Response to Prof. Dr. Franklin Schwartz

Dear Prof. Dr. Franklin Schwartz,

Thank you very much for reviewing our paper entitled “Exploring river–aquifer interactions and hydrological system response using baseflow separation, impulse response modelling and time series analysis in three temperate lowland catchments (HESS-2021-422)”. We appreciate your time and comments which will help improving the manuscript.

In the following sections you will find our detailed responses and explanations (in blue) to your comments and suggestions (in *italic*). A revised manuscript will be prepared later with tracked changes made to the original manuscript based on your and other’s comments, awaiting the decision from the editor.

We are looking forward to your further assessment.

On behalf of all authors,

With best regards,

Min Lu

Corresponding author

1. General comments

The paper by Lu et al examines surface water groundwater interactions in lowland catchments in Belgium. The purpose of the study was to fill a gap in knowledge related to these catchments (Line 61). Their approach relied on an impulse response modeling to establish baseflow from knowledge of water table fluctuations. Those baseflow estimates would then be employed to evaluate methods of hydrograph separation and to learn something about the hydrology of these lowland basins.

- Thank you for this comment. As outlined in the introduction section (Line 73 – 74), the first objective of this study is to use the data-driven impulse response modelling to evaluate the hydrological system response (in magnitude and time) to system input of climatic drivers (use case 1; section 3.3.2) or groundwater level (use case 2; section 3.3.3.) in the three temperate lowland catchments. Further, we found that the simulated baseflow from the impulse response modelling (use case 2) can at a certain level provide feedbacks (Line 75 –77) on the separated baseflow from hydrograph separation approaches. To be more precise, the "simulated baseflow" should be adjusted to "simulated groundwater inflows" (to the river). See detailed explanations in the reply to "What is baseflow" part below.

2. Specific comments

Study Design

Intuitively, I question the motivations for study, discussed in the introduction. There are many different kinds of watersheds worldwide and it is not clear why the knowledge gap in this case was worthy of the time spent. Another question is the apparent need for another study designed to evaluate the efficacy of various baseflow separation techniques. The paper itself identified the key problem (Line 216) "Limitations for these hydrograph separation methods are their intrinsic difficulty to validate the separated baseflow and the lack of any representation of the physical processes of the river-aquifer exchange". This problem is well known and has been widely explored (e.g., Partington et al., 2012). The positive aspects mentioned in the paper "fast", "efficient", "widely used" and quantitative (line 218) really don't justify techniques know to be little more than guesses in most applications. The choices to address this problem in my opinion are to minimize this aspect of the study in the paper, demonstrate with field data that one of the approaches does work well enough to be useful, or to use a modelling approach like SWOT that might be useful.

- Thank you for raising the questions and doubts. In the manuscript, we did not mention in detail the study/project background. This study is not a stand-alone one, as it is part of the Future Floodplain project (https://www.futurefloodplains.be/en/) which focuses on the interplay between (geo)hydrology, ecology and geomorphology in the selected catchments. These sites are the focus areas for the research partners and stakeholders.

- We work on the (geo)hydrological package of the project. On the one hand, we need to fill the missing knowledge gaps of river-aquifer interaction in these catchments. On the other hand, we need to provide input for the ecological package of the project, for instance, the characteristic groundwater levels (average highest and lowest groundwater levels). Their ecological modelling requires the input to assess groundwater sensitive species in the floodplains and near the rivers.

- As we mentioned in the response to the general comments, the aim of this study is to evaluate the lowland hydrological system response using a two-step approach (2 use cases) and to explore whether it is potentially feasible to estimate the groundwater contribution to the river from the groundwater level perspective. Although we used the traditional hydrograph separation methods, we did not intend to focus on evaluating methodological differences between varying baseflow separation techniques. We only found that Nathan and Eckhardt methods are more in line with a groundwater-level-based approach in our lowland environment. In the revised manuscript, we will describe this point more clearly.

- Thank you for suggesting the field and modelling approaches. We know that the study of river-aquifer interactions can be very complex. From a broader research perspective, we have divided the river-aquifer interaction study into three main parts: (1) data-driven modelling and simulation at a catchment scale, (2) multi-method field approaches at local scales, and (3) comprehensive numerical modelling approach including both current and future scenarios (climate and land use change). This paper is focused on the first part, and including aspects of the others would make it even more lengthy. Hence we consider this out-of-scope for the current work.

The study in my opinion suffers from an over-reliance on theoretically based approaches. On line 48, the paper mentions several field-based approaches, but suggested that these were scale-inappropriate. There are other techniques not mentioned that have been used in other studies, e.g., isotope tracers and geochemical hydrograph separation. These of course come along with their own problems but have been applied to basins of this scale, which are small in area. The paper would be helped by field-based data/observations that could validate any of the empirical conclusions.

