Responses to Anonymous Referee #1

We thank the referee reviewer very much for reading our work and insightful comments. Those comments really let us know the unclear part of our manuscript and help us a lot to improve our manuscript.

Since the manuscript is still under discussion phase, we would like to write this quick response to explain some most important issues which are missing in the manuscript. As comments from the other referee reviewers are not ready yet, we are not going to present the fully revised manuscript in this response. Of course, once the other reviewers' comments are available, we will incorporate those modifications into the final revision.

Before we reply to any specific questions of the comments, we would like to clarify two points.

The first point is that we would like to explain the linear groundwater reservoir in mHM, which was not directly explained in the manuscript since it has been included in the references(Kumar et al., 2013; Samaniego et al., 2010). mHM contains a linear reservoir to generate daily baseflow (please see Figure 1). The generated baseflow of each grid are further routed into streams using Muskingum-Cunge method. In the coupled model mHM#OGS, we take spatially distributed recharge and routed baseflow generated by the linear reservoir, then feed these two boundary sources to GIS2FEM (the coupling interface to convert unit and adjust time step), and then to OGS as upper boundary conditions. The baseflow is still calculated by the linear reservoir in mHM and routed into runoff (please see Figure 1). We have now noticed that the detailed explanation of the linear groundwater reservoir is essential and will include it into the revised manuscript.

The second point is that we are not aiming to develop a fully physically-based model. We are not aiming to study the mechanistic interaction of soil-zone processes and the groundwater heads. Instead, we are aiming to develop an open-source regional-scale model which can predict catchment runoff and groundwater head dynamics simultaneously, while preserves all existing and well-tested mHM features, e.g., the parameterization scheme (Kumar et al., 2013; Rakovec et al., 2016; Samaniego et al., 2010, 2017).

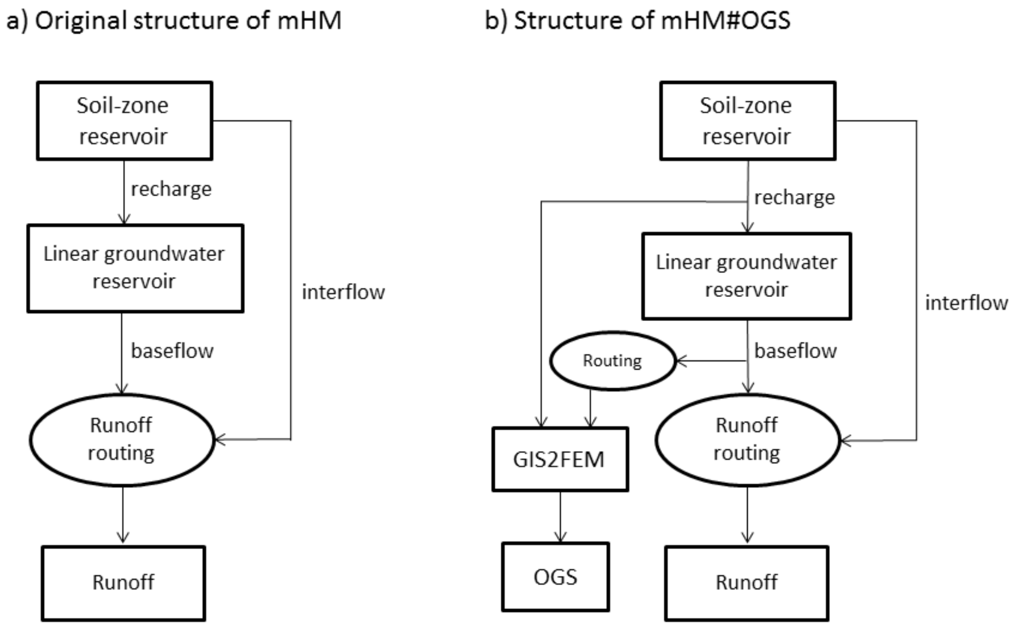

Figure 1 mHM#OGS as an approach into realization of groundwater head

Major comments

1. The authors present a coupling approach for a land surface hydrologic and ground water flow model, mHM and OGS respectively. The manuscript contains sections on the coupling, model setup over a real catchment and verification of the results. The model coupling is not explained appropriately and it's not clear, whether the coupling approach satisfies the current state-of-the-art published in GMD. Based on the provided explanation, the results cannot be assessed unfortunately.

