Author Reply to Short Comments by Dr. A. Werner

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 Dr. Adrian Werner for the comments. The corresponding replies are listed as follows:

SC 1: The manuscript by Somaratne et al. reviews data from three field cases and then attempts to offer an interpretation regarding the role of sinkholes versus diffuse recharge in aquifers overlain by sinkholes or point recharge features. The manuscript lacks the usual elements of scientific presentation and logical argument, and seems to be compiling conclusions that are not sufficiently supported by evidence or citation. Much of the manuscript is dedicated to the complexities of flows in karst aquifers, but the focus of the paper is on recharge pathways (unsaturated zone processes), and this presents as a mismatch between the research objective and the assertions that are offered based on literature review.

Author Reply 1: We would like to highlight that one of the contributions of this paper is the presentation of evidence to support the initial argument and supports the conclusions drawn from the study. This is provided through a body of data including stable isotope and chloride measurements as well as salinity profiling. We acknowledge that, at first sight, the paper may appear inconsistent with approaches in journal publications, we have tailored our literature review around the key elements that 'set the context' of the argument, primarily the complexities of flow in karst and to describe other works that have been undertaken that facilitates this paper. Non-homogeneity in karst system is well known to hydrogeologists experience with such aquifers. The purpose of inclusion is to show that our study findings are in line with other similar works. However, whilst there is a significant body of literature available addressing the complexity of karst hydrogeology (some of which is presented here), no literature can be found addressing theoretical issues in relation to the use of the conventional CMB method in point-discharge dominated aquifers.

However, we thank Dr. Werner, and have revised the manuscript to include the following: "*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,*

The problem arises with the maintaining above assumptions because different recharge processes may operate simultaneously, such as 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.*

We critically examined the validity of 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 chloride mass balance (CMB) method, and compare this to point recharge estimates."

The focus of the study is not, as suggested in Dr. Werner's comments, the unsaturated zone recharge processes and pathways. The focus is provided in the title (...functions of sinkholes and characteristics of point recharge...) and is given above. As mentioned above, to the best of our knowledge, no similar studies (testing the validity of conventional CMB method in point recharge dominant groundwater basins), have been published. This paper aims to fill this knowledge gap with comparative data from different karstic groundwater basins.

SC 2: The major emphasis on the complex nature of karst aquifers is also found to contradict the later notions of the manuscript, which purports that seemingly stable freshwater bubbles reside in the vicinity of point infiltration in karst aquifers, when such a notion seems highly unlikely under conditions of strong heterogeneity, and high temporal variability, where preferential flow paths are surely more likely to dissipate small freshwater bubbles to downgradient areas once recharge stops.

Author Reply 2: We would like to clarify the notions of heterogeneity and the existence of freshwater bubbles, in light of Dr. Werner's comment of an apparent contradiction.

Whilst it could be perceived as such, and although suggested by Dr. Werner, we do not specifically state in the paper that 'seemingly **stable** fresh water bubble reside in the vicinity of point infiltration in karst aquifer'. We admit that the sentence "*In Poocher Swamp, recharge from a large volume of creek water concentrates into two sinkholes resulting in formation of a fresh water bubble"* could be misinterpreted to also imply steady state in a heterogeneic system, but it is a matter of scale

In the first instance, we acknowledged that strong heterogeneity exists, eg. on page 11431, line 8-11: "*Overall, these results show* ***that non-homogeneity exists at point recharge sources (drainage wells), aquifer monitoring wells, within conduits (e.g. Engelbrecht Cave) and along the flow paths*** *themselves, even though the groundwater system is* ***under steady-state in terms of salinity and chloride mass****."* Here we acknowledge the existence of non-homogeneity near point recharge sources, but state that **overall in the aquifer salinity is stable with time**. The phrase *'groundwater system is under steady-state* ***in terms of salinity and chloride mass***' should not be misinterpreted as a confirmation of the existence of **stable** fresh water pockets or bubbles. This steady-state condition is brought to light in order to show that the aquifer system can be in a steady-state in terms of **salinity and chloride** (hence, that no long-term increasing or decreasing trends are observed) despite the presence of strong heterogeneity at point recharge sources. This is the case of all three study basins.

In Page 11433, dot point 2, it is stated that "*Point recharge through sinkholes or drainage wells spreads through interconnected conduits with mixing occurring throughout the flow paths*."

We have also written in the conclusion, page 11435, line 8-10 : Even though diffusion and **dispersive mixing continues over time, non-homogeneity exists at point recharge sources and along flow paths".**

SC 3: In the case of the extremely transmissive and heavily pumped Uley South aquifer, small groundwater mounds that might occur under any major recharge point sources, during the wet season, would surely spread and disperse with the ambient groundwater during the extended dry season (which coincide with periods of highest pumping). In any case, the notion of stable freshwater bubbles in Uley South is not defended with field data obtained by the authors. Rather, it is more likely that the transient nature of that particular system would lead to break-down of any freshwater bubbles and mixing due to the extensive pumping network and the high seasonality of rainfall.