- Thank you for raising the concerns about field approaches. We have carried out multi-method field approaches in the focus zones of the catchments (part of the whole catchments). We have collected river water and shallow groundwater samples at different seasons for geohydrochemical (major ions and cations, Radon-222) and isotopic (H2 and O18) analysis. We use heat tracer for estimating river-aquifer interactions at local scales and are currently working on it. We also explored the thermal infrared imagery technique together with Radon-222 analysis in the study sites at local scales (https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.13839). These are the main focuses of the second part of our river-aquifer interaction studies.

The decision to forego a rigorous physically based modeling, approach e.g., HydroGeoSphere, in the study design was surprising. That model was used in various baseflow application e.g., Olsthoorn et al. (2012) – an application looking at the efficacy of hydrograph separation methods (cited in the paper), and with geochemical approaches (Jones et al., 2006). Even if the study was focused on refinement of the impulse-response approach, it would have been prudent to start with a simple well constrained model-based proxy (like Olsthoorn et al. 2012).

- Thank you for pointing out the numerical modelling approach. We did not forego it. Numerical modelling of river-aquifer interactions is one of the most important approaches for us to learn and understand the river-aquifer interaction of the hydrological system. This is the main focus of the third part of our project. Based on our previous modelling experience, we chose MODFLOW-based numerical modelling. We are currently working on it and will compare the groundwater inflow to the river from numerical MODFLOW approach and data-driven modelling approach (of this manuscript).

What is Baseflow?

I think it is important for the authors to explain their concept of baseflow. The implicit definition in the paper is that stream baseflow is due to groundwater. For developed watersheds, baseflow is flow in the

stream between storm-runoff events. That water could be groundwater, but it also might include slow surface-water discharge from impoundments, storm-water ponds, dewatering, or discharges of treated sewage, etc (Liu et al. 2013). With this expanded definition in mind, the authors need additional field data to support their assumption that baseflow is groundwater.

Development of a watershed (farming, cities etc.) also has the potential to reduce baseflows by decreasing natural groundwater recharge due to tile drains, stormwater collection systems and fast runoff from pavements and altered land cover. To provide context for this study of low land basin these possibilities need to be explored with additional field data and observations.

- Thank you for the comments on the baseflow. We agree it is necessary to explicitly define the concept of baseflow in our study. In the revised manuscript, we will define baseflow from the hydrograph separation as (total) baseflow, which includes the groundwater inflow to the river (groundwater contribution), and other intermediate water that sustains streamflow between rainfall events. The “simulated baseflow” will be adjusted to “simulated groundwater inflow” to the river. Section 3.3.3 will be groundwater inflow modelling instead of baseflow response modelling. We will also adjust the corresponding terms throughout the whole manuscript where necessary, and hence adopt the more nuanced definition of baseflow, as suggested.

- We have checked the paper by Liu et al. (2013). The studied streams are located in an urban setting (average impervious coverage ~ 50%). The baseflow is mainly composed of groundwater inflow and water released from the storm-water detention ponds (Liu et al. 2013). Unlike the urban streams influenced by anthropogenic activities, the three catchments of this study are dominated by crop and meadow, and have relatively low urban coverage (Line 129 – 131). Zwarte Beek (Dirk Maes, 1992) and Mombeek valleys are nature reserves with low human impacts. The Belgium government has carried out nature-based solution for floodplain restoration and “zero management” polices to reduce the human impacts on catchments such as Dijle since 1990 (Turkelboom et al, 2021). Therefore, the three catchments are mostly under the natural conditions, which makes it feasible to implement the impulse-response modelling, especially under climatic drivers. We will add more description regards to the natural state of the catchments in the revised manuscript.

Questions Concerning the Data

The descriptions of these study watershed appear relatively meager in terms of hydrologic data. First, in looking at the stream hydrographs, it seemed that that discharges were unusually constrained in a narrow range of discharges. I think that for the two smaller basins at least mean daily discharges do not provide adequate temporal resolution of discharge conditions.

- Thank you for raising this question. We described the hydrologic data such as precipitation, stream flow in the study area section, providing the average values or the value range, with some graphical representation of the data (Fig. 2 and 3). We will add some more statistical description of the data in the revised manuscript. We chose daily discharge values over finer resolution (e.g. hourly) because we simulated the impulse response modelling over a relative long period (30 years) and focused on the temporal evolution at a coarse temporal resolution. Using daily values for all three catchments helped us to compare the difference between them. For event based or finer temporal resolution studies, we agree it is better to have much finer temporal scales than daily.

In most watersheds, groundwater-level hydrographs are relatively uncommon. The record shown in the paper appears to have combined bits-and-pieces of hydrographs from different wells. But I could be mistaken. The assertion that forcing from precipitation provides a single simulated water-level fluctuation for an entire catchment is a serious simplification that has not really been appropriately justified and is not appropriate. The job of the land-surface component of hydrologic models is to redistribute water on the land surface due to topography, land cover, and soil conditions, which together provide for huge variability in local infiltration rates. Similarly, the hydrologic response of shallower wells could be substantially different than deeper wells because of local variability in hydrogeologic parameters. For example, there are no indication as to whether aquifers are fractured at shallow depth etc.

