# Responses to Referee Review 2

We are grateful to the second referee reviewer for his/her comprehensive and insightful comments. Our responses to the reviewers' comments are given below. The original comments from the referee reviewer were marked with blue color, and our response in black. The page and line numbers in our responses refer to those in the marked copy of the revised texts.

General comments

The authors of the manuscript propose a combined three-level modeling approach to investigate the influence of climate change on the groundwater levels and groundwater travel time in a small agricultural watershed in central Germany. They use 5 different global circulation models, which provide climate data for mesoscale hydrologic Model mHM. In turn, mHM predicts values of groundwater recharge, which are in turn used as input in a 3D saturated groundwater flow model implemented in OpenGeoSys. Thus, their work is a valuable contribution to the development of comprehensive modeling approaches describing hydrological systems. This type of analysis is much needed in view of the discussion on the possible effects of global warming. The main finding is that the influence of climate change on the groundwater travel time is more pronounced than the influence on groundwater levels.

We agree with the comments of the first reviewer, who pointed out important limitations of the manuscript. They are related to (i) neglecting of unsaturated zone processes and the influence of shallow groundwater table on surface hydrology, (ii) use of coarse-grid model for calculating recharge rates, (iii) other possible sources of uncertainty, besides the differences between climate models. In the revised version, these issues were addressed by providing additional simulations and extended discussion.

Response:

Thank you very much for your overall evaluation of our study. We will revise the manuscript carefully based on your comments.

My general comments related to the current version of the manuscript are as follows: 1. We would like to see more information about the actual values of recharge and recharge/precipitation ratio in different scenarios. Does the recharge change proportionally to the precipitation in all scenarios, or maybe there were some nonlinear effects, such as those mentioned by the authors on page 3, lines 2-4?

Response: Thank you so much for these important observations. We fully agree with the reviewer that the actual value and ratio (as a proportion of precipitation) of recharge are critical to the understanding of climate effect. These behaviors are shown in Figure 1. We can see that the actual annual recharge rates are between 100 mm to 145 mm depending on different climate scenarios and warming levels. We can also observe that the change in recharge rate is not proportional to that in precipitation. For example, the recharge ratio in GFDL-ESM2M increases from 0.178 to 0.212 following the increase of warming levels. Conversely, the recharge ratio in HadGEM2-ES decreases slightly in 3 degree warming. This phenomenon indicates a non-linear relationship between the changes in recharge and precipitation depending on different climate models.

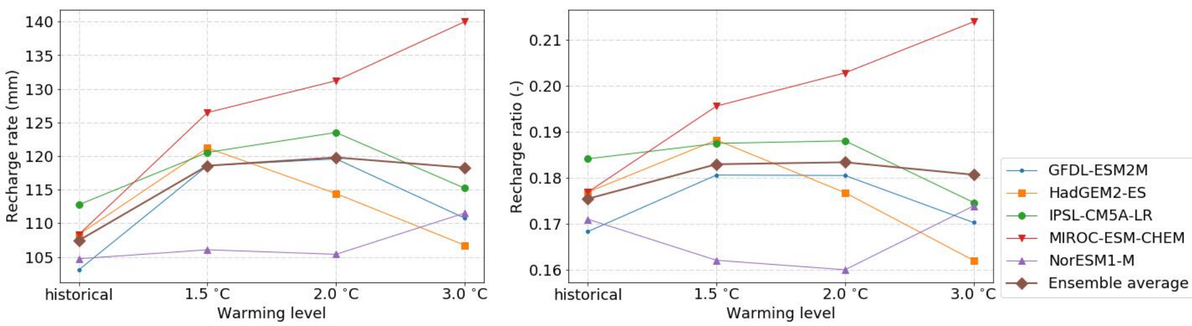


**Figure 1 Actual recharge rates and recharge ratio (as a proportion of precipitation) under different warming levels.**

2. What was the spatial variability of recharge obtained from mHM? Even using 5x5 km grid you should see some differences in the watershed area. Was the degree of variability similar in all scenarios?

Response: This is an important observation. To answer this question, we take a close look at the spatial pattern of recharges in different climate scenarios. Specifically, we find that the spatial patterns of projected recharges appear to be very similar among each other (Figure 2). However, the relative changes in recharges are different among different GCMs (Figure 3). This spatial variability can be attributed to the heterogeneous topography and land use (e.g., the forests in western hilly areas and the croplands in central lowlands) . Alternatively speaking, the degree of changes depends on the local topographic, morphologic, and hydraulic properties of soils. This shows the importance of deploying a spatially distributed hydrological model in projecting regional hydrological responses.

