# Author Reply to Referee 5 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 5 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 processes of the revised manuscript. The corresponding replies are listed as follows:

**Referee 5-1:** This study of karst hydrogeology, a generally neglected aspect of hydrogeology in Australia, could be an important addition to the literature (particularly in Australia), but unfortunately at present it is not sufficiently well argued to justify the conclusions made, and cannot be accepted in its current form.

**Author Reply 5-1:** The authors thank the Referee for acknowledging the importance of karst hydrogeology and some aspects have been neglected in the Australian context. Our study primarily focuses on the validity of applying conventional CMB to estimate recharge in point recharge dominant groundwater basins, which has a world-wide application.

We agree that in the current form, the paper needs revision and following comments received from Referees, extensive revision and restructuring has been undertaken. The Results and Discussion sections have been revised directing the reader to data and analysis that leads to conclusions of the paper.

**Referee 5-2:** However, I would encourage the authors to make the suggested changes so this becomes a worthwhile and significant study.

Firstly, the authors need to become more familiar with the principles of karst hydrology. In the well-cemented limestones that characterize much of North America and Europe, karst conduits (caves) carry the bulk of groundwater flow. In the porous limestones of SE Australia, groundwater flow is shared between the granular porosity and karst conduits, but the groundwater flow through even a porous limestone aquifer is generally mostly through the conduits, because groundwater in the conduits flows several orders of magnitude more quickly than in the granular porosity (Waterhouse's study of the Gambier Limestone shows this clearly). In a bore it is easy to intersect groundwater within granular porosity, but very difficult to intersect a conduit, so the former contribution to the overall groundwater flow in the limestone aquifer is emphasised at the expense of the latter (this is the mistake that Ordens et al. have made).

**Author Reply 5-2:** The Authors thank the Referee for valuable guidance. Manuscript will be re-revised to include work of Waterhouse (1977) in Mount Gambier aquifer and the landmark study of

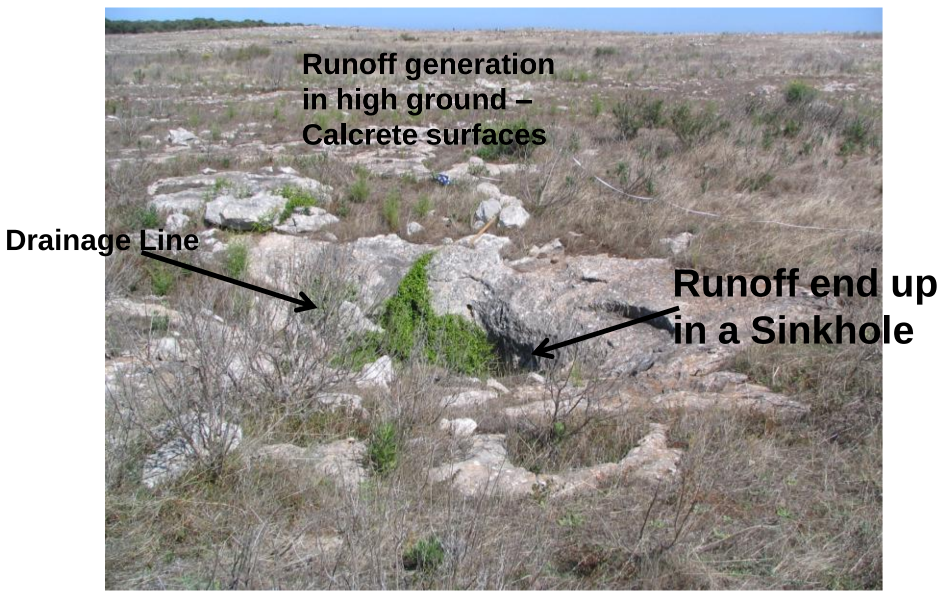
Herzeg et al (1997) in the Poocher Swamp sinkhole associated conduit flow.  Outcomes of these studies will be linked to the Results and Discussion of this study to consolidate our findings.

