Author Reply to Referee 2 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 2 for his/her insightful comments. The corresponding replies are listed as follows:

Referee 2-1: Somaratne et al. have studied the hydrological functions of sinkholes and point recharge at three karst systems in Australia. The study presents some interesting ideas and data, but the paper is somehow confuse and not ready for publication. I recommend rejection, but would encourage the authors to continue their study and prepare a more complete and thought-out paper later on.

Author Reply 1: Following five Referee Comments, a major revision was undertaken and restructured the manuscript. Site description, Methodology, Results and Discussion are separated from each other and bridging sentences are included to direct the reader.

It appears that the major problem associated with the paper was the structure rather than data and the results. The 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

Referee 2-2: It is interesting to think about fresh-water plumes related to point recharge at sinkholes. It is also interesting to study the propagation of these plumes in the aquifer and to investigate how this influences representative sampling and the use of natural tracers for recharge quantification.

Author Reply 2: Thanks for the comment.

Referee 2-3: Several major shortcomings of the paper prevent me from recommending it for publication:
The structure is confusing. The Methods chapter does not focus on methods but presents detailed descriptions of three study areas, including some results found during this study, such as the density of sinkholes. The Results chapter does not focus on results, but starts with some general statements

concerning the importance of recharge quantification in managing aquifers. After the results chapter, there should be a discussion or conclusion chapter, but instead, chapter 4 deals with Recharge. The research approach, as well as the results and conclusions are not fully convincing.

Author Reply 3: We agree that there were shortcomings of the paper with regards to its structure. Following four Referees Comments, we have restructured the manuscript and provided additional information. The description of the sites separated from the Methodology section. More information added to the methodology such as: "*The micro-purge (low-flow) sampling procedure (Vail, 2013) is employed to gain representative groundwater samples for major ion analysis within the open hole section of monitoring and drainage wells. Low-flow purging is considered superior to bailing and high-rate pumping as it results in a more representative sample than the typical "three volume" well purge methodology. In addition to micro-sampling, a grab sampling technique was also used for water sampling for chemical analysis. It is assumed, that the hydrostratigraphy in the well is in hydraulic equilibrium prior to sampling. To collect the sample by this method, an electronic depth sampler connected to a geophysical logging line is advanced to the target sampling depth and the unit is electronically opened, allowing groundwater to enter the sampler. Salinity profiles were obtained using Hydrolab sonde (Eco Environmental, 2013) connected to a logging truck cable and lowered down the well from surface to the well base, recording Electrical Conductivity (EC) data along the way.*"

Results and discussion expanded to include following points 1-4 below that leads to conclusions of the paper:

" 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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In the revised Manuscript, Section ‘4. Recharge’ no longer exit.

Referee 2-4: The paper presents some interesting measurements, such as EC profiles in wells or EC in a water cave. This is interesting, but it is not clear if and how these EC anomalies are actually related to point recharge. Such anomalies can also be found in other hydrogeological settings and can be related, for example, to seawater intrusion, upconing of brackish water caused by aquifer over-pumping, limits between local and regional flow systems (Toth), or to mixing of water from different aquifers. So although the data are potentially interesting, the presentation and interpretation is not sufficiently conclusive.

Author Reply 3: This is described in page 11430 Section 3.2 Line 22-page 11431, Line 1-7 as follows:

The extent of the Mount Gambier' Engelbrecht Cave was surveyed by the Cave Divers Association Australia and is depicted in Fig. 6. The contrast in salinity between the north-western and southern wings of the Engelbrecht Cave is due to the different levels of recharge entering the cave. The north-west wing is linked to drainage wells through a network of conduits, hence salinity of the water is lower (405 μS cm^{-1}) than in the south wing (640 μS cm^{-1}). The salinity profile of monitoring well BLA017 (Fig. 7) indicates a connection to the cave at depth 30.5 m. Two conductive zones, indicated by low EC (Electrical Conductivity) in the profile, are found in monitoring well BLA164 located about 2 km west of BLA017 (Fig. 7). The lower conductive zone at 33–34.5m depth (Fig. 7) is identified as the primary fracture pathway to the Blue Lake (Lawson, 2013). Salinity profiles obtained from drainage wells located in the zone of the primary fracture pathway further down gradient to BLA164 (Fig. 8) confirmed that low salinity water moves at greater depth. This indicates the existence of preferential pathways at different depths.

We agree with the Referee 2 that anomalies can also be found in other hydrogeological settings and can be related, for example, to seawater intrusion, upconing of brackish water caused by aquifer over-pumping, limits between local and regional flow systems (Toth), or to mixing of water from different aquifers. These issues are not, however, present at study sites. Rationale of sample sites selection is given in page 11427, Line 8-10 as : "Selected monitoring wells are away from brackish water upward leakage areas or salinity stratified wells, the swamp and coastal monitoring wells."

Additional comments:

Referee 2: The conceptual block diagram is useful to understand one of the three study sites. However, the other two study sites are difficult to understand based. Hydrogeological cross-sections would help.

Author Reply: The conceptual model development was based on observations described in Author Reply 3 above, and adopting the concept of Goldscheider and Drew, 2007. The purpose of the conceptual model is to show different recharge mechanisms such as point and diffuse recharge and the existence of preferential flow paths as indicated by salinity profiles. We do not consider presenting geological cross sections as they would not provide any additional information on recharge processes.

Referee 2: Karst systems are also characterized by a high degree of temporal variability. The paper mostly deals with spatial heterogeneity but largely misses the important aspect of variability.

Author Reply: Agree with the referee that karst systems are also characterized by temporal variability. However, temporal variations of point and diffuse recharge of the system in a few representing locations are not considered to be relevant to the topic under investigation. The aim of this study is not to understand or determine, in detail, flow paths or recharge at discrete locations, but to critically evaluate one of the important hydrological functions in groundwater basins. The focus of the study is to: assess the validity of a widely used recharge estimation method (application of conventional chloride mass balance (CMB) method) in karstic aquifers. We have therefore focussed on obtaining information in regards as spatial coverage of the basin since it forms an important criteria of the reliability evaluation. Moreover, testing of the validity of conventional CMB method requires spatial distribution of chloride in groundwater.

Referee 2: There are very different types of sinkholes or similar features. Not all are related to significant point recharge. Furthermore, there are different definitions and understandings of sinkholes. Point recharge mostly occurs where surface streams sink underground at swallow holes or ponors (some people would call this a sinkhole). However, most "sinkholes" in the US are rather collapse features, and most dolines in the classic Dinaric karst are geomorphologic depressions but not necessarily places of point recharge.

Author Reply: We agree with the Referee that there are different types of sinkholes and not all are related to significant point recharge. In selected sites however, the majority of recharge is contributed as point recharge and the paper quotes examples of such sites. In the Uley South basin, surface runoff terminates within hundreds of meters and enters a sinkhole. In this case not all sinkholes may be extending to watertable and beyond. It is to measure the influence of point recharge since catchments contributing to individual sinkhole are small. Sinkholes that are connected to the watertable bypass the soil zone, directly recharging the aquifer as point recharge. The unconnected sinkholes add runoff deeper into the unsaturated zone, which then rapidly drains into the watertable by mechanisms described by Gunn (1983).

Referee 2: A paper dealing with "sinkholes" should be more precise in using this term. It's not about terminology, but it's about understanding the systems and processes.

Author Reply: Agree. Perhaps 'solution features' may be more suitable ?. We believe have presented sufficient data to establish characteristics of point recharge in three basins.