Ultimately, any groundwater Cl concentration is likely to represent the historical recharge of a particular sample, and adding runoff to recharge that is derived from a groundwater Cl value is simply violating mass balance and creating water.

Author Reply: The aim of our paper is to improve the utility of a widely used recharge calculation method to include areas that it currently fails to adequately cater for. The basis of this is the soundness of the basic CMB method and its relative ease of determination. It is hoped that through our suggested amendments the method will continue to find favour with practitioners in point recharge dominated scenarios. Please read the document "Why the Conventional CMB Fails in Karst" .

Referee 1_C14:. I wish to thank the authors for their suggestion to contact Dr Werner at Flinders University. This produced a significant number of useful documents and references, which informed significantly the current review.

Lead Author Reply: Thank you very much for letting me know.