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Hydrology and Earth System Sciences Discussions

Interactive comment on "Spatio-temporal impact of climate change on the groundwater system" *by* J. Dams et al.

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The authors thank Mr Stoll for his fast and thorough review of our manuscript and appreciate the positive criticism and constructive comments. We hereby respond to all of the comments raised by Mr Stoll.

S. Stoll: P10200 l.10-14: How is the future water extraction (2070-2101) handled? Drier summers in future can easily lead to an increased water demand and thus to increased pumping activity. This could have a large impact on the water table projections.

Authors response: For this paper we choose not to integrate indirect consequences of the projected climate change such as human induced changes in groundwater extrac-

tion. Therefore, the water extraction for the period 2070-2101 is identical to the water extraction during the reference period. With this paper we do not have the intention to predict the future groundwater characteristics in the study area but to assess the direct impact of the climate changes on the groundwater system. We believe that including indirect consequences of the climate change would significantly increase the uncertainty range on the predictions. Dryer summers could indeed increase the groundwater pumping rate, however for example increasing greywater recycling and rainfall water harvesting in the future could counter this effect. Furthermore, introducing those plausible indirect consequences would also impede the analyses of the simulations: e.g. are groundwater level decreases caused directly by the climatic changes or by the human induced groundwater extraction. We agree that it would be interesting to assess the additional impact of increased groundwater pumping by an additional scenarios, however we believe that this is outside the scope of this article.

S. Stoll: P.10201 l.14-25: Although references for the downscaling approach are given, some more specific information about the downscaling would be good. As the study focuses on intra-annual changes it would be interesting to know how seasonal biases of precipitation are handled. For example, we found (Stoll et al., 2011) that it makes a huge difference if precipitation is corrected on a monthly or an annual basis.

Authors response: The applied statistical perturbation technique separates daily precipitation and evapotranspiration values for winter and summer seasons, for both seasons aggregated volumes are calculated for daily, weekly, monthly and seasonal scales. We will extend the description of the downscaling techniques to clarify the applied methodology.

S. Stoll: I have some concerns about the coupling between WetSpa and Modflow. Maxwell and Kollet nicely showed the interdependence of groundwater dynamics and land-energy feedbacks (Maxwell and Kollet, 2008). If I understand it correctly, there is only a 1-way coupling between WetSpa and Modflow. The output of WetSpa is used as recharge and stream stage boundary condition for Modflow. However, there is no feedback from Modflow to WetSpa (e.g. increased groundwater tables lead to increased soil moisture and thus to increased evapotranspiration). Given the shallow groundwater tables (in average about 2m below surface) in the catchment, this might lead to an underestimation of evapotranspiration. This could also alter the spatial recharge pattern. In valley bottoms, near to the streams this effect would be more powerful than on hillslopes. Related to that: To my knowledge, certain Modflow packages allow for evapotranspiration directly from the groundwater. Are such packages used?

Authors response: Indeed the WetSpa - MODFLOW coupling applied in this study is a one-way coupling, in which recharge and river head data is transmitted from WetSpa to MODFLOW but the MODFLOW information about the groundwater system is not applied to update the WetSpa model. Although we are convinced that a full coupling of the surface and sub-surface hydrology has significant advantages, we did not apply such an approach in this study. Basically there are two main reasons for this. The first reason is the calculation time of the models. To be able to investigate the spatial and temporal impact of the climate changes of the groundwater system both a high spatial and temporal resolution is required and the study basin should comprise at least a part of the river basin. Moreover, to incorporate the climate variability at least 30 model years is recommended. This leads to considerable calculation times, which have to be repeated for different climate change scenarios, in our case 28 times. Applying integrated models significantly increases calculation time which makes a spatio-temporal analyses as applied in this study difficult. Secondly, we are convinced that the WetSpa model is capable of simulating the groundwater recharge with a reasonable accuracy even though the groundwater system in the model is simplified. Figure 5 for example shows the baseflow predicted by the WetSpa model is very similar to the baseflow filtered from the observed discharge. The actual evapotranspiration (ET) calculated by the WetSpa model consists besides evaporation from interception storage and depression storage and ET from the soil/vegetation also of ET from groundwater. The ET from groundwater may be produced by the deep root system or by capillary rise in areas with shallow groundwater tables. ET from the groundwater only occurs when soil moisture

is less than field capacity and has a greater impact during summer than during winter. A linear equation is used to quantify the deep ET based on the potential ET and the groundwater storage at the time step. Because the deep ET is already accounted for in the WetSpa model we cannot use a ET package in the MODFLOW.

