Responses to Referee Review 1

We thank the referee reviewer for his comprehensive and insightful comments. Our responses to the reviewers' comments are given below. The original comments from referee reviewer 1 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

From the description provided in the methodology and materials section I argue that mHM and OGS, the mesoscale hydrological model and the groundwater model are decoupled. In fact, at line 13 of page 5 I read "The projected recharge from mHM calculations are fed to the groundwater model OpenGeoSys (OGS) for the assessment of groundwater quantity and travel time distribution." From this short description I concluded that vertical fluxes, including those of the unsaturated zone are modeled with mHM and that the resulting "deep" infiltration is used as recharge (i.e., as boundary condition) for OGS. In doing that the processes of infiltration and flow inside the aquifer are decoupled. This may be reasonable when the water table is deep, but I am wondering what is the impact of this assumption on the simulations showing significant rises of the water table. In this situation decoupling leads to significant errors as the water table gets close to the ground surface. This is relevant both for water levels and the following travel time analysis. The authors provide only limited information on this important point and do not discuss its implications in term of representativity of the model. Decoupling these two processes is a great advantage from a modeling point of view, but I am not sure it can be actually introduced at least in the scenarios showing the largest increase of groundwater levels.

Response:

We fully agree with the reviewer that groundwater dynamics can alter land surface response and feedback to the climate system, especially in cases that the groundwater level is shallow. The dynamic feedback from groundwater to land surface processes can introduce a second-order impact on the groundwater table and travel times. A fully coupled system, based on a mixed form of the Richards equation, is more realistic than the one-way system [1]. However, fully coupled model constantly suffers, among other things, from expensive computational burden, which limits its applicability in large-scale real-world models. It also introduces data burden involving several extra parameters, which are essentially unknown at the catchment scale. Due to the above reasons, we didn't apply fully coupled system in this study.

Following previous studies [4,5,6], we adopted here the one-way coupling between the (near) surface hydrologic and groundwater models for investigating groundwater resources. We have successfully demonstrated the utility of this model for adequately capturing the observed behavior of groundwater levels across the study basin [8]. The current modeling method, although less accurate than the fully-coupled model, is computationally more efficient – allowing us to understand the first order control of climatic variability on groundwater characteristics (groundwater level and travel times). Notably the applied Lagrangian particle tracking in the 3D groundwater model is computationally very expensive. The computational time performing a single model run is around 20 days using 40 cores on a super computer facility. Our analyses make use of large hydro-climatic ensemble scenarios (based on the multiple GCMs/RCPs and a hydrologic model, mHM combinations) – thereby accounting for the input uncertainties to the driving groundwater model, which is particularly important and recommendable for any climate change impact assessment studies [4,12,13,14]. Accordingly the one-way coupling method used here is a practical choice, allowing us to perform the large ensemble scenarios with reasonable computational resources (and time).

Nevertheless, we also agree with the reviewer that the limitation of the current method should be discussed in the manuscript. Accordingly, we modified the discussion section to include the following information (please check **l.26-35, p.18**, and **l.1-4, p.19**): *"A potential limitation of the current modeling framework lies in the simple one-way coupling approach that neglects the feedback from groundwater level change to the land surface processes. The change in groundwater table can alter the partitioning of water balances, which further exerts a second-order impact on the groundwater level and travel times. The fully coupled system, based on a mixed form of the Richards equation to solve unsaturated and saturated zone flow simultaneously, is more realistic than the one-way coupled system. However, fully coupled model consistently suffers from expensive computational burden, which limits its applicability in large scale real-world models. It also introduces extra parameters that are essentially unknown at the catchment scale. The current one-way coupling, although less accurate than the two-way coupling, is computationally more efficient – allowing us to understand the first order control of climatic variability on groundwater* *characteristics (groundwater level and travel times). Notably, the applied Lagrangian particle tracking in the 3D groundwater model is computationally very expensive. Moreover, we have successfully demonstrated the utility of this model for adequately capturing the observed behavior of groundwater levels across the study basin. Accordingly, the one-way coupling method used here is a practical choice, allowing us to perform the large ensemble scenarios with reasonable computational resources (and time).”*

Another aspect that is not fully explained is the validation of the groundwater simulations. The authors touch very briefly this point by saying that mHM has been validated at the European scale in a previous paper, but what about this specific small catchment or the larger, but still small compared to the European scale, Thuringian catchment? And what about the groundwater model? At page 8, line 17 I read: "The post-calibrated values of the hydraulic conductivity in each geological unit obtained from a previous study are assigned to the corresponding geological layers of the mesh (Jing et al., 2018a). Meanwhile, a uniform porosity of 0.2 is assigned to each geological layers (Table 2)". In a previous work (Jing et al., 2018a) the authors presented a comparison between observed and simulated heads at a number of observation wells (Figure 5 and related text on section 3.2.5) and for a number of recharge scenarios. The analysis is based on 400 calibrated Monte Carlo realizations and I am wondering if the authors used all the 400 realizations in the present work, or just one, in the latter case what was the criteria used to assign the hydraulic conductivity? Figure 5 of the previous paper shows apparently a good reproduction of the observed heads, but what puzzled me is that the standard deviation of the error is 4.6 m, a rather large portion of the variation presented in this manuscript as an effect of climate change.

Response: We thank the reviewer for these insightful comments. We agree with the reviewer that the validation of groundwater model is very important, and will add more information on the validation of groundwater model in the revised manuscript.

The mHM model has been validated both on the European scale and the catchment scale. The validation result of mHM model on the Thuringian basin is included in previous publications [7,8].

The groundwater model was validated using the observed groundwater levels in many monitoring wells. For the steady state model, a long-term average of observed groundwater levels is compared to the simulation results. The simulation results show a good correspondence to the observations (Fig. 1).

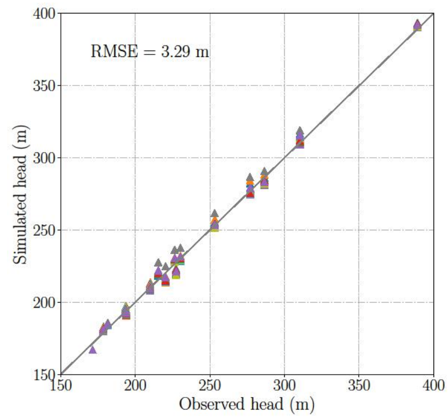

Fig. 1 Validation of groundwater model

The current hydraulic conductivity values for groundwater model are randomly sampled from the 400 parameter sets [9]. The reviewer pointed out that parameter values and its uncertainty can be critical to study results, with which we fully agree. In order to further investigate the parametric uncertainty in groundwater model, we expanded the current parameter set from only one set to 80 different sets. Those 80 parameter sets are all compatible with the groundwater level observations. The 80 parameter sets are randomly sampled from the parameter dataset used in our previous study [9].

The standard deviation of the residuals between observed and simulated groundwater table is 3 to 5 m, which seems to be large. However, the topography is complex in the study area, and the groundwater level difference between the highest and lowest monitoring wells is around 220 m. The CV (coefficient of variation) of the residuals is 2.09%, which is quite low, showing a good reproduction of groundwater dynamics.

According to these important comments, we modified the manuscript to include simulations using many realizations of hydraulic conductivity fields (80 members in total). We also expanded the study to investigate the parametric uncertainty in groundwater model associated with 80 different hydraulic conductivity fields. We presented a comprehensive uncertainty study in the revised manuscript.

The third issue I would like to comment is uncertainty. My impression is that combining a large number of GCM-RCM pairs introduced a large variability of the meteorological forcing and therefore to water levels and travel time distributions, which should be validated in some way. According to the presented analysis it is very difficult, if not impossible, to sort out unrealistic scenarios, or weight less them in the ensemble. On the other hand, uncertainty in the hydrological models is neglected, in particular that related to the groundwater model.

Response: This is another important observation by the reviewer. Substantial uncertainty persists regarding the impacts of climate change on mean precipitation based on the general circulation models (GCMs) under historical and future pathways scenarios [10, 11]. A large spread in projections occurs in many regions and variables due to a combination of variations in the climate sensitivity that determines the magnitude of the average global response, and large variations in the spatial patterns of change – particularly for precipitation [10]. It is a widely used (and recommended) approach to use a large ensemble of GCMs and greenhouse-gas emissions scenarios to account for the inherent uncertainties in impact assessment studies [4, 12, 13]. Besides, it is clear that when exploring the potential impact of climate change scenarios, ensemble spread provides some important, if incomplete, information about the range of plausible future climate changes. This uncertainty information significantly improves the usefulness of climate projection and impact information by (a) allowing policy makers to consider a plausible range of eventualities and (b) informing the appropriate use of uncertain climate projections [10]. We note that the underlying five GCM datasets selected here is a subset of a large CMIP5 archive; covering a range of 0.55 of the uncertainty of the entire CMIP5 ensemble for precipitation and 0.75 for temperature (McSweeney and Jones, 2016). Also these models are bias-corrected with observational datasets in the historical period using the trend-preserving bias correction (see Hempel et al., 2013 for more details); and have been the basis for a large number of impact assessment studies (ISI-MIP; https://www.isimip.org). Accordingly we did not perform any sub-selection and use all available ensemble of GCM-RCP combinations to assess the climate uncertainty, and provided the summary statistics (e.g., mean and SD) to show the possible future scenarios for groundwater resources across the Study area.

In the recent studies, we have evaluated the suitability of GCMs based hydrologic simulations using available streamflow datasets [Samaniego et al., 2018; Thober et al., 2018; Marx et al., 2018]. We agree with the reviewer that the uncertainty in groundwater model should be considered. Indeed in our previous study [9], we performed a detailed investigation on the issue of uncertainty. We modified the manuscript to include simulations using many realizations of hydraulic conductivity fields (80 members in total) – key source of uncertainty in groundwater models. We expanded the study to investigate the parametric uncertainty in groundwater model associated with 80 different hydraulic conductivity fields and contrasted the results with arising from the climate changes. We also presented a comprehensive uncertainty study in the revised manuscript (l.25-30. p.7, l.5-10, p.16, and l.1-10, p.17).

Overall I feel that the manuscript, although interesting and pleasant to read, cannot be accepted for publication in the present form. As it is the manuscript reads like an application of previously published modeling efforts, with little analysis of the results. However, I see value in what the author presented and I think that with some extra effort they may accommodate the above drawbacks, by explaining more the underlying hypotheses and limitations of the current analysis and improving and enriching the discussion of simulation results. With these changes I think this manuscript will be a valuable contribution to the community.

Response: With the responses provided above and the proposed modifications to the revised manuscript, we hope that reviewer may appreciate our work, and will overall find it as a valuable contribution.

Minor comments Page 9 line 6: The recharge seems to increase almost linearly with the temperature, which is strange considering the many nonlinearities involved in the infiltration process;

Response: Yes, but it only indicates that the spread in projected recharges increase in a near-linear way. If we look at the ensemble average of projected recharges, it shows a nonlinear relationship between the recharge and warming level (8.0%, 8.9%, and 7.2% for the 1.5, 2, and 3 degree).

Page 9, line 9: "The projected....." This seems to suggest that the number of combinations of GCM and RCM can be reduced, or even that similar results can be obtained by using only the GCM. Please elaborate a bit more.

