Editor comment: Theory of the generalized chloride mass balance method for recharge estimation in groundwater basins characterised by point and diffusive recharge

The review process of the manuscript has been very extensive and has raised debates about the suggested mass balance method as well as about the application of the method to the interpretation of chloride concentration measurements in several aquifer systems in Australia and also on the conclusions that would be drawn from this application. A large part of the discussion is on the hydrogeology of the aquifer systems and on the validity of assumptions. To my understanding, this part is not the main issue, as these relates to a previous discussion paper in HESSD that is currently under review. For this reason, I will concentrate in this concluding comment on the mass balances as a method for estimating groundwater recharge only.

Method discussion in the review process

Concerns about the method are raised in the interactive comment by W. Wood and in several parts in the comments of the anonymous reviewer 1. The debate about the methods is also very extensive, but to my point of view the key points are the following.

- The starting point is a steady state mass balance for chloride in the subsurface that can be used to infer from observations of chloride concentrations in groundwater samples (could also be in the unsaturated zone, but this is not considered here) on the groundwater recharge. The method is in the manuscript referred to as the conventional method. A remark to that: To my point of view there is no such thing as a standard method or conventional method for estimating groundwater recharge. Any method is based on assumptions that need to be questioned and discussed for each case. This is argued in different ways by the reviewers as well. The mass balance leading to the conventional approach is in the manuscript extended in order to account for point infiltration from sink holes or karstic conduits. This method is called the generalized method.
- The suggested mass balance in the manuscript is carried out making the following main assumptions. There are more assumptions in the details that I will skip. I will not go through the lengthy derivation of the model in the manuscript, which includes first more terms that are eventually dropped. I will only consider the final model that is applied to the observation data.
  - All mass and water fluxes are at steady state or time averages are considered that allow for a steady state assumption.
  - The different compartments (surface, unsaturated zone, porous aquifer, conduit system) are treated as fully mixed systems (zero-dimensional in space).
  - The groundwater is divided into two compartments that do not mix or exchange fluid or mass of chloride (the porous aquifer and the conduit system that is in the manuscript mostly called sinkholes). This follows from Eq. 10. To my understanding there is some confusion concerning this assumption in the review discussion and it is for this reason explained in more detail below. Groundwater recharge is here meant as the sum of both fluxes out of the compartments.

  - There is no surface inflow or outflow from the system and there is no interflow in the unsaturated zone.
  - Evapotranspiration occurs only in the unsaturated zone.
  - There are no subsurface sources and sinks of chloride.

  A mass balance for chloride is set up using these assumptions,which is solved for the groundwater recharge. To obtain groundwater recharge from the mass balance, all other quantities need to be known, including the total flow in the conduit system.

- The calculation of recharge is carried out with data that have been the content of a different manuscript in HESSD that is at the moment under review for HESS. The calculated discharge has been compared to the calculation of discharge using the approach of a zero dimensional (fully mixed) system for the groundwater (which is in the manuscript referred to as the conventional method) and it is found that using the generalized approach in the manuscript yields higher recharge rates. The data that are used caused a long debate in the review process. They are not the content of this paper, which makes this discussion difficult. But some remarks have to be made here. The approach in the manuscript to estimate recharge is made on very simplifying assumptions (as written above). What to my point of view is really missing in the manuscript is a systematic analysis of why all these assumptions can be made. It is not enough to state that they can be made. For example, the total discharge in the complete conduit system needs to be known. How accurate can such an estimate be? Another example: How sure can one be that there is no or negligible discharge from the sinkholes to the porous aquifer? Or: Were long time series of samples taken so that an annual average is available to justify a steady state assumption? Another concern is the description of the hydrology and hydrogeology. The settings are given with a reference, mostly to the manuscript under review in HESS. But these properties are essential and without a stronger documentation and reasoning, the question of the data is a question of believing or not believing. Being not familiar with the groundwater systems that are debated here, I could not follow the long discussion about the hydrogeological settings between the first reviewer and the authors. This illustrates that the information provided in the manuscript is not sufficient to really support the assumptions made or to get an estimate about the reliability.