**Referee 5-3:** Point recharge (at sinkholes) feeds karst conduits with very rapid groundwater flow; it is important to realize that sinkholes almost always feed conduits (otherwise the sinkholes would not exist). Some of the recharge around sinkholes will also seep slowly into the granular porosity around the recharge point. However, most of the recharge to the granular porosity of the aquifer is through surface recharge across the entire surface of the aquifer; recharge to the granular porosity from the point recharge areas would be a relatively minor contribution restricted to those areas. The authors need to reinterpret their data with this in mind; studying the recharge to the granular porosity around point recharge areas is useful, but remember that most groundwater flow is through the conduit that is fed by the sinkhole.

**Author Reply 5-3:** Authors agree with the view of Referee 5. In the revised manuscript, we have highlighted the fact that in the point recharge dominant zone in Uley South, 10 mg/L reduction of chloride concentration is a result of mixing of point recharge water with diffuse recharge and ambient groundwater. Referring to Fig. 6 & 7, we have described that low salinity water in upper part of BLA 107 and BLA 164 are the results of both diffuse recharge and point recharge mixing; and low salinity in the profile at depth in BLA 164, is the interception of conduits carrying low salinity water from point recharge source (drainage wells) These observations are supported with Herzeg et al (1997) observations at Poocher Swamp monitoring wells.

The findings regarding calcrete surface generated runoff and that flow to sinkholes, as well ascalcrete surface contributes to diffuse recharge, is supported by a presentation made by the first author two years ago to a group of local hydrogeologists. We present the relevant slide below, which is self explanatory. This photo shows the typical landscape of the Uley South basin.

Evidence for non-applicability of CMB Method
Main Catchment Features are numerous sinkholes



**Referee 5-4:** Therefore, applying the CMB method to the groundwater in the granular porosity around a point recharge area will always underestimate the amount of recharge through the sinkhole, because it is not sampling the conduit groundwater flow, which is completely separate. To estimate the conduit recharge, using the minimum groundwater chloride in the granular porosity around a point recharge area will give the best value, but this will still be an underestimation.

**Author Reply 5-4:** Agree with the Referee 5's Comment. Minimum groundwater chloride is still subjective.

**Referee 5-5:** Furthermore, on a Cl vs $\delta^{18}O$ plot, conduit flow directly recharged through a sinkhole will plot near rainfall, because the very rapid recharge allows only minimal evaporation. Groundwater in the granular porosity will have been recharged mainly through surface infiltration, and will have been subjected to evapotranspiration during infiltration, so it will have elevated chloride and heavier $\delta^{18}O$, and will plot well away from rainfall.

**Author Reply 5-5:** Agree with the comment. This is clearly evident in Fig. 4b and 4c, and the description given in page 11429 and 11430 under Section 3.1.

**Referee 5-5:** Groundwater in the granular porosity around recharge points will have been recharged partly by relatively rapid recharge through the sinkhole, so will plot in an intermediate position between rainfall and most groundwater. However, a lack of intermediate points between rainfall and most groundwater does not discount point recharge (contrary to Ordens et al), it just indicates either that there is little seepage into the granular porosity around the recharge point, or that this was not sampled, or both.

**Author Reply 5-5:** We agree with the comment. We have observed sample biasness because of the lack of monitoring wells near point recharge sources. In addition, small catchments feeding Uley South sinkholes or Mt Gambier drainage wells do not generate sufficient runoff volumes to generate a fresher water plume that extends to monitoring wells. It is very difficult to track conduits flow using a single monitoring well since the network of conduits and their depths are unknown. Herzeg et al (1997) used 3 wells at 10 m, 50 m and 150 m away from the two sinkholes in Poocher Swamp. The first two wells had been completed shallow, 6 m below water level and the third one (at 150 m) completed at 50 m depth (about 35 m below water level). Maximum water level rise had been observed at the well 150 m from the sinkhole indicating a direct sub-surface connectivity to sinkholes. This indicates the complex nature of tracking flow paths.