Response: See our response above.

We however fully agree with the reviewer that this point should be elaborated in detail. Accordingly, we added the following information into the manuscript*:" Nevertheless, differences in recharge induced by different RCPs can still be witnessed in Figure 3, indicating the necessity of considering multiple GCM/RCP combinations for providing a plausible range of predictive uncertainty."* (l.11-12, p.11)

Page 14, line 17 and following: this sentence is vague. Have these shallow local flow pathways actually been observed in the simulations and how realistic are they?

Response: These shallow local flow pathways exist in areas with complex topography and dense drainage network. In those regions, rising groundwater level may activate shallow groundwater flow paths and intensify shallow local flow pathways. This effect is evidenced by the simulation results. We modify the revised manuscript accordingly to clarify this point.

Page 15 line, 25: this disclaimer, saying that uncertainty may be even larger, since some uncertainty sources have not been considered is somewhat alarming because it casts doubts on the interpretation of the results.

Response: We agree with the reviewer that the more uncertainty sources, e.g., uncertainty in groundwater model, should be considered. We modified the manuscript to include simulations using many realizations of hydraulic conductivity fields (80 members in total). We also expanded the study to investigate the parametric uncertainty in groundwater model associated with 80 different hydraulic conductivity fields. We now present a comprehensive uncertainty study in the revised manuscript (l.25-30. p.7, l.5-10, p.16, and l.1-10, p.17).

Page 16, line 20: How can be that first-order effects of climate change are small and second-order effects are not negligible? If for not negligible you mean that they are however smaller than first-order effects, what is the reliability of their estimate considering the large uncertainty affecting these simulations? Please elaborate more

Response: In the context of this paragraph, the term “first-order effect” means the direct effect of climate change on recharge, and the term “second-order effect” means the effect on groundwater quantity and travel times introduced by the change of recharge. We want to deliver the information that although the relative change in recharge rate seems to be indistinctive, its further effect on groundwater levels and travel times can be significant according to our simulation results.

This original expression, as pointed out by the reviewer, may be somehow misleading. We modified this sentence as the following one: *“To summarize, climate change can significantly alter the quantity and travel time behavior of regional groundwater system through the modification of recharge, especially for the long term. Ensemble simulations indicate a remarkable predictive uncertainty in regional groundwater quantity and travel times, which is introduced by both climate projection and groundwater model.”* (l.3-8, p.20)

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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.

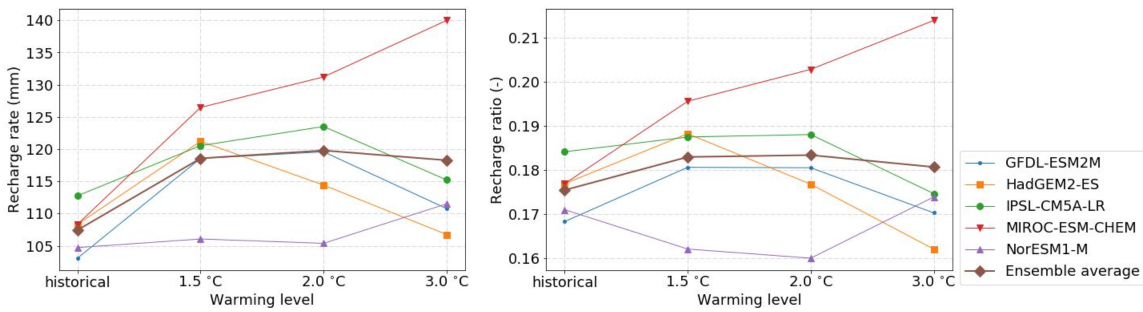

Figure 1 Actual recharge rates and recharge ratio (as a proportion of precipitation) under different warming levels.

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 spatially heterogeneous (Figure 3). This spatial variability can be attributed to the heterogeneous topography and land use. 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. We modified the manuscript accordingly (please check l.1-3, p.16).

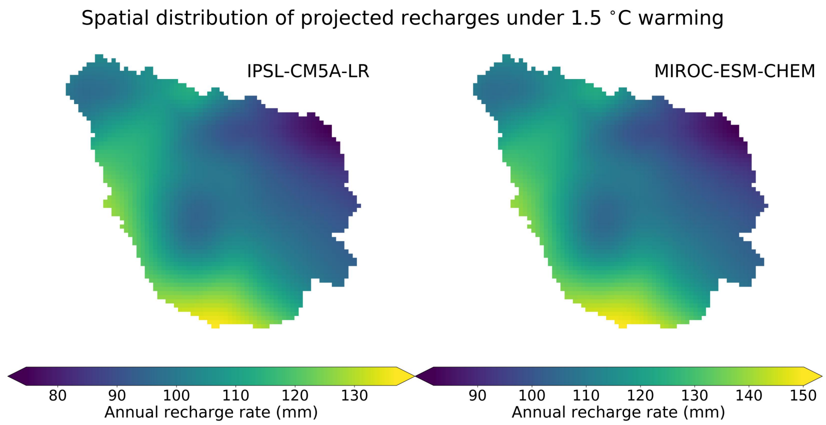

Figure 2 Spatial distributions of projected recharges under 1.5 degree warming.

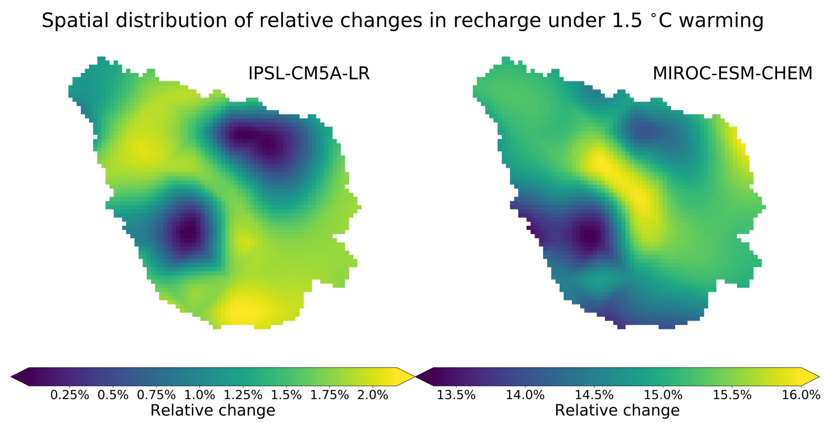

Figure 3 Spatial distributions of relative changes in projected recharges under 1.5 degree warming.

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 of Figure 9, we deleted it 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

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List of main changes in this revision

The page and line numbers in this document refer to those in the **marked copy** of the revised texts.

1. **The Main contributions** of this study within the existing literature are highlighted in the revised manuscript (please see l.4-5, p,18, and l.14-18, p.18).

2. The detailed discussions on the **limitations of current coupling approach** are added into the Discussion section (see l.26-35, p.18, and l.1-4, p.19). This corresponds to the first general comments from Referee Review 1.

3. A subsection elaborating the **validation of groundwater model** is added as subsection 4.3 (please check out the corresponding subsection in the revised manuscript). This also corresponds to the second general comments from Review 1.

4. An ensemble of simulations using a large number of hydraulic conductivity fields is set up to investigate **the predictive uncertainty introduced by hydraulic properties** (l.25-30. p.7, l.5-10, p.16, and l.1-10, p.17). A graph showing the results (Figure 9) has also been added into the manuscript. This also corresponds to the third general comments from Review 1.

5. A new figure (Figure. 8) and the elaboration on the **spatial pattern of projected recharge in different climate scenarios** (l.1-3, p.16) are inserted into the revised manuscript. This corresponds to the second general comments from Review 2.

6. The original Figure 9 has been removed to avoid the potential misinterpretation. corresponds to the third general comments from Review 2.

7. A new paragraph describing the manuscript organization is inserted in the end of the Introduction chapter (l.1-5, p.4).

8. The abstract has been moderately modified (l.10-16, p.1).

9. Many errors of spelling or grammar are corrected.

Assessing the response of groundwater quantity and travel time distribution to 1.5, 2 and 3 degrees global warming in a mesoscale central German basin

Miao Jing[1,2], Rohini Kumar[1], Falk Heße[1], Stephan Thober[1], Oldrich Rakovec[1,3], Luis Samaniego[1], and Sabine Attinger[1,4]

[1]Department of Computational Hydrosystems, UFZ – Helmholtz Centre for Environmental Research, Permoserstr. 15, 04318 Leipzig, Germany

[2]Institute of Geosciences, Friedrich Schiller University Jena, Burgweg 11, 07749 Jena, Germany

[3]Czech University of Life Sciences, Faculty of Environmental Sciences, Prague, 169 00, Czech Republic

[4]Institute of Earth and Environmental Sciences, University of Potsdam, Karl-Liebknecht-Str. 24–25, 14476 Potsdam, Germany

Correspondence: Miao Jing (miao.jing@ufz.de); Falk Heße (falk.hesse@ufz.de)

Abstract. Groundwater is the biggest single source of high-quality ~~fresh water~~ freshwater worldwide, which is also continuously threatened by the changing climate. ~~This paperis designed to~~ In this paper, we investigate the response of the regional groundwater system to ~~the~~ climate change under three global warming levels (1.5, 2, and 3 °C) in a central German basin (Nägelstedt). This investigation is conducted by deploying an integrated modeling workflow that consists of a mesoscale Hydrologic Model (mHM) and a fully-distributed groundwater model OpenGeoSys (OGS). mHM is forced ~~by~~ with climate simulations of five general circulation models under three representative concentration pathways. The diffuse recharges estimated by mHM are used as ~~outer forcings of~~ boundary forcings to the OGS groundwater model to compute changes in groundwater levels and travel time distributions. Simulation results indicate that ~~under future climate scenarios,~~ groundwater recharges and levels are expected to increase slightly under future climate scenarios. Meanwhile, the mean travel time is expected to decrease compared to the historical average. However, the ensemble simulations do not all agree on the sign of relative change. Changes in mean travel time exhibit a larger variability than those in groundwater levels. The ensemble simulations do not show a systematic relationship between the projected change ~~and~~ (in both groundwater levels and travel times) and the warming level, but they indicate an increased variability in projected changes with the enhanced warming level from 1.5 to 3 °C. ~~This study indicates that a higher warming level may introduce more uncertain and extreme events for the studied regional groundwater system~~Correspondingly, it is highly recommended to restrain the trend of global warming.

1 Introduction

The availability, sustainability, and quality of water resources are threatened by many sources, among which the changing climate plays a critical part (Stocker, 2014). A significant sign of climate change is ~~the~~ global warming, which has been evidenced by the analysis of long-term air temperature records (Masson-Delmotte et al., 2018). Not only the earth's surface

temperature shows a constant warming trend, but the sea surface temperature has also increased (Stocker, 2014). There has been adequate ~~proofs~~ proof that the massive greenhouse gas emissions since the eighteenth century accelerate the global warming process (Stocker, 2014). Consequently, it is urgently needed to estimate the change of meteorological variables (e.g., precipitation and temperature) in the future global warming scenarios. General circulation models (GCMs) combined with different emission scenarios or representative concentration pathways (RCPs) have been widely employed for climate impact study ~~(Collins et al., 2013; Thober et al., 2018; Marx et al., 2018)~~(Masson-Delmotte et al., 2018; Collins et al., 2013; Thober et al., 2018; Marx
.