S. Stoll: P.10203 l.27 - P.10204 l.5: I have some questions concerning the calibration: How many parameters (and which) are calibrated? The efficiencies are only reported for the calibration period. How is the performance of the models during the evaluation period? Is there a special reason why the models are calibrated separately and not simultaneously using a multi-objective optimization?

Authors response: The WetSpa model is calibrated on seven global parameters including: (i) interflow scaling factor, (ii) groundwater recession coefficient, (iii) initial soil moisture content, (iv) initial active groundwater storage, (v) maximum active groundwater storage, (vi) moisture or surface runoff exponent and (vii) maximum rainfall intensity. For the MODFLOW model the calibration parameters were selected based on a sensitivity analyses of a steady-state version of the model. The most sensitive parameters are used for the calibration of the transient model and include (i-vi) the horizontal hydraulic conductivity of the following zones: zones 2, 4, 6 and 3 in layer 2 and zones 6 and 1 in layer 1, (vii-viii) the river conductance of river1 and river2 and (iv) the drain conductance. Because we wanted to make optimal use of the available groundwater head observations (1991-2001) for the model calibration we choose not to include an evaluation period. Because at the moment there is no automatic coupling between the WetSpa and MODFLOW model we choose to calibrate both models separately.

S. Stoll: P.10204 l.19-23: It would be also very interesting to see how actual evapotranspiration is changing. Summer precipitation deficits can lead to decreasing soil moisture contents and thus to decreasing actual evapotranspiration, although potential evapotranspiration is increased. Related to that, changes of soil moisture contents could be very informative (also to evaluate the impacts to the agriculture).

Authors response: Including the actual evapotranspiration and soil moisture content would indeed be interesting, however, in this paper we wanted to focus on the groundwater system. Therefore, we excluded actual ET and soil moisture from the analyses but also for example changes in runoff. One of my colleagues investigates the impact of climate change on the soil moisture with a similar WetSpa-MODFLOW coupling for a different basin. He also has soil moisture measurements to validate the soil moisture content simulated by the WetSpa model. For the study area in this paper no soil moisture measurements are available.

S. Stoll: P.10206 l.7-10: How can the reported differences be explained? Is it solely a question of the geological properties or is it related to the recharge calculation itself (runoff processes, interception, exposition, snowmelt etc.).

Authors response: This is a very interesting point. We did not analyze the impact of the climate change on the spatial distribution of the groundwater recharge in detail, therefore we cannot answer this question at the moment. We will perform an additional analyses on the groundwater recharge for the different scenarios to find out the origin of the simulated spatial differences in groundwater head decreases.

S. Stoll: P.10207 l.17-18: I don't think that this is true. Almost all groundwater impact studies are carried out with the focus on future droughts. And also for surface water, many studies have been focusing on low flow (e.g. drought related studies in the EU-WATCH project).

Authors response: Studies focusing on the groundwater system indeed had an important focus on the droughts, however many studies have applied hydrological models that focus primarily on flood events. We agree that recently there was an important shift of the research focus towards the dry period, such as the EU-WATCH project to which you refer. We will adapt this sentence.

S. Stoll: Small remarks For the review about climate change effects on groundwater levels, perhaps our paper (Stoll et al., 2011) may be relevant, as we also focused on

the intra-annual response.

Authors response: The literature review was mainly carried out last year. We will perform an extra check on recent literature related to the topic of this paper to make the literature review up to date again. Stoll et al. (2011) is indeed also one of the few papers that analyze the predicted changes with a high temporal resolution and will be included in the introduction of this paper.

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