If the arguments of Ordens et al (2012) applies to Mount Gambier drainage wells ( where a gap of 43 mg/L exists), then one has to conclude that 'drainage wells are not directly recharging the aquifer, but rather distribute in the unsaturated zone and undergo evapotranspiration process'. This is not in fact the case as the drainage wells are openhole construction below watertable (direct recharge being visible in Fig. 2 – where recharge is occurring through the drainage wells).

**Referee 5-6:** To summarise, to determine point recharge using groundwater chemistry requires analyses of the conduit flow fed by the point recharge. Analysing groundwater within the granular porosity cannot accurately determine the amount of point recharge (although it can give an indication).
In the introduction, the authors need to refer to the definition of karst in the classic texts (e.g. Ford & Williams, White & White). The difference between allogenic and autogenic recharge is not important

for the Uley Basin aquifer, which is entirely autogenic in the area of study (this is shown incorrectly on Fig. 9). Dissolution cavities in karst aquifers are automatically hydraulically connected (this is integral to how they form); this is not due to 'further' dissolution, it is due to karst dissolution processes that are continually acting on these aquifers.

**Author Reply 5-6:**

Karst definition will be included in the revised manuscript (with citing several references).

Uley South study basin is bound by high topography and 'dry limestone' boundaries in the landward direction. Surface water from this area flows toward the central basin making allogenic input. In the revised manuscript we will elaborate this further. In page 11426, line 24-26 as:" *The basin is topographically closed and bound by coastline and sand dunes to the west **and inland to the north and east by topographic rises of dry limestone**, except along the north-eastern edge. The low lying central part of the basin contains numerous sinkholes."*

In Fig. 9, it is shown that there is no saturated limestone in the allogenic zone.

- Agree and deleted the word "further" and revised as "karst dissolution"

**Referee 5-7:** There needs to be a methods section, giving details of sampling and analysis.
The freshwater in the Murray Group limestone (is this the Gambier Limestone) around Poocher Swamp would be better referred to as a lens rather than a 'bubble'. This catchment is stated to generate 50-2000k m3 of freshwater a year; how was this calculated?
For the discussion of mixing, presenting the groundwater chemistry as Scholler plots would be far easier to interpret than Piper plots. The Mt Gambier data shows that groundwater is flowing in conduits (these may be enlarged fractures, but are better termed conduits

**Author Reply 5-7:**

- The range of annual runoff volume is (50-2000) k $m^3$. Creek discharge is estimated based on the daily measurement at gauging station located at Bordertown, 7 km east of Poocher Swamp. Data for the period 1980-2010 was used for the estimation.
- We agree that there were shortcomings of the paper with regards to its structure. Following five Referees Comments, we have restructured the manuscript and provided additional information. The description of the sites has been 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."*

- Poocher Swamp area belongs to the Murray Basin, and Mount Gambier area to the Otway Basin. Murray Group limestone in Murray Basin has an equivalent limestone layer to the Gambier Limestone in the Otway Basin.
- We agree with the Referee that Poocher Swamp fresh water bubble may be referred to as "the fresh water lens". We preferred to use "fresh water bubble" because at 70-80 m depth in the limestone aquifer, brackish water of salinity >800 mg/L occurs, as evidenced from town water supply well investigations. This indicates that the fresh water is floating on brackish water (and surrounded by brackish water). We used this word only to describe Poocher Swamp fresh water plume, all others are described as "pockets", as they are small fresher water plumes.
- It was assumed that entire creek flow recharge was point recharge. This may not be entirely through sinkholes, but through rapid recharge swamp beds as well. As indicated by Herzeg et al (1997), groundwater chloride near Poocher Swamp is about 40 mg/L, equivalent of Swamp water chloride. There is no saline water in the Swamp.
- We agree that the Scholler diagram may be easy to interpret. However, we prefer to use the Piper Diagram to show how the chloride data varies along a flow path (in the flow direction) between two end members. That is, chloride between Poocher Swamp (Low) and and WRG110 well (High).
- We agree that Mount Gambier data may be enlarged fractures, since several volcanic eruptions had occurred when the Blue lake was formed 30 million years ago.