Climate change may significantly alter the pattern of terrestrial hydrological processes, influence the spatial and temporal behavior of shallow water storages, and manipulate the degree and frequency of extreme events such as floods and droughts (Van Roosmalen et al., 2009; Sridhar et al., 2017; Thober et al., 2018; Marx et al., 2018). Hydrological processes and states (e.g., evapotranspiration, soil moisture, and potential recharge) are tightly coupled with ~~current climate and meteorological~~ the climate variables (e.g., precipitation, humidity, atmosphere temperature). The impact of climate change on the terrestrial water cycle is ~~, unfortunately,~~ uncertain. Climate model projections show a good consistency in future global averaged trends ~~,~~ but may disagree on the magnitude of regional-scale variables, particularly ~~when precipitation projection is involved in~~ for precipitation projection (Meehl et al., 2007). Many ~~past studies devote to~~ studies estimate the control and uncertainty of climate change on hydrological states and fluxes (Hunt et al., 2013; Samaniego et al., 2018; Renée Brooks et al., 2010; Hattermann et al., 2017; Goderniaux et al., 2009). ~~Among them, some studies indicate that the~~ The frequency and intensity of extreme events (e.g., soil moisture drought, ~~heat wave~~heatwave) may be exacerbated owing to anthropogenic warming (Samaniego et al., 2018; Kang and Eltahir, 2018; Marx et al., 2018). The global water scarcity is likely to be exacerbated due to the potential decline in ~~fresh water~~ freshwater resources under the 2 °C global warming ~~scenario (Schewe et al., 2014)~~level (Schewe et al., 2014; Singh and Kumar, 2019; Gosling et al., 2017).

As the single biggest source of the world's fresh water supply, groundwater plays a critical role in the sustainability of the terrestrial ecosystem and the environmental consequences of climate variability. Globally, groundwater makes up 35% of the total freshwater withdrawals, constituting approximately 36%, 27% and 42% of water consumption for households, manufacturing, and agriculture, respectively (Döll et al., 2012). Although the general knowledge of scale-dependent hydraulic properties of the subsurface hydrologic systems is still quite limited, they prove to be increasingly influenced by anthropogenic factors (Küsel et al., 2016). ~~Worldwide~~ The worldwide groundwater system can be affected by climate variability directly by a change in recharge or indirectly by a change in groundwater abstraction (Taylor et al., 2012). Furthermore, these effects may be adjusted through anthropogenic activities such as ~~land use~~ land-use change. Many recent studies ~~devote to evaluate~~ devoted to evaluating the impact of climate change on groundwater availability ~~(Engdahl and Maxwell, 2015; Goderniaux et al., 2015; Jackson et al., 2011; Taylo~~
~~. These past~~ (Woldeamlak et al., 2007; Maxwell and Kollet, 2008; Van Roosmalen et al., 2009; Jackson et al., 2011; Stisen et al., 2011; Ta
. These studies often use coupled climate-land-surface-subsurface models to investigate the potential response of groundwater storages to the outer forcings under different climate scenarios. Compared with the ~~land surface processes,~~ near land-surface fluxes/storages (e.g., soil moisture, evapotranspiration), the groundwater reservoir is less vulnerable to extreme events (Maxwell and Kollet, 2008). The slow response of groundwater to ~~meteorological~~ climate variability can be explained by the highly dy-

namic surface water/groundwater interaction, the existence of a variably thick unsaturated zone, and the big volume of groundwater storagesstorage. Quantification of uncertainty in future water resource projections and travel times (decades to centuries) of the regional groundwater system is critically important for regional water sustainability.

Due to the diverse patterns of the terrestrial water cycle in regions under different climate conditions, climate change will have diverse impacts on the groundwater recharge change. Sandström (1995), for instance, found that in Tanzania, a 15% decline in precipitation, without any change in air temperature, will result in a 40-50% decline of groundwater recharge, indicating a potential amplified change of recharge compared to that of precipitation. While some studies found a an increasing trend of recharge in some regions (Brouyère et al., 2004; Van Roosmalen et al., 2009), others indicate that climate change is likely to will likely lead to decreased recharge rates (Pulido-Velazquez et al., 2015; Woldeamlak et al., 2007; Havril et al., 2017). The changes of recharge, regardless of the sign of change, will significantly influence the groundwater levels , and may lead to ecological problems such as the vanishing of wetlands (Havril et al., 2017). Modification of groundwater recharge will control the flow paths and travel times of pollutants, which is critical to the sustainability of the regional groundwater system. Moreover, the modification of groundwater recharge can change the age distribution for water in both the vadose zone and the saturated zone, as well as significantly change the composite age distribution (Engdahl and Maxwell, 2015).

Groundwater travel time distribution (TTD) is a robust description of the storage and transport dynamics within aquifers under various external forcings. It has many implications for hydrogeological and environmental studies. For instance, significant time-lags of the streamflow response to external forcings have been observed by multiple studies (Howden et al., 2010; Stewart et al., 2012) (Howden et al., 2010; Stewart et al., 2012; Jing et al., 2019). Besides, the legacy pollutants in groundwater reservoirs can have a great impact on the total pollutant loads for agricultural catchments (Wang et al., 2016; Van Meter et al., 2017). Groundwater TTD, as a lumped description of the heterogeneous aquifers, sheds light on the assessment of groundwater responses to non-point source contamination subjected to a changing climate and land use (Böhlke, 2002; Engdahl and Maxwell, 2015).

Although there are plenty of studies that have focused on assessing the impact of future climate change on groundwater recharge (Tillman et al., 2016; Crosbie et al., 2013; Jyrkama and Sykes, 2007; Pulido-Velazquez et al., 2015), groundwater budget (Pulido-Velazquez et al., 2015; Engdahl and Maxwell, 2015; Havril et al., 2017), and groundwater-surface water exchange (Scibek et al., 2007; Smerdon et al., 2007), there is an absence of a systematic evaluation of both the groundwater quantity and TTDs under different warming levels that incorporates the uncertainty in climate projectionsuncertainties in both climate projections and hydrological parameterizations. In this study, we analyze the response of groundwater (quantity and travel time distributionsTTDs) to the 1.5, 2, and 3 °C global warming levels (above the preindustrial levels) in a central German basin (Nägelstedt) using a coupled hydrological model mHM-OGS (Jing et al., 2018). The key questions we aim to answer isare: (1) How can the flow and transport conditions of a regional groundwater system in future decades differ from the historical period with respect to various possible under different warming levels? (2) How much predictive uncertainty is associated with climate projection using different GCMsCan we quantify the degree of different uncertainty sources (e.g., uncertainties in climate projections and groundwater models) and their influences on the resulting groundwater simulations? To answer these questions, we pay particular attention to the assessment of the long-term effect of climate change to the groundwater

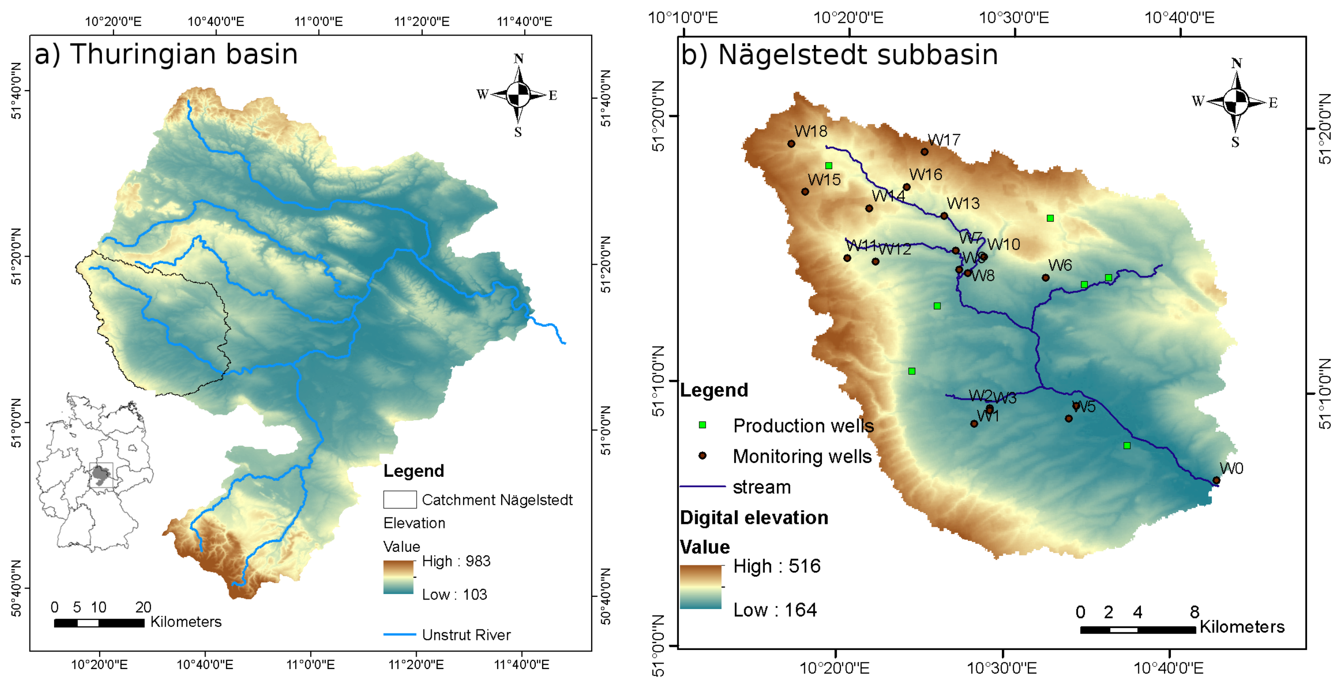

Figure 1. Study area and locations of pumping and monitoring wells within the Nägelstedt basin. Panel a) shows the relative position of Nägelstedt basin in the Thuringian ~~basin,~~ Basin and Panel b) shows the locations of pumping and monitoring wells in Nägelstedt basin.

~~systems using a well-tested sequentially-coupled model~~on the regional groundwater systems considering the buffering effect of groundwater aquifers.

This paper is organized into several sections: Section 2 describes the basic topographical, geometrical, and geological properties of the study area. Section 3 introduces the methodology and materials for this study. Section 4 shows the setup and validation for the mHM and OGS models. The simulation results are presented in Section 5. A comprehensive discussion on the simulation results is displayed in Section 6, and the main conclusions are drawn at the end of this section.

2 Study Area

As a sub-basin of the Thuringian basin, the Nägelstedt basin is located ~~at~~ in central Germany and it has an area of about 850 km^2 (Figure 1). It is a headwater catchment of the Unstrut river. The Unstrut river is a typical, meandering lowland river with only moderate flow velocity under natural conditions. The mountains surrounding the Nägelstedt basin drain almost simultaneously into the Unstrut during heavy precipitation events, which in the past led to regular, prolonged flooding of large parts of the floodplains. The topographic elevations of this catchment range from 164 m at the southeastern lowland to 516 m in the Hainich mountainous region. This region is classified as a Cfb climate region based on the Köppen-Geiger classification, where Cfb stands for warm temperate, fully humid, and warm summer climate (Kottek et al., 2006). It shows a leeward decreasing trend of areal precipitation and ~~an~~ rising mean air temperature from the eastern Hainich ridge to the Unstrut Valley (Kohlhepp et al., 2017). In the larger Thuringian basin, groundwater has been intensively extracted for domestic, industrial and agricultural uses. About 70% of the ~~fresh water~~ freshwater requirement for Thuringia is satisfied by groundwater (Wechsung et al., 2008).