   Thank you for your comment. Enabling the reader to independently reproduce the results is an important aspect of the publishing process of GMD. To improve that part, we will significantly revise the model section in order to make our approach more clear to the reader and avoid misconception on our work. We will also provide a fully accessible code, a test example together with all needed data in the Github repository.

2. Introduction The introduction is incomplete and misses some of the most important and heavily cited references of integrated models and modeling studies of the terrestrial water cycle. Apparently the authors are not aware of the state-of-the-art. Proper citation of the mentioned models is missing. Is the sole goal of the introduction to promote the work of the co-authors (e.g. statement p 3, l 12-15 and citations throughout)?

Thank you for your insights. We will revise the whole introduction section accordingly and cite all the up-to-date papers properly.

To better convey these points and avoid possible future misunderstanding, we will revise the introduction section in manuscript accordingly. In addition, we further expand our literature review by properly referencing integrated surface/subsurface hydrologic models (ISSHMs) such as InHM (Smerdon et al., 2007; VanderKwaak and Loague, 2001), Parflow (Maxwell et al., 2015), tRIBS ((Ivanov et al., 2004), CATHY (Camporese et al., 2010), GSFLOW (Hunt et al., 2013; Markstrom et al., 2008), HydroGeoSphere (Hwang et al., 2014; Therrien et al., 2010), MIKE SHE (Graham and Butts, 2005), MODHMS (Panday and Huyakorn, 2004; Phi et al., 2013), GEOtop (Rigon et al., 2006), IRENE (Spanoudaki et al., 2009), CAST3M (Weill et al., 2009), PIHM (Kumar et al., 2009; Qu and Duffy, 2007) and PAWS(Shen and Phanikumar, 2010), in the revised manuscript. The coupled land surface / groundwater models (CLSGMs) include ParFlow-CLM (Ferguson and Maxwell, 2010; Maxwell and Kollet, 2008; Maxwell and Miller, 2005; Rihani et al., 2010), tRIBS + VEGGIE (Ivanov et al., 2008, 2010), SWAT and MODFLOW (Guzman et al., 2015; Kim et al., 2008), PCR-GLOBWB-MOD (Sutanudjaja et al., 2014), SWMM-OGS (Delfs et al., 2012). Nevertheless, we will revise this section in order to convey comprehensive information of the state-of-the-art science.

Next, we would like to clarify that the within the context of our manuscript a “coupled model” is not the same as a “physically-based” or “mechanistic” integrated model. We will include this point into the storyline in the revised manuscript. What we want to develop is a hybrid model that is using two different modeling paradigms which can be easily applied in regional and continental scale, rather than a mechanistic integrated model. Our reasons for this decision is that more conceptual process-based models like mHM or Noah-MP are good at predicting quantities like discharge but are highly conceptualized and there suffering from interpretability of certain processes (e.g., base flow and interflow components). More mechanistic models like Parflow and HydroGeoSphere are highly interpretable but show consistently worse performance when predicting runoff (Paniconi and Putti, 2015). To the best of our knowledge, the skill of simulating groundwater head dynamics at regional scale of mechanistic models are always neglected and seldom assessed by the data (e.g. GW head, tracer). At the larger scale, the assessment of modeled groundwater heads dynamics can only be found in very few publications (De Graaf et al., 2015; Sutanudjaja et al., 2011).