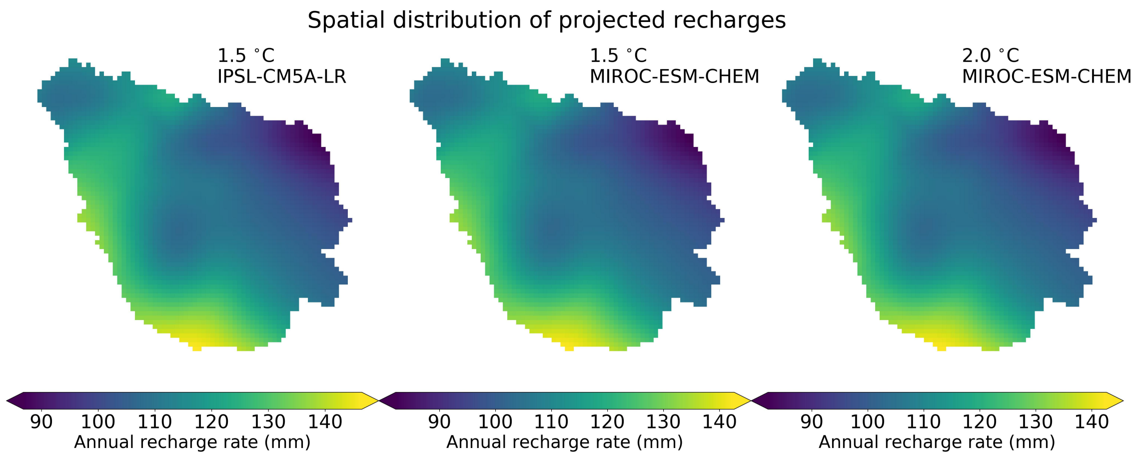


Figure 2 Spatial distributions of projected recharges under 1.5 and 2 degrees warming using two GCMs.

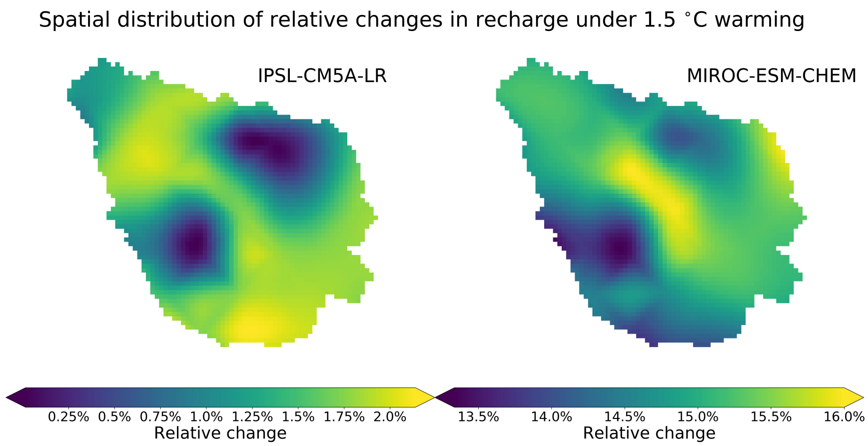


Figure 3 Spatial distributions of relative changes using two different GCMs in projected recharges under 1.5 degree warming.

3. On page 17, lines 10-15 the authors mention that their model is able to simulate correctly the appearance of additional groundwater discharge zones when the water table rises, as shown in Fig.9. This should be explained in more detail. How is this kind of boundary condition treated in OpenGeoSys? Is it possible that groundwater heads in the top layer of cells are above the ground level? It would be nice to see actual model results supporting the concept shown in Fig. 9.

Response: Thank you so much for your insights. We would like to clarify that Figure 9 in the manuscript is a conceptual graph that shows a possible consequence of the increased groundwater levels (Havril et al., 2018; Kaandorp et al., 2018; Toth, 1963). The current groundwater model is based on predefined geometry of stream network, and is not able to simulate the appearance of additional groundwater discharge zones. We discuss the possible consequences of a rising groundwater level, especially in areas where the groundwater depth is shallow. Many past studies have demonstrated that the rise of groundwater level in shallow groundwater aquifers will lead to the activation of additional discharge paths (Havril et al., 2018; Kaandorp et al., 2018; Toth, 1963). In the current model, the discharge zones (streams) are predefined and do not change in the simulations. Specifically, a fixed head boundary is assigned to the main perennial streams including one mainstream and three tributaries. From our simulations, we find that the large changes in groundwater levels happen at hilly areas, whereas changes in central lowlands are not as significant as those in hilly areas. We carefully checked all simulation results to ensure that the groundwater levels are all below the ground levels.

Note that this study is not designed to investigate the change in discharge zones under the climate change. Rather, it is designed to investigate the trend and the predictive uncertainty in the quantity and travel times of a regional groundwater system using ensemble simulations. To avoid possible misunderstanding and misinterpretation, we removed the original Figure 9 in the revised revision. We also modified the relevant discussions to avoid potential misinterpretations.

4. Technical correction: Page 5, last line "C" after "degree" symbol seems redundant.

Response: Modified as proposed.

## References

Havril, T., Tóth, Á., Molson, J. W., Galsa, A. and Mádl-Szonyi, J.: Impacts of predicted climate change on groundwater flow systems: Can wetlands disappear due to recharge reduction?, J. Hydrol., 563, 1169–1180, doi:10.1016/j.jhydrol.2017.09.020, 2018.

Kaandorp, V. P., de Louw, P. G. B., van der Velde, Y. and Broers, H. P.: Transient Groundwater Travel Time Distributions and Age-Ranked Storage-Discharge Relationships of Three Lowland Catchments, Water Resour. Res., 1–18, doi:10.1029/2017WR022461, 2018.

Toth, J.: A Theoretical Analysis of Groundwater Flow in Small Drainage Basins, J. Geophys. Res., 68(16), 4795–4812, doi:10.1029/JZ068i016p04795, 1963.