The extremely fertile soils in the meadows (wet black soil and loess) make the Thuringian basin one of the best agricultural basins in Germany. Approximately 88% of the total land use of this region is regarded as arable land (Wechsung et al., 2008). At the same time, the proportion of woodland and grassland has fallen sharply, leading to an extreme reduction in biodiversity in these areas (Wechsung et al., 2008). ~~The nitrogen inputs from agriculture fluctuate with time and positions from 5 kg/ha to 31 kg/ha (Wechsung et al., 2008).~~

The stratigraphy in this area is characterized by a succession of carbonate–siliciclastic alternations. The main aquifer system consists of several sedimentary rocks, including the Middle Keuper (km), the Lower Keuper (ku), the Upper Muschelkalk (mo), the Middle Muschelkalk (mm), and the Lower Muschelkalk (mu) (Seidel, 2003). The Middle Keuper consists of a marly series with gypsum and dolomite, whereas the Lower Keuper is ~~consitituted~~ constituted of grey clays ~~, schieferletten,~~ and dolomitic limestone. The Upper Muschelkalk (Hauptmuschelkalk) is mainly made up of shelly limestone, marl, and dolostone. The Middle Muschelkalk consists mainly of evaporites (gypsum, anhydrite, and halite), meanwhile, the Lower Muschelkalk consists of limestone and marls (Seidel, 2003; McCann, 2008; Jochen et al., 2014). Karstification occurs in the Muschelkalk formation, but has proved to be limited or concentrated in specific zones in this area (Kohlhepp et al., 2017).

The Nägelstedt basin is chosen as the study area for the following reasons: (1) It is a typical agricultural basin where potential non-point source contamination may threaten the sustainability and resilience of groundwater, and (2) the critical zone (CZ) in Nägelstedt basin has been comprehensively investigated using infrastructure platform from the Collaborative Research Center AquaDiva (Küsel et al., 2016; Kohlhepp et al., 2017).

3 Methodology and Materials

To investigate the impact of different climate change scenarios, we modified the modeling framework ~~originally developed by Thober et al. (2018) and Marx et al. (2018) from EDgE and HOKLIM projects by means of~~ from EDgE (EDgE – End-to-end Demonstrator for improved decision-making in the water sector in Europe) and HOKLIM (HOKLIM – High-resolution Climate Indicators for 1.5 Degree Global Warming) projects through coupling it to a three-dimensional subsurface model (Thober et al., 2018; Marx et al., 2018; Samaniego et al., 2018). Specifically, we use temperature and precipitation derived from five GCMs under three different RCPs to force the mesoscale Hydrologic Model (mHM), aiming to derive the land surface fluxes and states under different future warming scenarios. The projected recharges from mHM calculations are fed to the groundwater model OpenGeoSys (OGS) for the assessment of groundwater quantity and ~~travel time distributions~~TTDs.

3.1 Climate scenarios

We use five General Circulation Models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESMCHEM, and NorESM1-M) gathered from the Coupled Model Inter-comparison Projects 5 (CMIP5) to provide the climate variables to the mHM

Table 1. Time periods of 1.5, 2, and 3 °C global warming in five GCMs under three RCPs.

Warming level	RCPs	GFDL-ESM2M	HadGEM2-ES	IPSL-CM5A-LR	MIROC-ESM-CHEM	NorESM1-M
1.5 °C	2.6	-	2007–2036	2008–2037	2006–2035	2047–2076
	6.0	2040–2069	2011–2040	2009–2038	2012–2041	2031–2060
	8.5	2021–2050	2004–2033	2006–2035	2006–2035	2016–2045
2 °C	2.6	-	2029–2058	2060–2089	2023–2052	-
	6.0	2060–2089	2026–2055	2028–2057	2028–2057	2054–2083
	8.5	2038–2067	2016–2045	2018–2047	2017–2046	2031–2060
3 °C	2.6	-	-	-	-	-
	6.0	-	2056–2085	2066–2095	2055–2084	-
	8.5	2067–2096	2035–2064	2038–2067	2037–2066	2057–2086

model. Temperature and precipitation are derived from these GCMs under three representative concentration pathways (RCPs; RCP2.6, RCP6.0, and RCP8.5), which are available from the ISI-MIP project (Warszawski et al., 2014). RCPs are representations of emission scenarios, with RCP2.6, RCP6.0, and RCP8.0 representing low, medium, and high emission scenarios, respectively. This multimodel ensemble approach enables the consideration of uncertainty in climate modeling. Climate variables from GCMs are ~~further~~ downscaled to a 0.5 ° ~~C spatial resolution by means of~~ spatial resolution employing a trend-preserving bias correction approach (Hempel et al., 2013). The trend-preserving bias correction approach is capable of representing the long-term mean and extremes of catchment state variables (Hempel et al., 2013). The 0.5~~degree~~ -degree data is further interpolated ~~into~~ onto 5 × 5 km^2 grids ~~by means of~~ employing a external drift kriging (EDK) approach. The EDK approach can incorporate altitude effects at the sub-grid scale ~~,~~ and has been successfully used in many ~~past studies (Wood et al., 2011; Zink et al., 2017; Thober et al., 2018)~~studies (Zink et al., 2017; Thober et al., 2018; Samaniego et al., 0).

We use the period 1971–2000 to represent current climate conditions because 1991–2000 is the latest decade that ~~are~~ is available in the GCM data. The GCM data from this period serves as a baseline scenario for the future projection of climate change. A time-sampling approach is applied to estimate the ~~time span~~ period for different global warming ~~level~~ levels of 1.5, 2, and 3 °C (James et al., 2017). The five GCMs have different degrees of climate sensitivity due to the different climate projections, therefore providing different meteorological forcings to the mHM model. Specifically, different ~~time~~ periods of 1.5, 2, and 3 °C global warming are estimated by five GCMs under three RCPs (Table 1). We note that some combinations of GCMs and RCPs cannot be identified for the future climate projection before 2099, resulting in a total of 35 GCM/RCP combinations being used in this study (Table 1).

3.2 The mesoscale Hydrologic Model (mHM)

The disaggregated meteorological data are used as meteorological forcings of the mesoscale Hydrological Model (mHM) for a daily simulation. mHM is a spatially explicit distributed hydrologic model that applies grid cells as primary hydrologic units

~~,~~ and accounts for multiple hydrological processes including infiltration, surface runoff, evapotranspiration (ET), soil moisture dynamics, snow accumulation and melting, groundwater recharge, and discharge generation. mHM is forced by hourly or daily meteorological forcings (e.g., precipitation and temperature), and uses accessible physical characteristics including soil textural, vegetation, and geological properties to estimate the spatial variability of parameters ~~by means of~~ utilizing its unique Multiscale Parameter Regionalization (MPR) technique (Samaniego et al., 2010; Kumar et al., 2013). The MPR technique is capable of coping with fine-scale features because the effective model parameters are regionalized ~~on the basis of the~~ based on the underlining subgrid-scale information using a consistent upscaling algorithm. The mHM simulations have been successfully established across Europe, and the simulated land surface fluxes have been verified by eddy-covariance stations across Germany (Zink et al., 2017).

3.3 OpenGeoSys (OGS)

The porous media simulator OpenGeoSys (OGS) is used to simulate regional groundwater flow and transport processes. ~~OGS~~ There are two OGS versions available – OGS-5 and OGS-6, and we use OGS-5 exclusively in this study. OGS has been successfully coupled to mHM through a coupling interface – mHM-OGS (Jing et al., 2018). The coupling interface interpolates the grid-based recharge produced by mHM into the nodal recharge values spreading over the top surface of the OGS-mesh. In doing so, mHM and OGS are dynamically coupled as a surface-subsurface model such that the potential recharge produced by mHM can be fed to OGS and serves as the outer forcing of the groundwater module (Jing et al., 2018). Specifically in this study, we feed the projected 5×5 km^2 recharge from mHM under future climate scenarios to the coupling interface (mHM-OGS) to ~~force~~ run the groundwater model. OGS is based on the finite element method (FEM) and solves the partial differential equations (PDEs) of fluid flow ~~by means of~~ employing linear/non-linear numerical solver. OGS is capable of simulating single processes including saturated zone flow, unsaturated zone flow, and solute transport, as well as coupled processes including saturated/unsaturated flow, multi-phase flow, and reactive transport. Specifically in this study, OGS is used to compute ~~three dimensional~~ three-dimensional saturated zone flow.

Moreover, a Lagrangian particle tracking method – namely random walk particle tracking (RWPT) – is used to track flow pathways and compute ~~travel time distributions~~ TTDs of water parcels ~~(Park et al., 2008a, b; ?)~~(Park et al., 2008a, b; Jing et al., 2019). The RWPT method assumes that the advection process is deterministic, while the diffusion/dispersion processes are modeled stochastically (Park et al., 2008a). The RWPT method has been widely used to account for reactive transport processes and travel times ~~(Park et al., 2008b; ?; Engdahl, 2017)~~(Park et al., 2008b; Jing et al., 2019; Engdahl, 2017).

4 Model setup

We designed two parallel numerical experiments to investigate the effect of uncertainties in both the climate and groundwater models on the groundwater resources. For the evaluation of climate uncertainty, 35 GCM/RCP pairs are used, whereas one parameter set (related to hydrogeological features) is used for the groundwater model. In parallel, to assess the parameter uncertainty in the groundwater model, one sole climate realization is used, whereas many realizations of hydraulic conductivity

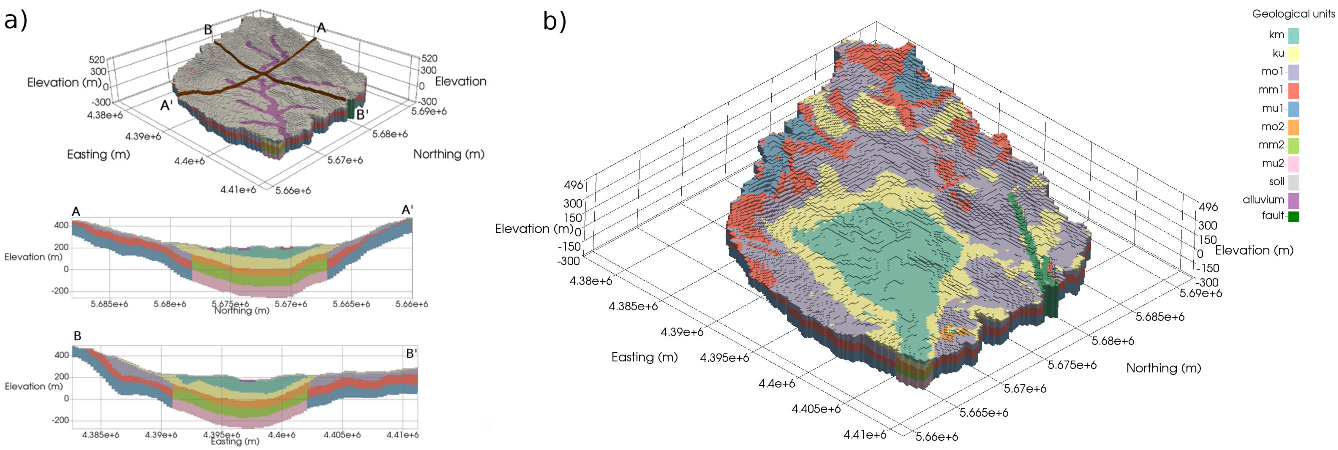

Figure 2. Geological zonation and three-dimensional mesh for the aquifer system in Nägelstedt basin (Jing et al., 2018). Panel (a) underlines the the spatial pattern of alluvium and soil layers. Panel (b) further displays the zonation of deep geological units. Full names of legends are listed as follows: km – Middle Keuper, ku – Lower Keuper, mo – Upper Muschelkalk, mm – Middle Muschelkalk, mu – Lower Muschelkalk.

fields constrained by the observations are used for the groundwater model. Specifically, this climate realization is the ensemble average of all 35 members of GCM/RCP combinations.