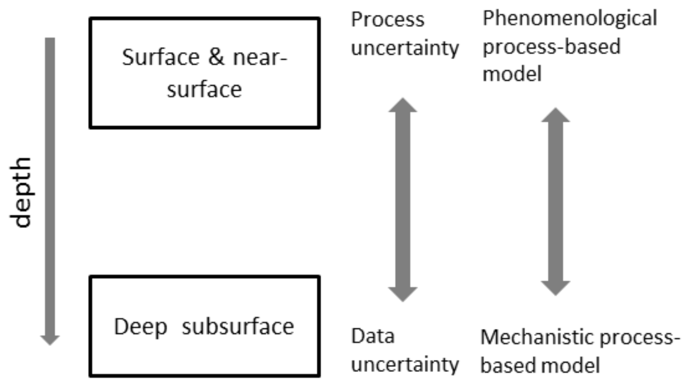

Figure 2 Different questions and challenges in surface and subsurface hydrology

The above mentioned different abilities of more phenomenological models (e.g., mHM, Noah-MP, etc) vs. the more mechanistic models (e.g., Parflow, Hydrogeosphere, etc.) is caused by the different challenges that are posed by the different compartments of the terrestrial water cycle. One of the main challenges in the surface & near-surface storage is process uncertainty, with the fact that processes like ET, land use, land cover, snow pack, etc. are extremely complex. The process uncertainty decreases as it goes deeper and deeper into the subsurface storage. In subsurface storage, hydrological processes are under Darcy's law and therefore conceptually simpler. Meanwhile, the data uncertainty becomes more significant in deep subsurface storage than in shallow storage (see schematic in Figure 2). Therefore, proper conceptualization is needed in the shallow storage in order to deal with this process uncertainty (please see schematic in Figure 2). Owing to this point, mHM was developed as a bucket-type model to better deal with this process uncertainty by optimally leveraging the information content in the discharge data. On the other hand, OGS is a mechanistic model, i.e., it has a very low process uncertainty but large amount of data uncertainty. It is therefore optimally suited to model processes in the deeper subsurface. To use the strengths and weaknesses of both these modeling concepts, we decided to separate our modeling domain into these two compartments, a strategy that is very common in hydrology (Benettin et al., 2015; Bertuzzo et al., 2013; Botter et al., 2010; van der Velde et al., 2015), and use this different modeling paradigms for each compartment.

We will also add the following two paragraphs into the revised manuscript:

At the larger, i.e., regional scale, most of the mechanistic integrated models are based on a continuity of pressure and flux on the SW/GW interface, while the momentum balance condition is always missing (Paniconi and Putti, 2015). The runoff is generally normalized as "storage-dependent runoff" by solving Richards equation, and the grid-wise generated runoffs are routed by a routing algorithm. These models can principally simulate the dynamic interaction of different processes with SW/GW components, e.g., the interaction of soil moisture and GW head (Cuthbert et al., 2013; Maxwell and Miller, 2005; Rihani et al., 2010; Sutanudjaja et al., 2014), the storage-runoff correlation (Fang and Shen, 2017; Huntington and Niswonger, 2012; Koirala et al., 2014; Liang et al., 2003; VanderKwaak and Loague, 2001), and the dynamical interaction between ET and GW head (Chen and Hu, 2004; Koirala et al., 2014; Yeh and Eltahir, 2005).

In constract to that, in this study, we present a one-way coupling model mHM#OGS and focuses on the representation of Infiltration-Excess Recharge (IER) and Linear Baseflow (LB) through a case study of a mesoscale catchment. The basic scientific question we want to answer is: Can spatially distributed groundwater heads and their dynamics be reasonably captured by expanding on the abilities of a phenomenological model like mHM at the regional scale? Based on the case study, we would conclude that this expansion was successful since in addition to predicting discharge, our coupled model is also able to predict head measurements as well. Since our focus is the predictive accuracy of mHM (compared to interpretability and inference), we consider the physical plausibility of the coupling of recharge and baseflow to be a means to that end and not an end in itself. Improving the plausibility of these processes will, if done right, also lead to higher predictive power. We will elaborate on these points on more details in our answers to Comment 7.

3. Model description Section 2.1 and 2.2 must be expanded. At least, the reader must get some idea about the basic principles that are used to model the different processes mentioned in passing, in order to assess the validity of the coupling. In section 2.3, figure 1b, suggests one-way coupling only i.e. mHm provides "groundwater recharge and base flow as boundary conditions to mHm" (p 3, l 16-17). Since mHm does not include groundwater, how can the calculation of these fluxes be mechanistic (p 3, l 15), because groundwater recharge strongly depends on the dynamics of the water table? Thus, the scarce information provided in this section in combination with the statements in the introduction are misleading to the reader.

   This is an important observation by the reviewer, since these sections need to contain the relevant information to enable the reader to replicate our results. To address this current shortcoming, we will expand section 2.1 and 2.2 and make the description more clear. We would like to state our basic coupling principle as the following paragraph and add the two paragraphs into the revised manuscript:

   The current mHM#OGS model is a one-way coupling model and focuses on the assessment of infiltration-excess recharge (IER) and linear baseflow (LB). Considering the different equation systems of two models (ODEs in mHM and PDEs in OGS), the mechanical coupling that fully satisfy conservation of mass, energy and momentum is theoretically impossible. The one-way coupling method can guarantee conservation of mass and was used in this study.

We will also add Figure 1 and its corresponding explanation into the revised manuscript. We believe the readers will get a clear picture of our modeling approach in the revised manuscript.