- A big part of the debate in the review process is on the spatial variability of observations, the averaging of chloride concentrations and the assumption of mixing. The comment of Prof. W. Wood brings this very well to the point. If a system is sampled that is in a mass balance assumed to be fully mixed, sufficient sampling has to be done to allow for a reasonable average that is representative for the whole system. This is the only point where the spatial variability of observation data comes to play. As outlined above and argued for in full detail below, a mixing between conduit (or sinkhole) water and porous aquifer water is not covered by the mass balance approach made in the manuscript. The two systems are assumed not to exchange water or chloride. For this reason, to be consistent, all spatial variability of the chloride concentration observations has to be assigned to the strong heterogeneity of the porous groundwater system alone. I believe that some part of the review debate about the exchange between sinkhole and porous aquifer was quite misleading in this respect. Considering this fact, it is then a very relevant question if the spatial sampling density allows for the assumption that the average concentration in the whole porous aquifer system can be estimated from the observations.

Some part of the debate was also about chloride concentration observations close to sinkholes. Measurements close to sinkholes that show a lower chloride concentration than other measurements in the system only demonstrate that there is possibly infiltration from the sinkhole into the porous aquifer system. They do, however, not allow for a quantification of fluxes, in particular if this infiltration is not considered in the mass balance that the quantification is based on. With a mass balance that does not account for the infiltration, in fact such sampling points would have to be avoided, as they are surely not representative for the average in the system.

Conclusions

As the authors write, the main contribution of the manuscript is the theory, meaning the method to calculate groundwater recharge in the presence of conduit flow (or sinkhole flow). For this reason, the focus of the comment is on this part. The suggested approach is seen as a generalization of a conventional method. However, to set up a mass balance that has sinkhole flow additional to the flow through the unsaturated zone into and through the porous aquifer is as such to my understanding not a new scientific contribution. One could figure out many different extended systems and write down a mass balance for them (for example the case three considered below, but one could include also root water uptake from plants, or any other effect). So the system could be generalized on and on. To solve the mass balance for one unknown, once it is set up and assuming all other terms can be estimated, requires only some algebra.

A suggestion for a specific mass balance that is a new scientific contribution would require a strong argumentation for the need of the specific extension of the mass balance. A discussion would be needed why and for which cases the extension of the mass balance is reasonable and leads to a better understanding of the system or to better estimates of a discharge or something else. This reasoning is made here with the three case studies that all rely on data that are the topic of a manuscript in review in HESS and this is a critical point. After the discussion in the review process, I do not see that they allow for a solid justification of the assumptions made above. The description of the complex hydrogeology of karstic systems is very much simplified (in terms of steady state assumption, in terms of the assumptions of fully mixed systems that can be sampled with few observation points, in terms of the assumption of conduit flow and porous medium flow as two systems that do not exchange mass or chloride, to name only some). As written above, a clear discussion on why this simplification can be made would be needed. That the manuscript discussing the data is in review and thus not published is one issue. However, having read the HESSD manuscript in which the data are presented first, I think that the documentation of the hydrogeology of the system, the observations, their spatial variability, their sampling density in time and space etc., do not allow for a justification of the assumptions and certainly not for the strong quantitative conclusions made in the manuscript for the whole aquifer systems. Also, as written above, the discussion of mixing in the groundwater system is misleading. I do not see that revisions could solve these problems and would therefore not suggest to send the manuscript into the review process in HESS.

This conclusion does deliberately not refer very much to the reviewer comments, as the review discussion had a quite harsh tone. However, all reviewer and interactive discussion comments were very critical about the method and in particular its application to the aquifer systems considered in the manuscript.

Approach of conduit flow (or sinkhole flow) and porous groundwater flow as two separate systems

The point above about the separation of compartments is here described in more detail:

All systems are in the manuscript treated as fully mixed. A system that is not mixed at the inlet and outlet areas does strictly speaking not allow for a zero-dimensional (meaning no profiles of quantities in any direction) description. This does not mean that a real system has to be completely mixed, but one has to reason why a zero-dimensional approach can be made (for example samples are taken at the outlet and / or the spatial density of samples is very high).