4.1 mHM model setup

~~Fed by the five GCMs, the~~ The down-scaled meteorological dataset, corresponding to 5 GCMs, with a spatial resolution of 5 × 5 km^2 is used as the outer forcing of mHM. The model is set up across Europe ~~using land use dataset~~ and is forced with spatially distributed meteorologic observations obtained from the E-OBS dataset ~~(Haylock et al., 2008)~~(Haylock et al., 2008; Samaniego et al., 0) . Global parameters of mHM are calibrated against discharge observations ~~using~~ from the GRDC database. All ensemble simulations are established with the same morphological, land use, and soil type data ~~in order~~ to keep the relevant parameters consistent throughout this study. Furthermore, the mHM model was validated using observations from many gauging stations across Europe with a period 1966-1995 ~~(Marx et al., 2018)~~(Marx et al., 2018; Thober et al., 2019; Samaniego et al., 0). The calibration-constrained parameter set is ~~derived and~~ used for groundwater recharge projection. The projected groundwater recharge, with a spatial resolution of 5 × 5 km^2, is further downscaled to a 250 × 250 m^2 spatial resolution using the bilinear interpolation ~~in the study site for~~ for establishing the fine-scale OGS groundwater model.

4.2 OGS model setup

A 25-m Digital Elevation Model (DEM) is used to determine the outer bounds of the catchment and the top surface elevation of the three-dimensional model domain. A ~~three dimensional~~ three-dimensional stratigraphic mesh is set up ~~on the basis of~~ based on the above information and bore log data from ~~Thuringian State office~~ the Thuringian State Office for the Environment and Geology (TLUG) (Fischer et al., 2015). The mesh consists of 293,041 structured hexagonal elements with a size of 250 m in the

x and y direction as well as with a 10 m resolution in the z direction. The parameter zonation approach is used to represent the heterogeneity of hydraulic properties–hydraulic conductivity in this study. The geological zones within the three-dimensional mesh representing Nägelstedt catchment are displayed in Figure 2. Ten different sediment units are delineated based on the stratigraphy in this area, including Middle Keuper (km), Lower Keuper (ku), Upper Muschelkalk 1 (mo1), Upper Muschelkalk 2 (mo2), Middle Muschelkalk 1 (mm1), Middle Muschelkalk 2 (mm2), Lower Muschelkalk 1 (mu1), Lower Muschelkalk 2 (mu2), alluvium, and the uppermost soil layer (Figure 2). The geological unit "alluvium" represents sandy outwash and gravel near streams, whereas "soil" denotes the uppermost soil layer with a depth of 10 m. The post-calibrated values of the hydraulic conductivity in each geological unit obtained from a previous study are assigned to the corresponding geological layers of the mesh (?)

For the uncertainty study of climate scenarios, a post-calibration hydraulic conductivity field sampled from many realizations that are all constrained by head observations is adopted for the OGS groundwater model (Table 2). In parallel, to assess the groundwater model uncertainty, 80 realizations of hydraulic conductivity fields randomly sampled from many hydraulic conductivity fields are used to cover a plausible range of values (Jing et al., 2019). Meanwhile, a uniform porosity of 0.2 is assigned to each geological layers layer (Table 2).

Given that this study is designed to assess the potential response of the regional groundwater system to global warming scenarios, a steady-state groundwater system could be assumed. This assumption is made because the future warming level is a long-term average, and on such a temporal scale (decadalover the 30-year baseline), the short-time fluctuations of climate forcings are essentially damped in the regional groundwater system (Maxwell and Kollet, 2008).

The bottom and outer boundaries of the model domain are impermeable, and no-flow boundary conditions are assigned onto these geometries. The spatially distributed recharges estimated by mHM under future climate scenarios are mapped onto each grid nodes node of the mesh surface by the model interface (mHM-OGS). Long-term averaged pumping rates are assigned as Neumann boundaries to each production wellswell, wherein the pumping rates are obtained from the literature on the basis of based on long-term historical data (Wechsung et al., 2008). The total long-term averaged pumping rate over the Nägelstedt catchment is 18870 18 870 m^3/day, and it is set constant for all climate scenarios. A fixed head boundary is assigned to the main perennial streams including one mainstream and three tributaries (Figure 1). For the Lagrangian particle tracking model, about 100000 100 000 spatially distributed particle tracers are injected through the top surface of the mesh. The spatial distribution of particle tracers is consistent with the spatial distribution follows the pattern of simulated diffuse recharges for each climate scenario.

4.3 Model calibration

We use the observed discharge and groundwater head over 50 years (1955-2005) to calibrate the mHM and OGS model. The established mHM model for the study area has been calibrated using the observed discharges at the outlet of the catchment in the previous study (Jing et al., 2018). The OGS groundwater model has also been successfully calibrated using the long-term averaged head observations at many monitoring wells (Figure 3). Figure 3 reveals that all 80 sets of hydraulic conductivity

Table 2. Main hydraulic Hydraulic parameters used for the groundwater modelensemble simulations with different climate scenarios.

Geological units	Hydraulic conductivity (m/s)	Porosity (-)
km	1.145×10^{-4}	0.2
ku	3.714×10^{-6}	0.2
mo1	3.936×10^{-4}	0.2
mm1	2.184×10^{-4}	0.2
mu1	2.258×10^{-5}	0.2
mo2	3.936×10^{-5}	0.2
mm2	2.184×10^{-5}	0.2
mu2	2.258×10^{-6}	0.2
alluvium	1.445×10^{-3}	0.2
soil	3.026×10^{-4}	0.2

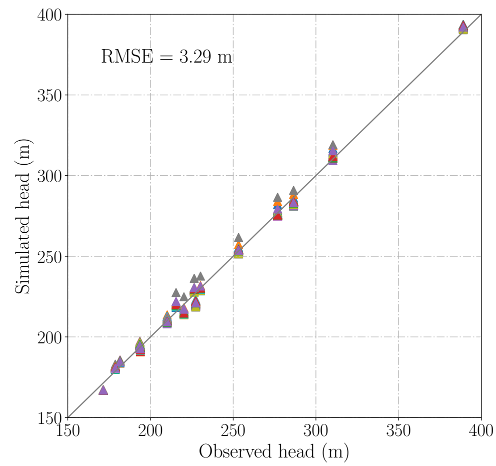

Figure 3. Groundwater model calibration: comparison of simulated to observed groundwater heads at several monitoring wells located across the study area (Figure 1) using 80 different hydraulic conductivity fields.

fields are compatible with the groundwater head observations with a small value of Root Mean Square Error (RMSE) being observed.

5 Results

This sectiondisplays In this section, we present the ensemble of simulated changes in groundwater recharges, levels and travel time distributionsTTDs. For the sake of clarity, we use the plus sign to represent simulated values of increases and minus sign to represent decreases.

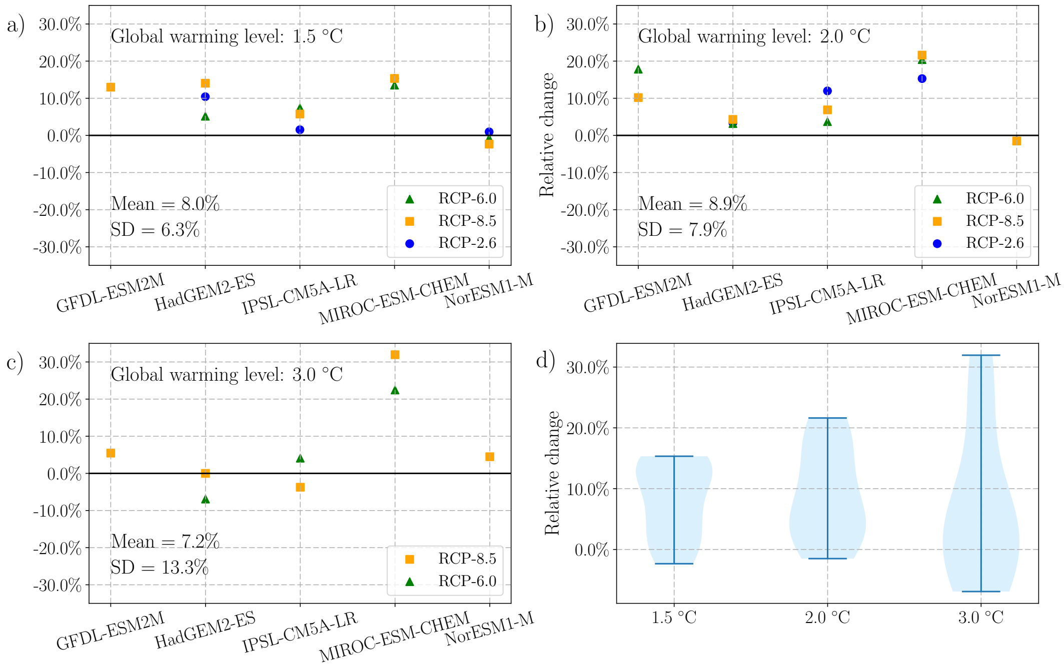

Figure 4. Projected changes in groundwater recharge rate under three warming scenarios compared to the baseline scenario 1971-2000. Panel a), b), and c) are the scatter plots showing the individual simulation results, and panel d) is the violin plot showing the uncertainty of ensemble simulations.