4. Section 2.3.2 with the title “Boundary condition-based coupling” provides the basic equations, yet leaves the reader wondering how the coupling is really done. Something is said about the exchange of fluxes via qe and qe’ (p 7, l 3), but these are sources not boundary fluxes. What is equation 2? The upper boundary condition for the groundwater flow model? Shouldn’t the coupling be performed via equation 2 as promised in the section title? In addition, the authors state that “the coupling interface converts time series of variables and fluxes to Neumann boundary conditions...”. How does that fit in? This reader is left confused.

   Again, this is an important observation by the reviewer. We admit that the qe and qe’ in equation 1 is redundant and will confuse the readers. It is the equation 2 that works to connect mHM and OGS. We will delete the equation 1 and revise section 2.3.2 carefully to make sure the “boundary condition-based coupling” is properly presented. With regard to the sentence “the coupling interface converts time series of variables and fluxes to Neumann boundary conditions...”, it means that the boundary condition-based coupling is performs by interpolating recharge and baseflow in the interface GIS2FEM, e.g., from coarser grid size in mHM to the finer grid size in OGS. In the revised manuscript, we will restructure this section following the reviewer’s comments.

5. Figure 2 is not instructive. What is GIS2FEM doing? Interpolating? How does the coupling work in the vertical direction for each column? As I understand, mHm has a fixed column depth. Can the water table rise into the column along e.g. river corridors? And where does the baseflow go in OGS? How is groundwater storage in mHm (p 7, l 9-10) related to OGS? There is apparently no backward exchange with mHm due to baseflow and exchange with river networks, and no capillary rise. This reader is left confused.

   We appreciate this constructive criticism. Explaining this tool appropriately is indeed necessary for the understanding of the coupling procedure and must therefore not be omitted. GIS2FEM is the model interface which is used to interpolate recharge and baseflow between different grid sizes of two models (p 7, l 19-24).

   The baseflow is not determined by OGS. Instead, it is determined by the linear reservoir in mHM and then routed into the runoff (see Figure 1). The water table cannot rise into the column along river corridors because we use the linear groundwater storage in mHM to calculate baseflow. The linear reservoir is a simplified reservoir with an overall aim of predicting runoff, whereby the dynamic interaction with groundwater head is conceptualized and simplified in order to keep the robustness of parameterization scheme, which is a unique feature of mHM.

6. On p 7, l 17-18, what do the authors mean by conversion between volumetric flux, specific flux and water head? Where in the coupling is this conversion required and why does the cell sizes need to be adjusted (there is actual re-gridding going on)?

   Thank you for your questions. The conversion is in terms of unit conversion, e.g., from distributed recharge in mHM (m/s) to volumetric recharge in OGS (m^3/s). There is no re-gridding going on. The boundary fluxes are directly interpolated from mHM to OGS using the interface GIS2FEM.

7. From table 2 it appears that in the author's eyes, coupling and integrated modeling of the terrestrial water cycle simply means to pass groundwater recharge values from a 1D hydrologic land surface scheme to a steady state groundwater flow model and return a head value back as some lower (boundary) condition for the hydrologic scheme (not indicated in figure 1). I feel, in the geosciences, we moved beyond this type of approach quite some time ago.

   Thank you for your comments. We are, however, afraid, that some of the reviewer's comments here are at least in part based on a misunderstanding. We will modify table 2 accordingly so that the right information can be clearly conveyed. The reviewer said "pass groundwater recharge values from a 1D hydrologic land surface scheme to a steady state groundwater flow model and return a head value back as some lower (boundary) condition for the hydrologic scheme", which is unfortunately a misunderstanding. The modeling system is basically one-way pass, which means infiltration-excess recharge (IER) and linear baseflow (LB) are calculated by mHM alone, and then passed to OGS as an upper boundary condition to force the transient groundwater model (please see Figure 1).

   To better motivate this strategy, we would like to elaborate on this decision by continuing the discussion form Comment 2. As mentioned there, we are not aiming to develop a single, seamless, mechanistic, integrated model. Instead, we are trying to establish a "hybrid model" that bridges the gap between two distinct models and makes use of the best of their abilities (see also our answers to Comment 2). These two models have different paradigms and address different challenges; First mHM, which aims for a good prediction ability of discharge across multiple time scales as well as multiple spatial-scale catchments. All of it in a computationally efficient way by using ODE's for each compartment. Second, OGS which solves computationally-expensive PDEs that directly implement flow and transport processes by using modern tools like Finite Element Method (see schematic in Figure 2). In order to achieve a two-way coupling model, strong revisions to the implementation of these tools are necessary that will affect in particular the parametrization process of mHM.

