Author Reply to Referee 3 Comments

Hydrological functions of sinkholes and characteristics of point recharge in groundwater basins

By N. Somaratne, K. Smettem, J. Lawson, K. Nguyen, and J. Frizenschaf

The authors would like to thank Referee 3 for his/her insightful comments. They clearly highlight the need for a major revision, restructuring the manuscript and additional transparency and explanatory text to guide the reader through the logical thought process. We hope that the following explanations will help clarify the underpinning thought process of the revised manuscript. The corresponding replies are listed as follows:

Referee 3-1: In this study, water isotopes and major ions are used to characterise the hydrological characteristics of point recharge at three karst aquifers in Australia. In addition, chloride measurements in the groundwater and the chloride mass balance method (CMB) are tested for their adequateness at the three locations. The authors conclude that the system shows strong effects of karstification and that the CMB method is difficult to apply under such conditions.

Author Reply 3-1: Agree

Referee 3-2: But it is difficult to understand how the authors came to these conclusions. The paper is written in a unstructured way and a lot of information is missing or appears too late at wrong locations in the manuscript. In more detail:

3-2-1 The introduction provides no state of the art about karst system characterization, karst recharge and the CMB method.

Author Reply 3-2-1: Agree and revised the manuscript to include brief description of karst system characterization and limitation of CMB method citing references. Basic premise of the CMB method is given as follows: "*One of the inherent problem of the presence of karstic features such as sinkholes on hydrological functions may be recharge estimation using conventional chloride mass balance (CMB) method. The fundamental basis of conventional CMB method is that recharge mass flux crossing the watertable plane can be calculated if (Wood, 1999; Gee et al. 2005):*

- *Chloride in the groundwater originates from precipitation directly on the aquifer, and no unmeasured runoff occurs,*
- *Steady influx of water and chloride,*
- *Chloride is conservative in the system and 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 basic premise of the conventional CMB method is violated".

3-2-2 The methodology section focuses on a detailed but unsystematic description of the study sites. Only few lines explain some of the methods.

Author Reply 3-2-2: We agree with the comment and methodology section completely revised. The methodology now includes: Groundwater sampling method (micro-sampling and grab sampling), salinity profiling using sonding technique and, classification of groundwater using piper diagram. In addition, description of point recharge estimates and calculation of recharge using conventional CMB method is in the methodology section. Revised methodology is in two pages. Methodology section in restructured manuscript is as follows:

Abstract
1. Introduction
2. Description of the study basins
   2.1 Uley South basin
   2.2 Mount Gambier Blue lake capture zone
   2.3 Poocher Swamp fresh water bubble
3. Methods
   3.1 Point recharge estimates
   3.2 Recharge calculation by the conventional CMB method
4. Results and Discussion
   4.1 Characteristics of point recharge-chloride to $\delta^{18}O$ relation
   4.2 Groundwater mixing zones
   4.3 Comparison of point recharge to conventional CMB estimated recharge and chloride distributions in diffuse and point recharge dominant zones
5. Conclusion

3-2-3 In the results and discussion section the reader confronted with a mixture of methodology, results from methods that were not explained before, and conclusions that are not based on the previous findings.

Author Reply 3-2-3: Major revision was undertaken and restructured the manuscript as described in Author Reply 3-2-2 above. Site description, Methodology and Results and Discussion are separated from each other but bridging sentences are included to direct the reader.

Referee 3's statement on "conclusions that are not based on the previous findings" is more a result of the paper organisation / structure problem rather than data and results. We thank the referee for raising this issue. If the above referee's statement is based on Specific Comments (7), (17) etc., we have clarified these (see replies to (7) and (17) below) providing data and results of our analysis. In the revised manuscript, the reader is directed to these data with additional explanatory notes.

3-2-4 Only a short section "recharge" finally focuses on the recharge processes and point recharge. This section is too short and repeats again study area, methods, and the mixture of results discussion and conclusions with the same problems as mentioned above.