5.1 ~~Impact~~ Climate impact on groundwater recharge

Relative changes of simulated mean annual ~~recharges~~ recharge under 1.5, 2, and 3 °C warming ~~using five GCMs~~ for every GCM are shown in Figure 4. Projected changes of mean annual recharge vary from -4% to +15% for 1.5 °C warming level, ~~meanwhile those range~~ and from -3% to +19% for the 2 °C warming level. The simulated changes under the 3 °C warming scenario range from -8% to +27%. The simulation results from 29 out of 35 total GCM/RCP combinations suggest an increase of groundwater recharge, while only 6 individual simulations projected decreased recharge rates. The projected changes are more dependent on the used GCMs than the RCPs, which can be expected because differences among RCPs are ~~weakened~~ moderated by analyzing different warming levels. Nevertheless, differences in recharge induced by different RCPs can still be seen in Figure 4, indicating the necessity of considering multiple GCM/RCP combinations for providing a plausible range of predictive uncertainty. The ensemble averages of relative changes suggest an increase of 8.0%, 8.9%, and 7.2% for the 1.5, 2, and 3 °C warming, respectively. Meanwhile, the standard deviations (SDs) ~~exhibit an increasing tendency with the increasing~~ increase with the warming level. With the increase of the global warming level, the predictive variability in groundwater recharge is also expected to increase (Figure 4~~b~~).

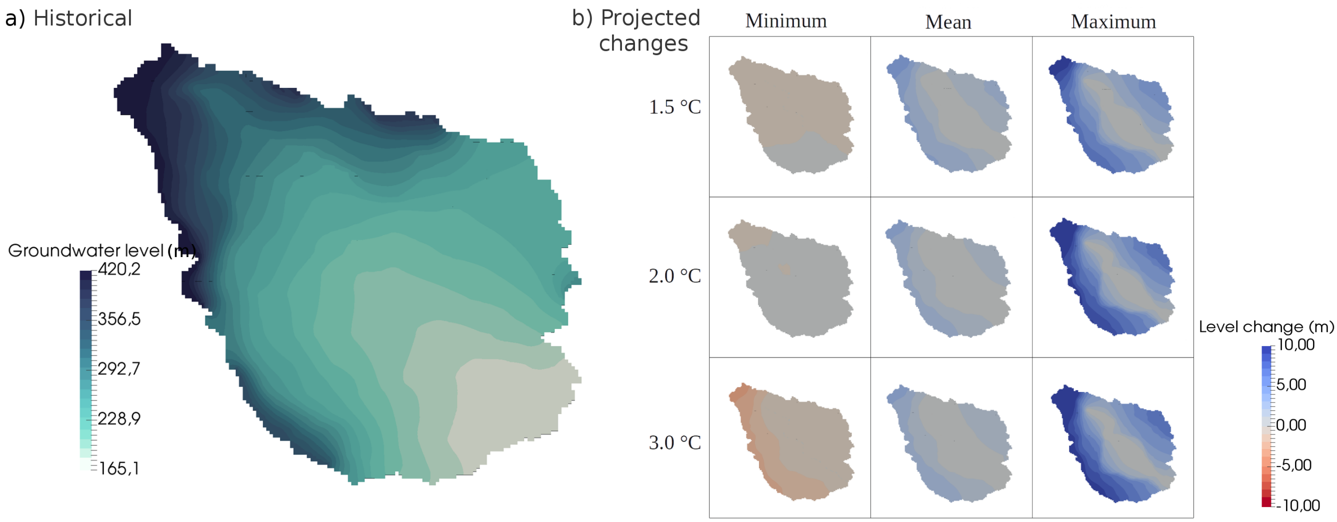

Figure 5. Contour maps of groundwater levels in Nägelstedt catchment. Panel a) shows the long-term average of groundwater levels in the historical period 1971-2000. Panel b) shows the changes in simulated groundwater levels under 1.5 °C, 2 °C, and 3 °C warming scenarios compared to the baseline scenario 1971-2000 using the maximum, median, and minimum projected recharges.

Generally, ~~calculations~~ results indicate that the projected groundwater recharge rate is expected to be greater than the 1971-2000 average. The increases in groundwater recharge are below 20% in magnitude in the majority of GCM/RCP realizations, whereas three GCM/RCP realizations suggest a decrease of groundwater recharge in the study area. The simulation under 3 °C warming scenario represents the ~~greatest SD~~largest standard deviation, i.e., the ~~greatest predictive~~ highest uncertainty. Note that ~~the predictive uncertainty~~ this uncertainty among different simulations is mainly introduced by the climate projection using various GCM/RCP combinations, given that mHM is the only hydrologic model used in this study and the ~~parameter values~~ underlying model parameterizations are the same for all simulations.

5.2 ~~Impact~~ Climate impact on groundwater levels

Changes of simulated spatially distributed groundwater levels under future climate scenarios using the minimum, median, and maximum projected ~~recharges~~ recharge are shown in Figure 5. Generally, the areas of topographically-driven flow (e.g., slope) ~~appears~~ appear to be more sensitive to the changes of recharge compared to the lowland plain. Under 1.5 °C warming scenario, the simulated groundwater levels using maximum recharges present an increase ranging from 0 to 10 m compared to those under the baseline scenario, whereas those using minimum recharges exhibit a slight decrease. Under the 2 °C warming scenario, groundwater levels are expected to increase compared to the base case using median and maximum projected recharges, whereas marginal differences can be found in the simulated levels using a minimum projected recharge. Under the 3 °C warming ~~scenario~~level, the simulated changes in groundwater levels show the highest variation among the three warming ~~scenarios~~levels. Simulations using the maximum recharge suggest a significant increase of groundwater level compared to the

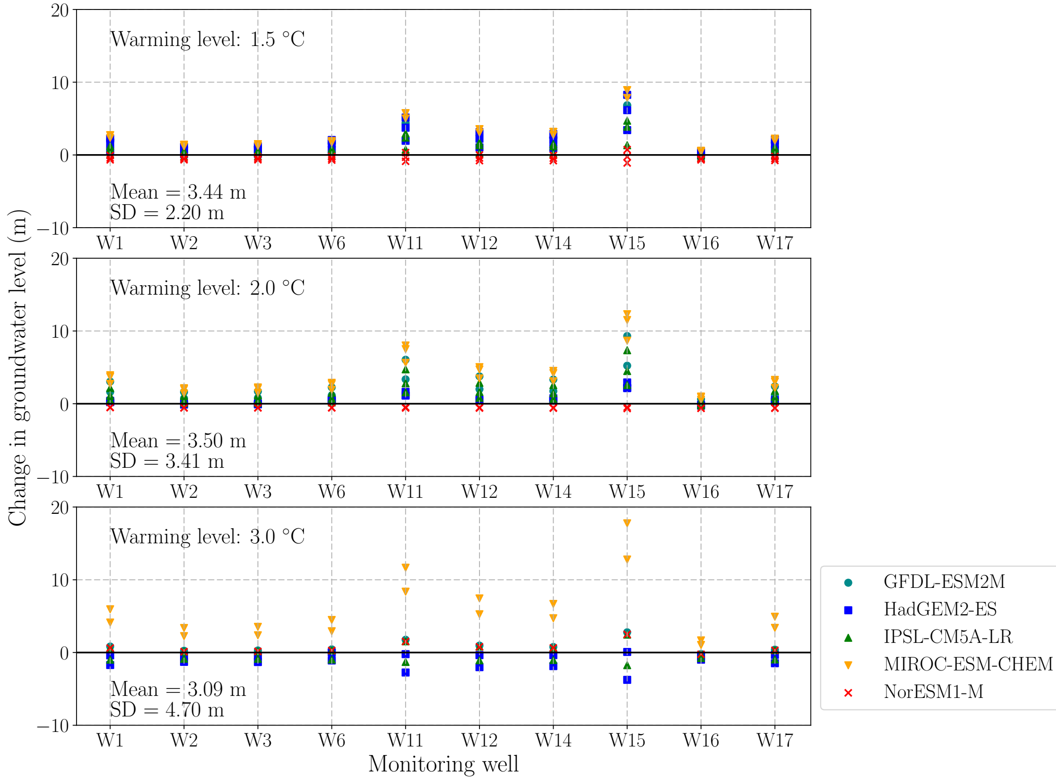

Figure 6. Changes of simulated groundwater levels in monitoring wells under three warming scenarios compared to the baseline scenario. The positions of monitoring wells are shown in Figure 1b.

1971-2000 historical average, while simulation using the minimum recharge results in a moderate decrease of groundwater levels (up to a decrease of 5 m at the northeastern mountain).

Figure 6 further shows the changes in groundwater levels at several monitoring wells, of which the locations are displayed in Figure 1. In general, changes in groundwater levels are induced by the changes in groundwater recharge such that more groundwater recharge results in higher groundwater levels and vice versa. The uncertainty of groundwater level changes increases ~~following the continuous global warming from 1.5 °C to 3 °C~~with the warming levels, which can be evidenced by an increasing standard deviation of simulated groundwater levels from 2.20 m for 1.5 °C warming to 4.70 m for 3 °C warming (Figure 6). The ~~forecasts of~~ projected changes in groundwater levels present a ~~wide range of~~ widespread variation associated with the variability of GCMs. Simulated groundwater levels tend to have the largest increase under three global warming ~~scenarios using meteorological forcings from~~ levels for the MIROC-ESM-CHEM model. In contrast, simulated groundwater levels ~~using meteorological forcings from~~ based on the NorESM1-M model show minimal changes compared to the baseline scenario. Although differing in magnitude, the changes ~~of~~ in groundwater levels for different wells show a consistent trend (either increasing or decreasing) under the same GCM/RCP realization. The simulations show no systematic relationship be-

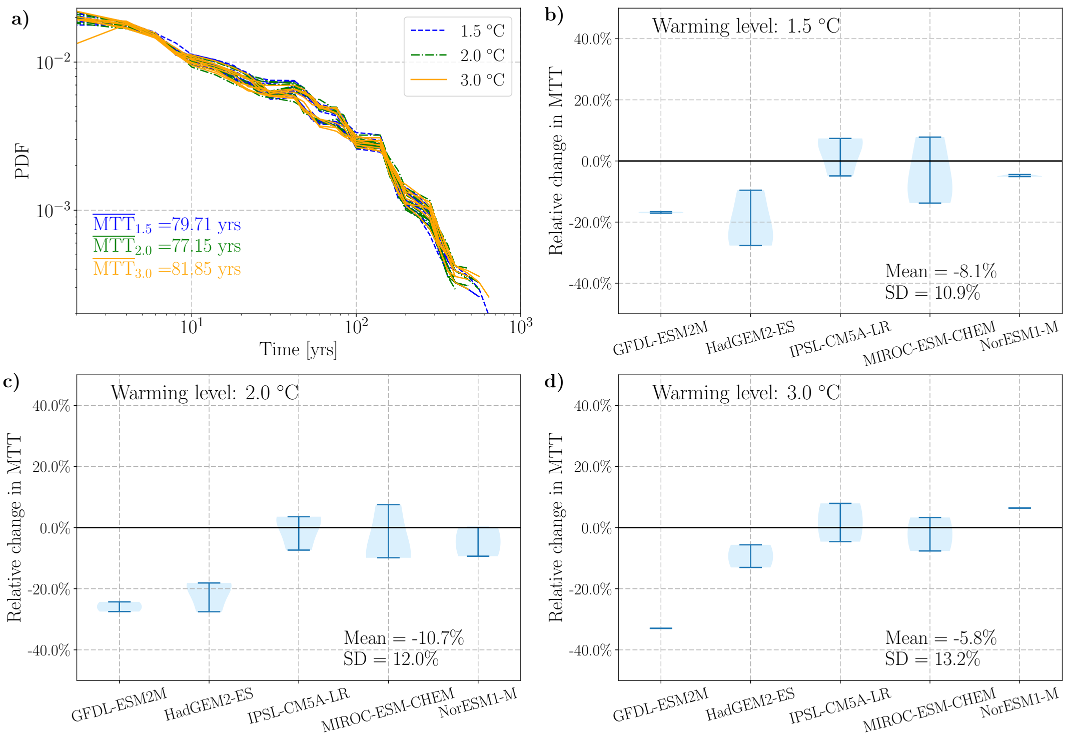

Figure 7. Simulated TTDs in Nägelstedt catchment under 1.5 °C, 2 °C, and 3 °C warming scenarios. Panel a) shows the probability density function (PDF) of TTDs for the ensemble simulations. Panels b), c), and d) show the relative changes of mean travel times (MTTs) under future climate scenarios compared to the base case.

tween the change in groundwater levels and the change in global warming level, but they do indicate an increased variability in groundwater level change following the increased warming level – which can be evidenced by the increased ~~SD~~ standard deviation values from 1.5 to 3 °C warming level (Figure 6).