The currently described one-way coupling can be seen as the intermediate move towards such a fully-coupled hybrid model. However, next to leading to such a more thorough coupling, the one-way coupling, described here, has a number of advantages that make it a viable modeling strategy in and of itself. First, the one-way coupling can be regarded as a safe or conservative approach, such that the parametrization process, which is one of its most salient features of mHM, remains fully intact. That way, we do not compromise any of its well-established features, such as calibration of model parameters at different scales and good runoff prediction ability, while getting in addition very good estimates of groundwater storage, flow paths and travel times. The lack of mHM to provide good estimates for these quantities has been noted in the past (see, e.g., Heße et al. 2016; Rakovec et al. 2016) and extends therefore the predictive abilities of mHM. Second, using such a one-way coupling will allow users of mHM to simply extend currently established catchment models and extend their abilities in the aforementioned way. Using a more sophisticated two-way coupling, would mean that user would have to re-establish these models almost from scratch. Third, even in the future, a one-way coupling would allow to easily expand the predictive power of a mHM catchment model if the practitioners later decide to do so, therefore leaving the option open. In short, unlike a two-way coupling, the one-way coupling described here allows the user to expand the abilities of mHM without sacrificing any of its well-known and well-established properties (Kumar et al., 2013; Rakovec et al., 2016; Samaniego et al., 2010, 2017).

In addition to improving the predictive power of mHM, OGS is gaining a strong advantage for the description of the top boundary condition, i.e., the recharge, which is temporal and spatially variable through the input of mHM. Even more, the recharge fluxes provided are based on mHM’s phenomenological process description, which significantly better describes the surface level recharge fluxes than common approaches through empirical relations derived recharge rates. In the future, we additionally plan to advance in the description of water fluxes between surface and groundwater compartments through the coupled feedback between both simulation tools.To further explain the motivation for the presented one-way coupling, we like to detail some relevant research questions that can now already be answered with our model; Kumar et al (2016) have demonstrated that the Standardized Precipitation Index (SPI) has a limited applicability and low reliability in characterizing groundwater drought. Our model can be a useful tool in predicting groundwater drought & flood under different climate conditions (please check Figure 11 and 13 in the referenced manuscript). Moreover, the coupled model can be used to quantify the catchment scale legacy nitrogen stores in groundwater reservoirs. Recent research shows that a large portion of legacy nitrogen can be older than 10 years (Van Meter et al., 2017). The current version of mHM#OGS fits well with the long-term simulation of nitrogen transport in terrestrial water cycle. The combination of process uncertainty at surface hydrology and data uncertainty at subsurface hydrology is challenging to understand travel time distributions (TTDs) at catchment scale (Benettin et al., 2015; Bertuzzo et al., 2013; Botter et al., 2010; van der Velde et al., 2015). The coupled model mHM#OGS is valuable at TTDs simulations based on the high-reputation of two modeling codes in each other's fields. In addition, field and modeling experiments at large scales suggest that the way bottom boundaries, bedrock interfaces, and other layers are treated will have a large impact on hydrological response (e.g., groundwater heads) (Broda et al., 2011; Buttle and McDonald, 2002; Ebel et al., 2008; Uchida et al., 2002, 2003).

Finally, we would like to conclude by saying that establishing a fully tow-way-coupled hybrid model, which also accounts for dynamic interaction of SW and GW, is a high priority. However, based on the challenges outlined above as well as the problem that such a model would sacrifice some of the predictive power of mHM (e.g., discharge), we consider the present coupling strategy a valuable and viable alternative in its own right, both for the meantime and the future.

To better convey these points, we will revise the introduction section of the manuscript accordingly.

8. The description of the study area and model setup, calibration etc. belong into a separate section.
   The results can not be assessed unfortunately, because of the poor explanation of the applied modeling and coupling techniques.

   We appreciate this observation. If other reviewers do not explicitly argue against this notion, we will separate this section into two sections in the revised version of the manuscript. There, we will also provide the source code of the coupled system, the test case along with all needed data in the Github repository in order to facilitate all interested people.

9. Language and grammar require considerable improvement.

   Thank you. We will thoroughly revise the manuscript and check it with a native English speaker.

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