Author Reply 3- 2-4: Agree and manuscript completely revised. More bridging sentences are added to guide the reader through results. New section "Comparison of point recharge to conventional CMB estimated recharge and chloride distributions in diffuse and point recharge dominant zones" covers two pages.

Referee 3-3: In my opinion the analysis in the form it is presented does not support the conclusions, i.e. there is no conclusive picture about the functions of sinkholes and the characteristics of point recharge. In this form the manuscript is not adequate for publication in HESS. To reach the required level analysis, figures, tables, and finally the manuscript structure need strong improvements, which unfortunately fall beyond major revision.

Author Reply 3: It appears that the Referee 3's decision on: "the analysis in the form it is presented does not support the conclusions, i.e. there is no conclusive picture about the functions of sinkholes and the characteristics of point recharge" based mainly on the structure of the paper but not the scientific rigour or analysis. We thank the Referee 3 for his helpful comments, and we acknowledge that there a major revision is required. For example, in the revised manuscript, we direct the reader to data source and basic assumptions of conventional CMB method as given below:

Revisions are highlighted.

"Results are summarised to four influencing factors affecting the validity of conventional CMB method:

1. In diffuse recharge zones, recharge water is aerially distributed across the surface of watertable and the chloride concentration in recharge water is in equilibrium with the groundwater. No contrasting chloride data was found in the diffuse recharge zones (Fig. 1, 2 and 3) in adjacent monitoring wells. This is because when the recharge flux moving through unsaturated zone, it is subjected to evapotranspiration process enriching the chloride concentration. The degree of enrichment of chloride varies, depending on strata type (granular porosity) and variation, depth to watertable, vegetation type and rooting depths. In this case the basic assumption that recharge flux crossing the watertable plane is in equilibrium with ambient groundwater chloride is valid.

2. In contrast to point 1, for point recharge sources, the chloride concentration in recharge water remains at, or close to that of surface runoff and hence is not at equilibrium with ambient groundwater chloride concentration. This is clearly seen in Fig. 4 (b) and Fig. 4c, chloride vs δ^{18}O plots. In Fig. 4b, the recharging water remains at surface water concentration but with slight mixing with groundwater (chloride concentration of 12-27 mg L^{-1}), which is not in equilibrium with ambient groundwater chloride or diffuse recharge chloride concentration of > 62 mg L^{-1} (Fig. 4b and Table 1). In this case basic assumption that recharge flux crossing the watertable plane is in equilibrium with ambient groundwater chloride is invalid. It is easy to intersect groundwater within granular porosity to get representative samples but not in karstic systems.

3. Preferential flow paths exist as evidenced from Fig. 7 (BLA 164) and Fig. 8, leading to lower salinity zones of water found deeper in the aquifer. This is due to the existence of a preferential pathway carrying point recharge source water. This observation is consistent with Herzeg et al. (1997) observation. Point recharge through sinkholes or drainage wells spreads through interconnected conduits with mixing occurring throughout the flow paths. The degree of heterogeneity and the extent of the network of conduits are usually unknown. It is therefore very difficult to intersect groundwater within conduit; generally not possible to get a representative average, or weighted average of chloride samples by measurement.

4. Average annual volume of point recharge is much smaller than the typical aquifer storage volume. For example, when volumes expressed in depths, point recharge (0.075 m) to saturated thickness (15 m) ratio for Uley South is 0.005, for Mount Gambier Blue Lake capture zone is 0.0065, and Poocher Swamp fresh water bubble is 0.0022. Therefore, surface runoff with low concentrations of chloride reaching groundwater is insufficient to cause noticeable changes in chloride concentrations due to mixing, unless a large volume of recharge takes place at a single location as in the Poocher Swamp fresh water bubble.

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Referee 3: Please find below some comments that might help to conduct the necessary improvements.