Overall, calculations of spatially distributed groundwater levels help to understand more of the response of groundwater quantity to the projected climate change, but they provide little clue on the change in the groundwater transport process. ~~A strong~~ Strong spatial variability in changes ~~of~~ in groundwater levels reveals the high ~~sensitivity for climate change~~ climate change sensitivity in mountainous areas and relatively low sensitivity in lowland plain areas.

5.3 ~~Impact~~ Climate impact on groundwater travel time distributions (TTDs)

~~Travel time distributions (TTDs)~~

TTDs provide a robust description of the flow pathways of water parcels through the subsurface as well as the storage of groundwater within it. Simulated TTDs in Nägelstedt catchment under 1.5, 2, and 3 °C warming ~~scenarios~~ levels are shown in Figure 7. Figure 7a ~~)~~ shows the probability density function (PDF) of TTDs for the ensemble simulations. Generally, the

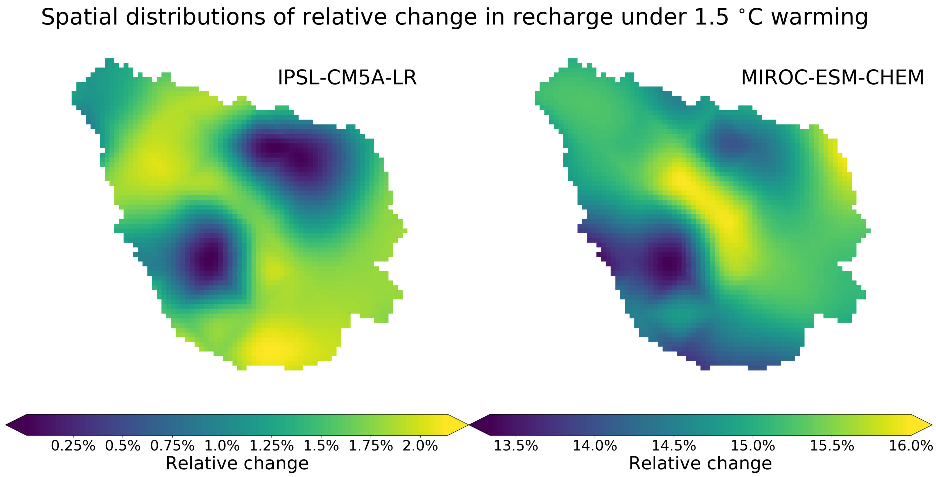

Figure 8. Spatial distributions of relative change in diffuse recharge using two different GCMs under 1.5 °C warming. This figure indicates varying spatial organizations of diffuse recharge change for different GCMs.

simulated PDFs show a fairly consistent shape with a long tail extending to hundreds of years for all GCM/RCP combinations. The long-tail behavior of simulated ~~PDFs of~~ TTDs can be explained by the direct influence of hydro-stratigraphic aquifer system, whereby some geological units present very low hydraulic conductivity values (e.g., mm2 and mu2) and therefore, remarkably slow down the movements of particles in these layers. The mean travel time (MTT), which by definition is the mass-weighted average of travel times for all water parcels within the simulated subsurface system, is a typical ~~metrics~~ metric for characterizing the timescales of catchment storage. The calculated ensemble averages of MTTs for 1.5, 2, and 3 °C warming ~~scenarios~~ levels do not exhibit notable differences (79.71, 77.15, and 81.85 years, respectively).

To analyze the ~~trend~~ changes of MTTs under the future climate scenarios, the relative changes of MTTs under 1.5, 2, and 3 °C warming ~~scenarios~~ levels are shown in panels b), c), and d) of Figure 7. In general, simulations using the data from GFDL-ESM2M and HadGEM2-ES tend to decrease MTTs compared to ~~the base case. Simulations using meteorological data from~~ that of the baseline scenario. TTD Simulation results based on the IPSL-CM5A-LR and MIROC-ESM-CHEM, however, do not agree on the sign of changes in MTTs~~with a~~. A maximum relative change of less than 10% is observed for these two model cases. The ensemble average shows that the MTT is expected to decrease in future ~~time periodsthan the historical average~~periods, but a small number of ensemble simulations suggest an increase in MTT. This degree of variability is propagated from the variation in projected recharges ~~using~~ corresponding to different GCM/RCP combinations. The simulations do not show any systematic relationship between the change in TTDs and the change in the warming level, but they do show an increased uncertainty in projected change in TTDs following the increased warming level – which can be demonstrated by the ~~increased SD values~~ corresponding increased standard deviation values of MTT from 1.5 to 3 °C warming (Figure 7).

Overall, changes in the simulated TTDs provide more ~~details on the response of the system to the~~ overview on the groundwater system response to climate change and how the ~~water cycle~~ groundwater is impacted other than considering only the ground-

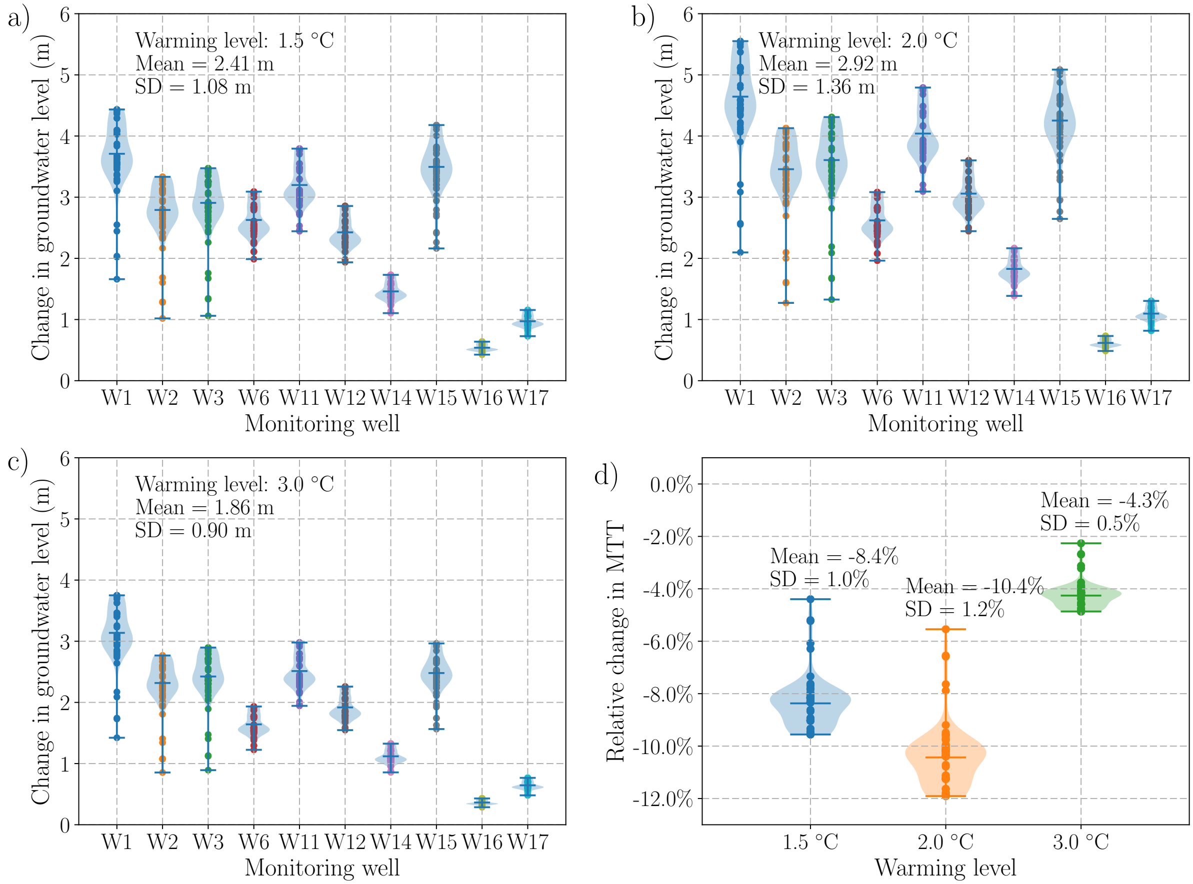

Figure 9. The predictive uncertainty in simulation results related to different hydraulic conductivity fields. Panel a), b), and c) show the changes in groundwater levels, whereas panel d) shows the projected relative changes in MTTs using 80 different hydraulic conductivity fields.

water quantity. The simulated changes in MTTs exhibit a higher variability than the simulated changes in groundwater levels. This is partially because the simulated recharges have different attributed to the fact that the simulated changes in recharge have varying details of spatial patterns for different GCM/RCP realizations and the (Figure 8). This spatial variability results in a non-linear relationship between projected changes in MTT and those in the groundwater level. This observation is in line with the previous finding that TTDs are more sensitive to the spatial pattern of diffuse recharge than the groundwater levels are (Barthel and Banzhaf, 2015; ?)(Barthel and Banzhaf, 2015; Jing et al., 2019).

5.4 Predictive uncertainty related to the groundwater model

This subsection displays simulation results using 80 different hydraulic conductivity fields that are all conditioned by the head observations and reality. The spread of hydraulic conductivity values in each geological unit can be found in Jing et al. (2019)

. Note that only one climate model is used for this group of simulations, which guarantees the simulation results are only controlled by different hydraulic conductivity values. Figure 9 displays the spread of changes in simulated groundwater levels and MTTs using 80 different hydraulic conductivity fields at 17 selected monitoring wells. The spread of results varies with the location of monitoring well, provided that the local topographic and hydraulic properties around each monitoring well are different. Wells near the mainstream (e.g., W14 and W16) show smaller variations than those located far away from the mainstream (e.g., W1, W3, and W15), indicating the buffering effect of the groundwater aquifer. By comparing the spread of projected changes in groundwater levels in Figure 9 to those in Figure 6, we find that the spreads induced by different GCM/RCP are remarkably larger than those induced by accounting for different hydraulic conductivity fields. Moreover, the sign of projected changes in groundwater levels in Figure 6 can be either positive or negative, whereas those in Figure 9 show a consistent positive sign. The spread of projected relative changes in MTTs ranges from -12.0% to -2.4%, which is also significantly smaller compared to that related to different climate models (Figure 9d). This comparison indicates that predictive uncertainties in groundwater level are primarily contributed by climate projections and secondly by hydraulic parameters.