**Referee 5-7:** The modelling of surface runoff gives very important numbers. I presume that there is no surface drainage in any of the three catchments, so this runoff is entirely diverted underground. The amount of granular flow in each catchment can be calculated using Darcy's Law, and compared with the surface runoff numbers. The excess will be conduit flow. In section 4.2, 'equilibrium' is used incorrectly; it has a very specific chemical meaning.

Section 4.3 needs to be thought through more clearly using the concepts given above.

In particular, the CMB method will reliably estimate point recharge if you have an analysis of water from a conduit that was directly recharged at the sinkhole. The discussion needs to be changed to reflect this.

**Author Reply 5-7:**

- There is no surface drainage or runoff leaving any of the catchments, except Poocher Swamp overflow during high flood events, and recharge through another sinkhole down-gradient.
- Regarding the application of Darcy's law, we agree with the Referee but would like to stay with testing the validity of conventional CMB as the main objective.

With regards, to revision of maps, roads and street layers will be removed from maps.

With regards to comment on reliable estimate of recharge using chloride measurements, we provide basic assumptions in conventional CMB below from the revised manuscript: "*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 flux of water and chloride in unsaturated zone,*
- *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."*

Measurement of of chloride directly recharging from sinkholes violate above assumptions, and not representative chloride of the groundwater.

**Referee 5-8:** It is unwise to use Hutton's formula to estimate rainfall chloride, although because all 3 sites are relatively close to the coast, the estimates are probably reasonable. For each basin, the map needs to be based on a DEM (the freely available SRTM DEM is OK); an accompanying surface geology map of exactly the same area would be useful. The locality map needs to include a blow-up of South Australia showing the location of each area. It is not necessary to show roads and urban areas. For each basin, a cross-section with horizontal and vertical scale is needed. The Uley Basin 3D diagram is good but is not to scale. It is important to know the thicknesses of the various units.

**Author Reply 5-8:**

- Hutton (1976) equation used calculated rainfall chloride for consistency although rainfall chloride data was available for Uley South basin at several locations.
- We have attempted to use DEM (Digital Elevation Model) data to delineate sub-catchments for each cluster of sinkholes in Uley South. This attempt failed due to some inconsistency (>2 m) of DEM data observed when compared with surveyed measuring point elevations of aquifer monitoring wells. Therefore, delineation of sub-catchment was abandoned.
- We agree that Geological base maps and cross sections are useful to understand geological layers of the aquifers. However, they provide little or no information relevant to point recharge. Therefore no changes were made to the text.
- No roads are shown in Fig. 3 Poocher Swamp fresh water bubble. Access Roads were shown in Fig. 1 for the Uley South basin, because initial survey of sinkholes was undertaken along the access roads as given in the map. In Fig. 2 showing the Blue Lake capture zone, streets were shown in shaded colour to show sub-catchments (sub-divisions) within the town that contains drainage wells. We agree that there may be too many dot points (400 drainage wells) but the purpose is to direct the reader to where the chloride measurements were undertaken in relation to point recharge.
- With regards to Uley basin 3-D diagram, this is a conceptual diagram to illustrate different recharge mechanisms operating in the basin with resulting fresh water pockets near point recharge.

We agree the Figure is not proportionate and requested the drafting company to reproduce a figure with reduced thickness (compared to aquifer width), and show shaft of sinkholes by thin blue lines. These lines would then end at 3 different possibilities either at the unsaturated zone (not all sinkhole connected watertable), or at the upper part of the watertable , or at a deeper part of the watertable. Will insert "Not to a scale" in the Figure.