Specific comments:

1. P11424L12: “diluted”, in this context I rather expect “enriched”. Please correct or clarify.

Author Reply: Agree and revised.

2. P11424L25: The duality of karst hydrological processes does not stop with recharge; it also appears in the phreatic zone and at the karst springs.

Author Reply: Agree and revised as’ distinct recharge feature of the karst systems’, (paper is focus on recharge rather than other features of karst systems).

3. P11424L19-P11425L26: The introduction misses a link to the current state of the art in the relevant fields (karst system characterization and recharge assessment). Consequently the research questions and the scope of this study are not clear.

Author Reply: Agree and added the following section: **“***In characterizing properties of a karst aquifer, it is therefore important to determine how the data obtained by a particular test method are influenced by the fast-flow regime, slow-flow regime, or both. Quantitative water tracing tests, conducted with fluorecent 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).*

4.P11426L9-13: This is actually the only part of the methods that describes the methodology (with only 5 lines obviously too short). The rest of the section is rather a study site description. There is no description about the methods that will be used and the date that will support the analysis.

Author Reply: Agree and completely revised the manuscript as follows:

Section 2. Description of study groundwater basins

Section 3. Method (include method employed in groundwater sampling (low-flow and grab sampling), , salinity profiling, analysis and presentation of water type using piper diagram).

Section 3.1 Point recharge estimates

Section 3.2 Recharge calculation by conventional CMB method.

5. P11426L14-P11428L22: The description of the study sites is too detailed and not systematic. I recommend providing a table that shows the important characteristics of the three basins, the available data, and their sources, and shorten the text strongly.

Author Reply: We acknowledge the referee’s point that a lot of local hydrological information is presented in the study areas. This was done to provide the reader with an overview of the complexity of the areas that are subject to recharge assessments. No changes were made to the text

6. Figs. 1-3: The three figures of the study sites show different types of information, which makes their comparison very difficult. In addition, a lot of information is shown, that is not relevant for the study. Please simplify and unify.

Author Reply: It was our intent to only display in the figures the most significant elements discussed in the paper, namely the location and spatial distribution of measurement sites relative to sinkholes or drainage wells, as they are essential to later illustrate how they feature in the validity tests for conventional CMB method.

However, roads (Uley South) and streets (Mount Gambier) layers were removed.

7. P11429L3-10: This general information does not belong here since it has only little relation to the results (as does the link to Fig 4a at this location).

Author Reply: This is a vital information to hold (or not) that conventional CMB method is valid (or not). For conventional CMB method to be valid, chloride concentration in recharge flux crossing the watertable plane needs to be equal to ambient groundwater chloride concentrations (recharging water undergoes evapotranspiration process and hence enriched in chloride). This is a basic assumption inherent in the conventional CMB method.

What the Figure 4b, and 4c show is that unless we take samples at the recharging point (4b-drainage wells) or near recharge source (4c-Poocher Swamp), we cannot fill the gap in chloride concentration between rainfall and groundwater. In Fig. 4a, it is not possible to obtain representative samples because the small catchment (about 0.07 km^2) recharging through sinkholes is insufficient to generate large plumes that extend to monitoring points.

No changes were made to the text.

8. P11429L16-P11430L6: These two paragraphs appear rather like conclusions. In addition, the methods that brought their findings are not explained in the methods section.

Author Reply: The method section contains "Hydrological functions of sinkholes and characteristics of point recharge were assessed using chloride vs $\delta^{18}O$ relation", Only results are presented and discussed in this section. The sentence ('Therefore, a gap between groundwater and rainwater chloride data points in the chloride vs $\delta^{18}O$ plot, is not necessarily an indication that sinkholes are not directly recharging the aquifer) is moved to the Conclusion section.

9. P11430L8-20: The use of major ions and piper diagrams was nowhere mentioned in the methods section. Therefore, the results presented here are hardly understandable.