6 Discussion and conclusions

~~Conceptual graph showing the influence of rising groundwater level on the regional groundwater flow pattern due to climate change.~~

~~We~~ In this study, we systematically explore the response of a regional groundwater flow system to different global warming scenarios by means of the ~~sequential coupling of a computationally-efficient~~ sequentially coupled land surface model (mHM) and a ~~physically-based~~ groundwater model (OGS). The results of ensemble simulations manifest that groundwater recharge is likely to increase moderately ~~for~~ under all three warming levels in a central German river basin. However, the ensemble simulations do not all agree on the sign of ~~relative change. This finding~~ projected changes in groundwater recharge. This is consistent with a previous finding that low flows are expected to increase slightly in this region under future climate scenarios , considering that baseflow is the main component of low flow and recharge feeds the baseflow(Marx et al., 2018). Similar increasing trend in climate-induced recharge rates has been suggested ~~by many researchers~~ for other regions such as a northern European catchment (Treidel et al., 2012), high plains of USA (Cornaton, 2012), upper Colorado catchment (Tillman et al., 2016) and Snake River basin (Sridhar et al., 2017). ~~Meanwhile, the seasonal pattern of recharge can be significantly modified by climate change (Chen et al., 2018).~~

The simulated changes in groundwater levels also manifest similar increases ~~for~~ under all three warming ~~scenarios~~levels, but show a strong spatial variability depending on the local topography and elevation. These changes can be critical to groundwater/surface water interaction because the increase or decrease in groundwater table would modify the dynamics of groundwater discharge into streams (Havril et al., 2017). ~~Rising~~ In areas with complex topography and dense drainage network, rising groundwater level may activate shallow groundwater flow paths and intensify shallow local flow pathways ~~(Figure ??)~~(Toth, 1963; Havril et al., 2017; Kaandorp et al., 2018). This way, the mixing behavior of groundwater storage can also change, because the activation of shallow flow paths will lead to a stronger systematic preference for discharging young water ~~(Kaandorp et al., 2018; ?). Those above mentioned processes can be properly reproduced by the coupled model mHM-OGS, given that the coupled model is physically based and is capable to explicitly represent the spatial heterogeneity.~~ (Kaandorp et al., 2018; Jing . Moreover, changes of groundwater levels will impact the land surface processes such as evapotranspiration, soil moisture~~dynamics~~ , and overland flow (Kollet and Maxwell, 2008; Huntington and Niswonger, 2012).

The ~~remarkable~~ influence of climate change on the catchment-scale groundwater ~~travel time distributions~~ TTDs is of critical importance to the sustainability of the ~~hydrological~~ groundwater system. Simulated ~~mean travel times~~ MTTs suggest a moderate decline for three warming ~~scenarios~~levels, which is not surprising since the travel time of water parcels is directly controlled by the recharge rate. ~~With simulated~~ A critical finding of this study is the non-linear relationship between the change in MTT and that in the groundwater level, which is mainly attributed to the spatial variability in diffuse recharge change. With weighted-average MTTs being at a centurial time scale, climate-induced variations can significantly affect the long-term sustainability of the regional groundwater system ~~. Decline~~ (Engdahl and Maxwell, 2015). The projected decrease in groundwater MTTs will remarkably shorten the life span of non-point source pollutants (e.g., nutrient and pesticide) in groundwater aquifers and ~~change the spatial and temporal~~ may introduce substantial changes in the spatiotemporal distributions of pollutant concentrations within the aquifer system. Given that the nutrient budget of the connected surface water body is linked with the groundwater system, the water quality of the surface water body in this region (e.g., the Unstrut river) will ~~response~~ respond accordingly in the future, although with a long delay ~~. This finding is inline~~ (Molnat and Gascuel-Odoux, 2002; Böhlke and Denver, 1995) . This observation is in line with many recent studies, wherein they highlight the importance of legacy nutrients in catchments as a reason for long-term catchment response (Haygarth et al., 2014; Van Meter et al., 2017).

One essential topic when assessing future climate impact is ~~uncertainty. Within the ensemble simulations~~ to quantify the uncertainties in the projected changes. This study provides original insights on the uncertainty propagation from the outer forcing (associated with climate models) and the internal hydraulic properties (associated with groundwater models) to the groundwater travel times. Among simulations corresponding to different GCM/RCP combinations, simulated changes in hydrologic variables (e.g., recharge, groundwater level, and mean travel time) vary not only in ~~absolute value,~~ their absolute values but also in sign (positive or negative) because of the large variations in different climate projections. The contribution of climate model induced to the predictive uncertainty is also found to be greater than that of hydraulic parameters in the groundwater model. Within the current modeling framework, predictive uncertainty and error may also be introduced by other sources, such as the internal variability in climate projection using different initial states, internal parameter uncertainty in the mHM model, ~~the parameter uncertainty in OGS model,~~ and the down-scaling algorithm. Enhancements in climate projection and downscaling algorithms can effectively reduce the variability in the projected impacts of global warming on the regional groundwater system. Nevertheless, the dominant source of uncertainty is highly likely ~~to lie in~~ due to the climate projections ~~using various~~ of varying GCMs and RCPs (Taylor et al., 2012; Thober et al., 2018; Marx et al., 2018). Except ~~the above mentioned~~ for the above-mentioned climate projection uncertainty, other uncertainty sources have not been assessed in this study. This fact indicates that the range of predictive uncertainty ~~estimated~~ quantified in this study is only a conservative ~~estimation~~estimate.

A potential limitation of ~~this study is~~ the current modeling framework lies in the one-way coupling approach that do not account for the feedback from groundwater level change to the near-surface processes. The change in groundwater table can alter the partitioning of water balances, which further exerts a second-order impact on the groundwater level and travel times (Liang et al., 2003; Leung et al., 2011). A fully coupled system, based on a mixed form of the Richards equation to solve unsaturated and saturated zone flow simultaneously, is more realistic than the one-way coupled system. However, a fully coupled model consistently suffers from an expensive computational burden, which limits its applicability in large-scale real-world case study It also introduces extra parameters that are essentially unknown at the catchment scale. The current one-way coupling, although less accurate than the two-way coupling, is computationally more efficient – allowing us to understand the first-order control of climatic variability on groundwater characteristics (groundwater level and travel times). The applied Lagrangian particle tracking in the 3D groundwater model is computationally very expensive. The total computational time performing a single model run is around 14 days using 8 cores on a computer cluster facility. Moreover, we have successfully demonstrated the utility of this model for adequately capturing the observed behavior of groundwater levels across the study basin (Jing et al., 2018). Consequently, the one-way coupling method used here is a practical choice, allowing us to perform the large ensemble scenarios with reasonable computational resources (and time).

The second potential limitation of this study is the discrepancy between the ~~contradiction between~~ fine-resolution groundwater model and coarse-resolution mHM simulations. mHM simulations in this study were established within the scope of the EDgE/HOKLIM project, which focuses on the impact of future climate scenarios on European water resources. All databases used for mHM model setup are on a European scale and typically have coarse spatial resolutions (e.g., 5 × 5 km^2). Although the MPR technique embedded in mHM facilitates the characterization of subgrid-scale features, it does not guarantee that all subgrid-scale features can be captured if the resolutions of input data are too coarse (Samaniego et al., 2010; Rakovec et al., 2016) . We note that this is a common problem when utilizing coarse-resolution forcings to drive fine-resolution physically-based models. ~~Simulation~~ In this respect, simulation results in this study can be considered as first-order approximations ~~on the basis of~~ based on currently available databases. The conclusions drawn in this study can be tentative and therefore, open to revision.

The steady-state nature of ~~simulations~~ groundwater simulations used here is reasonable for the assessment of long-term climate impact on regional groundwater system because 1) it reduce the computational burden, 2) the temporal fluctuations under the future climate cannot be reasonably projected, and 3) high-frequency fluctuations in external forcings have minor influences on long-term ~~travel time distributions~~ TTDs (Engdahl, 2017). However, ~~transient behavior can be very~~ analyzing the likely future changes in transient behavior of groundwater dynamics can be important for many cases where the temporal scale is small and the input forcings are highly dynamic. In recent years, the subject of the transient behavior of TTDs has become more and more prevalent in groundwater hydrology ~~(Woldeamlak et al., 2007; Cornaton, 2012; Engdahl, 2017)~~ (Woldeamlak et al., 2007; Cornaton, 2012; Engdahl, 2017).

We note that the results in this study are only suitable for the Nägelstedt site in central Europe. In other regions of Europe, groundwater recharge change induced by global warming may have distinct behaviors than those shown in this study. For example, some studies indicate ~~an~~ a decrease in groundwater quantity in Mediterranean regions due to the decrease in projected precipitation (Pulido-Velazquez et al., 2015; Moutahir et al., 2016). Besides, baseflow is also expected to decrease, leading to ~~an~~ a potential increase in drought in Mediterranean regions (Marx et al., 2018; Samaniego et al., 2018).

We only consider the direct impact (i.e., impacts exerted through changed precipitations) of climate change on the regional groundwater system. Interactions between the climate and groundwater are exacerbated by ~~land use~~ land-use change, which is mainly exerted by the intensification of irrigated agriculture. In ~~south Australia and~~ South Australia and the southwest U.S., the transition from natural catchments to rain-fed cropland significantly ~~changes~~ alters the groundwater storage through the increase in recharge (Taylor et al., 2012). ~~The indirect influence~~ These indirect influences of global warming ~~to~~ on groundwater systems has not been considered in this study. ~~This influence~~ Such influences can be a dominant factor threatening the local groundwater system for many regions worldwide ~~(Taylor et al., 2012)~~(Wada et al., 2010; Taylor et al., 2012). Future investigations are needed to incorporate both the direct and indirect impacts of global ~~warming~~ changes on the sustainability of the regional groundwater system.

To summarize, climate change ~~has non-negligible second order impacts on groundwater hydrology although first order impacts are small~~can significantly alter the quantity and travel time behavior of the regional groundwater system through the modification of recharge, especially at longer time scales. Ensemble simulations indicate remarkable uncertainties in projections of future regional groundwater quantity and travel times, which are introduced primarily by the driving climate projections, and secondly by hydrologic/groundwater model parameterizations. In the study domain, moderate absolute changes in recharge rates, groundwater levels, and travel times that are ~~independent of the amount~~ nonlinearly related to the varying level of global warming are found. However, the variability of these changes increases with the ~~amount of global warming~~ warming levels that might also affect the cost of managing the groundwater system. ~~This increased variability indicates an increased possibility of extreme events in groundwater system following the increase in warming level.~~ Therefore, it is still advisable to ~~reduce~~ restrain global warming to 1.5 °C and avoid ~~a~~ global warming of 3 °C.

Code availability. The coupled model mHM-OGS can be acquired via the following online repository: https://doi.org/10.5281/zenodo.1248005. The mHM source code is available from: http://git.ufz.de/mhm/mhm. The OGS-5 source code is available from: https://www.opengeosys.org/ogs-5.

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Competing interests. The authors declare that they have no conflict of interest.

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