Author Reply 3: We agree with Dr. Werner that any localised recharge mound would spread out with time. The important points here is the non-homogeneity caused by groundwater mound (small or large). As stated in Author Reply 2, there is no mention in the paper that 'seemingly **stable** fresh water bubbles reside in the vicinity of point infiltration in karst aquifer' in the paper. What we have stated is fresh water pockets exist at point recharge locations. This we have shown through measurements of salinity and chloride. We re-iterate that they are not stable. This we have stated in Author Reply 2.

SC 4: The manuscript also requires additional evidence to defend the notions offered relating to recharge processes in the systems under investigation. Statements about recharge processes in each basin are offered prior to the presentation of data, and hence it reads that these are predefined notions and not interpretations arising from field data and previous investigation.

Author Reply 4: The authors confirm that statements about some primary, well known, recharge processes in each basin are being offered early in the paper, with no specific data presented to underpin these. The reason for this is twofold:

1. Recharge through two sinkholes in the Poocher Swamp, and recharge through 3 sinkholes and 400 drainage wells within the Mount Gambier Blue Lake capture zones has been well known ever since they were first investigated. More over farmers in Tatiara catchment knows where the fresh water pockets occurs (there are hundreds of them, largest being the Poocher Swamp fresh water bubble) as they have seen recharging through sinkholes in their paddocks as given in the Figure 1 below, and their irrigation wells have intercepted fresh water zones down-gradient to sinkholes (locally called runway holes). In fact this original common knowledge drove the initial development of the groundwater resource in this area. The authors did not consider it is essential to present evidence for this known process in this paper. With regards to Uley South recharge through sinkholes, we have cited 3 references to support recharge process in Page 11426, line 27-page 11427, line 1-2.
2. However, additional data was needed to address the specific objective of this study, in particular to determine the characteristics of point recharge (such as that indicated by Chloride vs $\delta^{18}O$ relationships, chloride distribution and salinity profiles), and to test the applicability of the conventional CMB method to estimate recharge. We provided the objective statement early in the paper and presented underpinning data to support it.

Figure 1. Recharging through the Scowns Runway Hole- Tatiara Catchment

(Photo: George Mackenzie, Department for Environment, Water, and Natural Resources, Naracoorte)

SC 4.1: There are also clear signs that previous literature has not been properly explored, and in some cases, the findings of previous literature are incorrectly cited. For example, Ordens et al. does not suggest that sinkholes are a minor component of recharge to the system, but rather, they suggest that sinkholes re-distribute surface water more so into the unsaturated zone rather than transporting surface water directly to the watertable. Time lags in water table responses to recharge plus other evidence point to this conclusion.

Author Reply 4.1:

What we have stated in page 11435, line 6-8 is: "*This study suggests that the presence of a gap between groundwater and rainwater chloride in the chloride Vs $\delta^{18}O$ plot, is not necessarily indicative of sinkholes* ***not directly recharging the aquifer***." The missing word in Dr. Werner's comment '**Not directly recharging**' is important here.

We provide an extract from Ordens et al. (2012) below:
"*The absence of intermediate data points between the rainfall and groundwater data points in Fig. 5 is* ***interpreted to reflect the fact that any rainfall that results in recharge first undergoes either or both of these processes (complete evaporation and transpiration) before reaching the water table*** *(or the screens of the monitoring wells). Most recharge occurs in winter, as can be inferred from the water-level observations (Fig. 2). The observed gap between Cl concentration of rainfall and groundwater should be taken as an indication that the contribution of* ***sinkhole-channelled rainfall that escapes evapotranspiration contributes only little to the total recharge amount,*** *as otherwise more intermediate data points would be observed in Fig. 5.*"

According to above:

- Runoff that entered sinkholes undergoes evapotranspiration process before reaching the watertable (this means runoff not **directly recharging** the aquifer).

- Sinkhole-channelled rainfall that escapes evapotranspiration contributes only **little to the total recharge amount** (this **means direct recharge is only little, compared to the total amount,** in other words **minor**).

Therefore, whilst we can appreciate the secondary interpretation offered by Dr. Werner, we believe that we have not incorrectly interpreted Ordens et al. (2012).

With regards to time lag, unless data loggers are installed in monitoring wells located near sinkholes area, time lag observed is not the recharge pulse reaching the watertable, rather time lag between recharge point and monitoring point. There are no such networks of data loggers installed in Uley South. For such study, Dr. Werner is directed to Herzeg et al (1997) where 3 data loggers were installed at monitoring wells near Poocher Swamp sinkhole. As the point recharge commenced (stream flow enters the sinkholes), most distance bore responded more than near-by wells due to interception of flow path or connectivity to the sinkholes (please refer to Journal of Hydrology, 192, 271-299)..