Author Reply: Agree with this comment. Method section completely revised (separating description of study basin) and expanded to include groundwater sampling for major ion chemistry and presentation of water types using the Piper Diagram.

10. Fig 5: Without any elaborations about the choice of the different wells for this analysis, the figure is difficult to understand.

Author Reply: Location of wells is given in Fig. 3. The choice of the wells from Poocher Swamp to (WRG 34 and WRG 35) to ambient groundwater well WRG 110 is along the flow direction. However, for further clarity, the relevant section of the paper revised as follows:

“The results of chemical analyses of groundwater in the fresh water bubble and the surface water samples taken from Tatiara Creek and Poocher Swamp, and groundwater samples taken from at monitoring wells WRG 34 and WRG 35 located adjacent to Poocher Swamp, town water supply wells, and monitoring well located outside the fresh water bubble are shown in the Piper diagram (Fig. 5).”

11. Fig 6: Just for mentioning two values of EC, it is not worth to show an entire figure. Please remove and provide information in the text.

Author Reply: Agree and deleted.

12. P11431L1-11: See comment 9; method not explained, results hardly understand able.

Author Reply: The Method section is revised to include how the salinity profiles were obtained by sonding. Generally, low salinity water (low in density) floats above high salinity water (high in density). Therefore, when diffuse recharge is governing the recharge process, freshly recharged low salinity water remains at or near the watertable. However, what the salinity profiles show is the contrary. A lower salinity zone of water found deeper in the aquifer in some of the aquifer monitoring wells as well as drainage wells (point recharge source). This is due to the existence of a preferential pathway carrying point recharge source water.

13. P11431L11: This would be the place for a discussion.

Author Reply: The whole section is now in Results and Discussion.

14. P11431L14- P11432L14: Repetition/study site description. This does certainly not belong here. In addition, no word about the determination of recharge was found in the methods sections.

Author Reply: Disagree with this comment. This is not a description of study sites, rather description of how the point recharge was estimated at each site. Three different methods were used for three basins. It is difficult to write the point recharge estimation method at each basin, without mentioning the ‘basin name’. Description is shifted to Method section (Section 3.1) in the revised manuscript. Only results (estimated point recharge are presented in the revised Results and Discussion.

15. P11432L15-18: It is not clear, what was done by the authors of this study and what was done in previous studies.

Author Reply: It was assumed total flow recharge through the two sinkholes in the Poocher Swamp, and hence average flow was taken.

16. P11432L21- P11433L8: This belongs to the methodology section.

Author Reply: Agree that part of the section, where the diffuse source chloride samples were taken belong to the methodology. This is added to groundwater sampling method. Authors consider the remainder of this section as part of the Results and Discussion. This is because results are also discussed here.

17. P11433L9-L27: These points, as well as the figure 9, appear like hypotheses about the characteristics of the systems. But the very little results presented here and before, and the difficulties in understanding them because of the majorly missing methodological explanations, do not support much conclusions about their validity or falseness.

Author Reply: This is an oversight and perhaps requires elaboration in the text. The results leading to each conclusions are described under each point below. The revised manuscript directs the reader to these results as given below:

"Results are summarised to four influencing factors affecting the validity of conventional CMB method:

1. In diffuse recharge zones, recharge water is aerially distributed across the surface of watertable and the chloride concentration in recharge water is in equilibrium with the groundwater. No contrasting chloride data was found in the diffuse recharge zones (Fig. 1, 2 and 3) in adjacent monitoring wells. This is because when the recharge flux moving through unsaturated zone, it is subjected to evapotranspiration process enriching the chloride concentration. The degree of enrichment of chloride varies, depending on strata type (granular porosity) and variation, depth to watertable, vegetation type and rooting depths. In this case the basic assumption that recharge flux crossing the watertable plane is in equilibrium with ambient groundwater chloride is valid.