The groundwater recharge is in the mass balance considered as the water leaving the groundwater system. Although this is not written down explicitly, there is no other way of seeing it, as a steady state mass balance (without sinks and sources) means inflow equals outflow. The groundwater system can therefore not be considered without outflow. There are different possibilities to conceptualize the groundwater system. A first one is to keep conduit water and porous aquifer water as separate systems that do not interfere and leave the system separately. A second would be to treat them as one system, but in this case they have to be considered as fully mixed in the mass balance. A third approach would be to keep the compartments separate, but to have a net inflow (Q_{inter}) from the conduit system into the porous groundwater. These two approaches are sketched in the figure below. The manuscript follows the first approach. Why the other approaches are not covered can be seen from the mass balances for the different systems.

With all the assumptions made, the relevant steady state balances are with the notation of the manuscript (all terms that are eventually set to zero taken out): Water at the surface:

$$P = Q_p + F \tag{1}$$

Water in the unsaturated zone:

$$R_u = F - E \tag{2}$$

Water in the groundwater system (including both sub-compartments, sinkholes and porous aquifer, in the first approach the sum is made at the outlet of the system, in the second approach at the inlet):

$$R = R_u + Q_p \tag{3}$$

Water in the groundwater system in the third case, 'out' indicating outlet

$$R_{u',out} = R_u + Q_{\text{inter}}, \quad Q_{p,out} = Q_p - Q_{\text{inter}}, \quad R = Q_{p,out} + R_{u',out} \tag{4}$$

Chloride at the surface:

$$Pc_p + D \approx Pc_{pD} = Q_p c_S + Fc_S \tag{5}$$

Chloride in the unsaturated zone:

$$Fc_s = R_u c_u \tag{6}$$

Chloride in the two groundwater compartments with the first approach:

$$Q_p c_s = Q_p c_s, \quad R_u c_u = R_u c_{gd} \tag{7}$$

Chloride in the one groundwater system with the second approach:

$$Q_p c_s + R_u c_u = R c_g \tag{8}$$

Chloride in the two groundwater compartments with the third approach:

$$Q_{p,out} c_s = Q_p c_s - Q_{\text{inter}} c_s, \quad R_{u',out} c_{gd} = R_u c_u + Q_{\text{inter}} c_s \tag{9}$$

In the first approach, inserting the right hand side of eq. (7) into (6) and inserting into (5), solving for R_u and inserting this into (3) yields eq. (13c) in the manuscript. The equations (13a), (13b) and (13d) in the manuscript are special cases of this equation. This illustrates that the concept of the balance in the paper is a groundwater system of two compartments, sinkhole system and porous aquifer, which do not exchange water or chloride.

That the mass balance in the manuscript does not cover the other two cases can be illustrated by solving these systems for the total recharge R. In the second approach (meaning that complete mixing is assumed in the groundwater system), inserting eq. (6) into (8) and inserting into (5) yields