SC 5: The primary point the manuscript makes is that gaps in Cl vs O18 data do not suggest that unsaturated zone (matrix) flow has a significant role in recharge mechanisms, but that rather, sinkholes produce localised pockets of freshwater that are routinely not sampled, hence leading to the Cl- δ^{18}O data-gap. This conclusion is indefensible for numerous reasons:

SC (5.1) the Uley South case (which is used as the primary example) clearly has a very high density of sinkholes, and hence the likelihood of sinkhole recharge "bubbles" being isolated and unmeasured by the extensive monitoring network seems extremely unlikely,

Author Reply 5.1: We agree with Dr. Werner’s comment (5.1). There is a likelihood or probability of intercepting fresh water pockets, or fresh water flow paths (conduits). Note that fresh water pockets or flow paths mixes with ambient groundwater, and diffuse recharge water from unsaturated zone (higher salinity/chloride). That is why there is an overall 10 mg/L less salinity in sinkhole areas than diffuse recharge zones where there are no sinkholes. This is described in detail under Section 4.2, page 11432-11433. An important point to note is in Mount Gambier capture zone, even though total storm water runoff discharge as point source to the aquifer through 3 sinkholes and 400 drainage wells, there is hardly any difference in chloride concentration in diffuse zone and point recharge dominant zones.

SC(5.2) the steady-state assumptions of the manuscript are grossly violated in all of the systems being assessed,

Author Reply 5.2: This is an oversight. We have never used steady-state assumption for fresh water pockets and extracts are given below:

What we have written in page 11431, line 8-11 is: “ *Overall, these results show* ***that non-homogeneity exists at point recharge sources (drainage wells), aquifer monitoring wells, within conduits (Engelbrecht Cave) and along the flow paths*** *themselves, even though the groundwater system is* ***under steady-state in terms of salinity and chloride mass****.”* Here we acknowledge the existence of non-homogeneity, near point recharge sources, but **overall in the aquifer, salinity is stable with time.**

What we have also written in conclusion, page 11435, line 8-10 is: Even though diffusion and **dispersive mixing continues over time, non-homogeneity exists at point recharge sources and along flow paths**.

SC(5.3) the idea that a gap in Cl vs O18 data is indicative that sinkholes do not contribute significantly to recharge has not been posed by anyone except the authors themselves, and hence they are trying to disprove a notion that they themselves invent.

Author Reply 5.3: What we have stated in page 11435, line 6-8 is :" This study suggests that the presence of a gap between groundwater and rainwater chloride in the chloride Vs $\delta^{18}O$ plot, **is not necessarily indicative of sinkholes not directly recharging** the aquifer." Here Dr. Werner has missed the words "**not directly recharging**", which makes the difference to the meaning.

Once again, we repeat the section from Ordens et al. (2012) below:
"The absence of intermediate data points between the rainfall and groundwater data points in Fig. 5 is **interpreted to reflect the fact that any rainfall that results in recharge first undergoes either or both of these processes (complete evaporation and transpiration) before reaching the water table** (or the screens of the monitoring wells). Most recharge occurs in winter, as can be inferred from the water-level observations (Fig. 2).The observed gap between Cl concentration of rainfall and groundwater should be taken as an indication that the contribution of **sinkhole-channelled rainfall that escapes evapotranspiration contributes only little to the total recharge amount,** as otherwise more intermediate data points would be observed in Fig. 5."

We interpret Ordens et al. (20012) statement 'sinkhole-channelled rainfall contributes only little to the total recharge amount" as sinkholes contribution to **direct recharge** is minor. Therefore, it is not the Authors' invention. What we have done is present our observations based on measured data, and provide interpretation correctly.

SC 6: Previous studies are careful not to make rapid conclusions from individual environmental indicators, but rather, plausible interpretations are offered and are based on a range of data types. Multiple-technique methodologies, and scepticism in interpreting small and/or single-technique data sets (due to non-uniqueness and uncertainty in most recharge estimation methods) are encouraged in landmark papers by Scanlon and others. The same wisdom should be encouraged by the authors, rather than the black-and-white message that is offered regarding the influence of sinkholes on Cl-O18 data sets.

Author Reply 6: We agree with Dr. Werner in regards to his comment about the general need to carefully craft statements around the absoluteness or full reliability of the results provided through the use of specific indicators or parameters. However, the aim of this paper is not to assess the robustness or reliability of the use of specific indicators (including the indicators used in this paper), but rather to provide insight in the evidence provided through the selected indicators (e.g.Cl- $\delta^{18}O$) in light of the validity of the use of conventional CMB in the context of point discharge dominated aquifers. In that light, a future effort could explore the reliability of the results presented in this paper as part of a separate, comparative study. Furthermore, we concur with Dr. Werner's reference to Scanlon and others offering views of caution. For example, we are aware and agree with Scanlon et al. (2002) that the importance of accurate recharge estimation and suggestion of using different methods to improve the reliability. On the other hand, we are also aware and agree with Healy and Cook's (2002) comment that the use of multiple methods does not necessarily guarantee reliable results.