- Thank you for raising the question about the groundwater-level hydrographs. It is common to quantify baseflow from a streamflow hydrograph perspective. We explored in this study the possibility to get a sense of groundwater contribution to the river from a groundwater-level hydrograph perspective, which is not so common but also can be considered as the innovative part of our study.

- As mentioned above, the three catchments have experienced little human impact during the study period. The aim of the study is to use a simple data-driven model to explore the hydrological system response under climatic drivers before applying a complicated numerical modelling including other influencing factors.

- Since most groundwater level observations are close to the river, we used the first principal component to get a collective representation of the relative state of the shallow groundwater levels across the catchment for facilitating the application of the impulse response model for the second use case (Line 328 – 331). The groundwater level observations in this study are from shallow depths so they represent the water table elevation, and fractures are not of concern in these shallow unconsolidated sediments. Locally, Roer-Valley Graben related faults influence groundwater levels in the region, but in the current study areas, there is no evidence they would reach up to the shallow aquifer.

It is also noticeable that the locations of groundwater observation wells are biased to specific parts of watersheds, and to locations close to streams. Are these completed in alluvial aquifers adjacent to the stream or at what depths? Are these wells special to have water-level records, what kind of records exist etc.? How often are water levels measured in these wells.

- Thank you for raising the questions. We tried our best to get as many groundwater level observations as possible from different monitoring agencies (e.g. Flanders and Wallonia have different monitoring networks and schemes). Since our focus is on exploring the river-aquifer interactions, the well locations close to the streams actually can provide more valuable information for the regional groundwater inflow to rivers. We have recommended that weighting scheme reflecting this might improve the approach further (Line 682 – 685), but consider it out of scope in the current work.

- In the second paragraph of the section “3.1.3 Data cleaning”, we described the groundwater level observations (Line 167-178). In general, groundwater level observations from different sources have different measurement intervals, which can be daily, weekly, biweekly or monthly. They are all from shallow aquifers, with the depth to water table less than 20m. We will improve the description of groundwater level observations in this part to be more clear.

Publication Strategy

With 23 Figures and 45 pages, this paper is overly long with several uncoordinated threads. Yet even at this size, there are major gaps in the description of the hydrogeological setting and data deficiencies that are concerning. My recommendations would be for the authors to rethink their publication strategy to create several papers with different purposes.

With modest effort, there might be a first paper to examine unique features of the hydrologic settings, especially basin morphology, elevation, land use land cover, in predicting hydrographs. It might be necessary to find an approach to reconstruct (downscale) hydrographs to improve resolution. Also, high-resolution water sampling of one storm – with specific conductance etc. together with a few groundwater samples could provide a better understanding of where inter-storm water is coming from.

A second paper might be designed to develop a more sophisticated understanding of water-level behaviors in a model system with a uniform rainfall to begin exploration of the impulse response modeling of the first link – precipitation groundwater.

Finally, a third paper might extend to modeling baseflow as you have done in this paper. But with a much better concept of how everything is working. I would also recommend that you only return to hydrograph separation with a tunable scheme that would integrate basic approaches with some kind of observational approach.

Jones et al 2006 DOI:10.1029/2006WR005416

Liu et al 2013 ISSN : 1866-6280

- Thank you for the suggestions. As this study is focused on the river and shallow aquifer interactions, we included a general description of the hydrogeological setting and focused on describing the surficial geology. We will improve the hydrogeological setting description in the study area section in the revised manuscript.

- We agree that the paper is long. Most papers cover only one study site, while in this study three catchments are included. The data preparation and method description are also described quite in detail. Considering your suggestions, we would like to shorten the manuscript a bit, for instance, reduce the description of the data preparation section, shift some figures (Figure 6, 10) to appendix or remove them if they are deviated from the main objectives, and leave out some less relevant descriptions in the original manuscript.

- We appreciate the suggested publication strategy of three papers. However, this work already is part of a larger strategy, with the field data interpretation and numerical modelling approaches being next. Therefore, we would prefer to address the length of the manuscript, and focus more on the main goal instead of splitting it up.

References

- Dirk, Maes. The use of monitoring systems in nature reserves, an example: "De Vallei van de Zwarte Beek" at Koersel-Beringen (Limburg, Belgium). Conference: 8th International Colloquium of the European Invertebrate Survey , 1992.
- Turkelboom, F., Demeyer, R., Vranken, L. et al. How does a nature-based solution for flood control compare to a technical solution? Case study evidence from Belgium. Ambio 50, 1431–1445, https://doi.org/10.1007/s13280-021-01548-4, 2021.