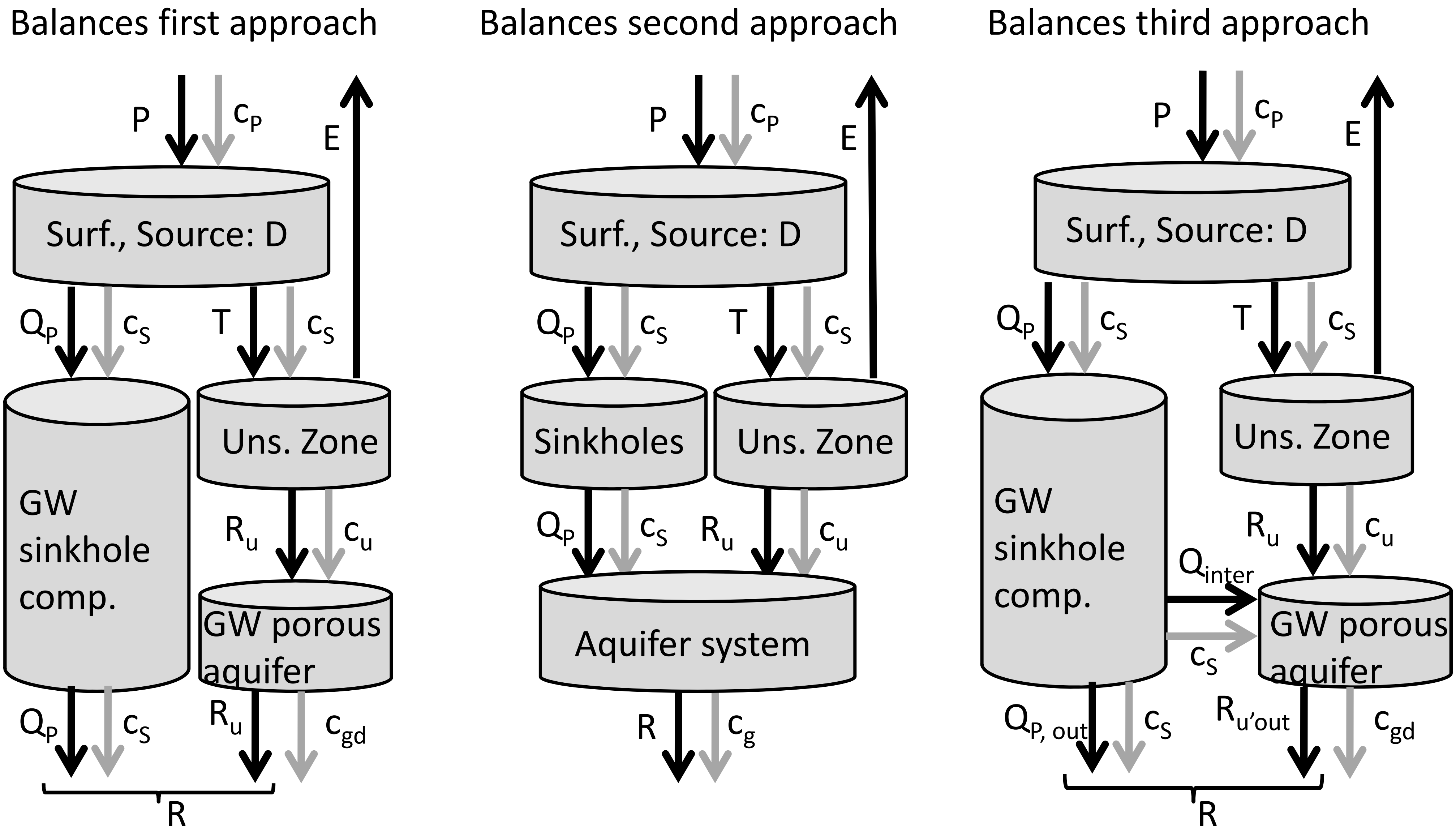
$$R = P \frac{c_{p+D}}{c_g}. \tag{10}$$

This is what the authors refer to as the conventional method. If the groundwater system is considered as one zero-dimensional system (thus fully mixed), it does not make any difference if there is sinkhole flow or not. If the third approach would be taken (meaning that some water from the sinkhole system discharges into the porous aquifer and is there mixed) yields (inserting eq. 5 solved for Fc_s into eq.(6) and inserting this into the right side of eq. (9), solving for $R_{u',out}$ and inserting into eq. (4))

$$R = \frac{P c_{p+D} + (Q_p - Q_{\text{inter}})(c_{gd} - c_s)}{c_{gd}}. \tag{11}$$

The third approach is somewhat pointless, because it requires that a good measure of the discharge from the sinkhole system into the aquifer is available.

The recharge with the three approaches could have been written down intuitively, but due to the long debates about mixing in the review process, I wanted to clarify this point with the balances. To summarize: In the approach of the manuscript, no mixing between sinkhole water and porous groundwater is included.



Balances first approach
P
c_P
E
Surf., Source: D
Q_P
c_S
T
c_S
GW sinkhole comp.
Uns. Zone
R_u
c_u
GW porous aquifer
Q_P
c_S
R_u
c_{gd}
R
Balances second approach
P
c_P
E
Surf., Source: D
Q_P
c_S
T
c_S
Sinkholes
Uns. Zone
Q_P
c_S
R_u
c_u
Aquifer system
R
c_g
Balances third approach
P
c_P
E
Surf., Source: D
Q_P
c_S
T
c_S
GW sinkhole comp.
Uns. Zone
R_u
c_u
Q_{inter}
c_S
GW porous aquifer
$Q_{P, out}$
c_S
$R_{u'out}$
c_{gd}
R