SC 7: There is no doubt that karst aquifers recharged through preferential pathways are extremely complex settings in which to study hydrogeology and ascertain optimal water resources management approaches. The current study suggests adopting a bi-modal approach to the use of the Cl-mass balance method, but there is no evidence given by the authors to support such an approach. What's more, the practical difficulties in applying such a strategy may be insurmountable - i.e. one would need to try to determine the extent over which stable freshwater bubbles, if they indeed exist, might occur, so that the breakdown into diffuse and sinkhole recharge could be produced.

Author Reply 7: We thank Dr. Werner for this particular comment, especially as it highlights the inherent dilemma that water resources researchers and managers face in their selection of the recharge estimation method. Firstly, we would like to offer the statement that simplicity of application should not be the primary criteria for selecting a recharge estimation method. A question also arises as to what would invoke a critical review of an existing, well-established, and relatively simple-to-use estimation method that is associated with a high degree of uncertainty. The higher the degree of uncertainty, the higher the risk for water resources managers. We have, in this paper, offered the perspective of the conventional CMB not being valid for recharge estimation in point recharge-dominated aquifers, supported by the presentation of field data in three such groundwater systems, providing relatively consistent messages despite their different hydrogeologic characteristics. We offer the thought provoking argument to the reader that the conventional CMB method could be improved by new research, focusing on the investigation and inclusion of the various components that make up the total recharge in a heterogeneous karst aquifer dominated by karst (shafts and conduits) leading to different point and diffuse recharge mechanisms. This latter complexity is not currently captured mathematically in the conventional CMB method.

SC 8: It is therefore no surprise that the authors make no attempt to apply the method that they recommend. In reading the Reviewer's comments, I wholeheartedly agree with the assertions made there, and also find that there are no significant advances on the current body of knowledge contained within the manuscript.

Author Reply 8: Since this comment is in agreement with Referee 1, **w**e provide the Author Reply to Referee 1 below:

Whilst it is clear to the experts in karst systems, many hydrologists and hydrogeologists apply conventional CMB method to karstic systems taking average or weighted average groundwater chloride concentrations to estimate basin recharge. Our paper illustrates that important components of the recharge mechanisms are missed through this method and, hence, make its application in those cases undesirable. We have also highlighted that it is not possible to get representative samples when mixing occurs. **What is new in this paper is a clear finding that the application of conventional CMB method for recharge estimation in karstic aquifers is not valid (even though it is widely used, see Ordens et al. 2012).** To date, limitations, uses and misuses of the CMB method have been mentioned in literature, but the particular aspect (of reliability in point recharge dominant basins) has not been investigated and hence potentially erroneous recharge estimate can result if the conventional CMB is used in point recharge dominant groundwater basins. **Furthermore, we suggest that the duality of the recharge mechanism in karst aquifers needs to be incorporated into CMB method** in order to appropriately include both point and diffuse recharge components.

SC 9: On a positive note, endeavouring to assess recharge processes in complex systems is a worthwhile undertaking given the lack of understanding of the surface-subsurface flow within such settings, and the authors ought to be commended for their ambitions to characterise the various components on recharge in these sorts of systems. Future efforts would be strengthened by focused field investigation programs and the application of various environmental (and forced) tracer techniques, combined with localised conceptualisation and modelling to untangle the complicated interactions between sinkholes, permeable sediments, highly seasonal rainfall-runoff processes, and the flow and transport within underlying karst aquifers.

Author Reply 9: The authors thank Dr. Werner for his comment and acknowledgment of the general intent of this work, specifically his recognition of the need to further explore recharge processes in complex systems. Our statement of the conventional, but simple, CMB method warranting improvement sits squarely within this recognition. **We hope we have provided the research community with sufficient, thought-provoking evidence to further this particular discussion**. In this same light, **we concur with Dr. Werner that it would be worthwhile to develop modelling efforts in the future to support the theoretical advancement of the CMB.**

It is already evident that Dr. Werner, Referee 2 and Referee 4 suggested that it would be worthwhile to develop modelling efforts in the future to support the theoretical advancement of the CMB. This in itself a major task and beyond the scope of this article.

For the development of such model(s), either theoretical or empirical we have presented sufficient data and a conceptual model. All that is required is estimated point recharge, chloride concentrations in diffuse recharge zone, evidence of mixing (measured chloride concentrations), average annual rainfall and measured or estimated chloride concentration of rainfall.