2. In contrast to point 1, for point recharge sources, the chloride concentration in recharge water remains at, or close to that of surface runoff and hence is not at equilibrium with ambient groundwater chloride concentration. This is clearly seen in Fig. 4 (b) and Fig. 4c, chloride vs δ^{18}O plots. In Fig. 4b, the recharging water remains at surface water concentration but with slight mixing with groundwater (chloride concentration of 12-27 mg L^{-1}), which is not in equilibrium with ambient groundwater chloride or diffuse recharge chloride concentration of > 62 mg L^{-1} (Fig. 4b and Table 1). In this case basic assumption that recharge flux crossing the watertable plane is in equilibrium with ambient groundwater chloride is invalid. It is easy to intersect groundwater within granular porosity to get representative samples but not in karstic systems.

3. Preferential flow paths exist as evidenced from Fig. 7 (BLA 164) and Fig. 8, leading to lower salinity zones of water found deeper in the aquifer. This is due to the existence of a preferential pathway carrying point recharge source water. This observation is consistent with Herzeg et al. (1997) observation. Point recharge through sinkholes or drainage wells spreads through interconnected conduits with

mixing occurring throughout the flow paths. The degree of heterogeneity and the extent of the network of conduits are usually unknown. It is therefore very difficult to intersect groundwater within conduit; generally not possible to get a representative average, or weighted average of chloride samples by measurement.

4. Average annual volume of point recharge is much smaller than the typical aquifer storage volume. For example, when volumes expressed in depths, point recharge (0.075 m) to saturated thickness (15 m) ratio for Uley South is 0.005, for Mount Gambier Blue Lake capture zone is 0.0065, and Poocher Swamp fresh water bubble is 0.0022. Therefore, surface runoff with low concentrations of chloride reaching groundwater is insufficient to cause noticeable changes in chloride concentrations due to mixing, unless a large volume of recharge takes place at a single location as in the Poocher Swamp fresh water bubble."

Figure 9, was the culmination of above results.

Additional Information:
Aquifer storage volume is proportional to the saturated thickness of the aquifer (given in the Description of study basin). Therefore, recharge and aquifer storage volume is expressed in terms of depth and compared in the table below.

Basin	Point Recharge (m)	Saturated thickness (m)	Ration of Point Recharge/Saturated thickness
Uley South	0.075	15	0.005
Mount Gambier capture zone	0.390	60	0.0065
Poocher Swamp	0.125	55	0.0022

Despite the Poocher Swamp having the lowest ratio, it also has the only measurable plume, due to relative concentration of the point recharge (2.5 GL/year). Had there been a case, total point recharge volumes of 8.5 GL/ year in Uley South and 6.6 GL/year in Mount Gambier capture zone recharge through one or two sinkholes (instead of hundreds of sinkholes and drainage wells) there would be large measurable plumes developed.

18. P11434L1-11: This belongs to the methods section.

Author Reply: Agree and shifted to Methods Section in the revised manuscript.

19. P11434L12-24: Again, too little mentioning of results.

Author Reply: Completely revised and discussed in four pages.

20. P11435L2-6: This is well known and has not to be mentioned in the conclusions of a research paper.

Author Reply: Authors agree that this conclusion is not new and well known to the expert in karst hydrogeology. The purpose of inclusion of this sentence is to show to readers that the approach we have taken and results that are presented is consistent with previous work conducted elsewhere and hence to demonstrate that this is not a local issue.

21. P11435L10-20: Like many parts of the manuscript the conclusions do not clearly relate to the rest of the text. In my opinion the analysis, in the way it is presented here, does not support them.

Author Reply: Authors trust that reasons leading to this comment are resolved, particularly in (7), (9) and (17) above.

Technical comments:

1. P11424L2-3: Please rephrase

Author Reply: revised.

2. P11425L1-24: There is no relation between these sentences, which makes them difficult to read.

Author Reply: Bridging sentences were added throughout.

3. P11426L10: change “Vs” to “vs”.
Author Reply: Agree and corrected.