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Hydrology and Earth System Sciences Discussions

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Interactive Comment

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

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Response to comments of Anonymous Referee #2

Comment:1) There is insufficient methodological description to understand what the authors have actually done - this is particularly the case regarding the climate inputs but also the model linkage and calibration. The approach to climate model downscaling (particularly for GCMs) has implications for the impacts results obtained

Authors' response: We tried to avoid including too much detail on both model description and climate scenario development in the paper in order to focus on the aim of the paper, which is to show the plausible impact of climate change on the groundwater system. However, we agree that due to this relatively short description of the methodology, readers might be confused about the model built up and characteristics of the climate change scenarios. For example the GCM outputs are not directly used in this study but are mentioned because these GCMs are used to drive the included RCMs runs within the PRUDENCE project. To improve the clarity of the applied methodology we will extend the description of the models, including the model linkage, and the climate change scenarios.

Comment:2) The validity of the baseline models is unclear - The authors are lucky enough to have access to a large amount of data – 10 years of flow data and over 10,000 head observations over 10 years. Despite this, the authors have not validated their model. They have fitted it to data and then assumed the model is robust to be used with driving data from outside the climatic range of the fitting data. This is a fundamental flaw in the paper

Authors' response: We are aware that especially for hydrological models, a validation based on a dataset that is not used to calibrate the model results is a better estimate of the validity of the hydrological model than the obtained efficiencies during the calibration period. For the WetSpa model we will add an additional validation run. With respect to the groundwater heads we have carefully considered whether or not to include a validation period. Although 10,000 head observations might seem a large amount of data, we do not believe that this amount is very abundant due to the fact that these head observations are measured distributed over more than 100 observations wells and often the temporal resolution of the observations is higher than the simulated heads. Furthermore, at the beginning of the calibration period few measured groundwater heads are available while at the end more heads became available. We therefore chose to include all available data to calibrate the groundwater flow model. This also guarantees that we capture the maximum observed climatic range in the model performance, reserving data for validation would reduce this. Evidently, we have to assume that by taking up maximum amount of climatic variability in the model it is robust to

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be applied under future climatic conditions (as no calibration or validations for these conditions is possible). From the simulated groundwater head series we observed that the results are relatively stable for both wetter and dryer years during the calibration period. Although this does not give an absolute guarantee as a validation run would, we do believe that this modelling procedure ensures a maximum robustness, sufficient for the climate change application in this study. Many previous groundwater studies have also used all available data to calibrate the groundwater model and hence have used the same philosophy (e.g. Goderniaux et al., 2009; Woldeamlak et al., 2007; Toews and Allen, 2009).

Goderniaux, P., S. Brouyère, H. J. Fowler, S. Blenkinsop, R. Therrien, P. Orban, and A. Dassargues (2009b), Large scale surface-subsurface hydrological model to assess climate change impacts on groundwater reserves, J. Hydrol., 373(1–2), 122–138.

Toews, M.W. and Allen, D.M. (2009). Simulated Response of Groundwater to Predicted Recharge in a Semi-Arid Region Using A Scenario of Modelled Climate Change. Environmental Research Letters 4, 035003. doi.org/10.1088/1748-9326/4/3/035003

Woldeamlak, S., O. Batelaan, and F. De Smedt (2007), Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium, Hydrogeol. J., 15(5), 891–901.

Comment: 3) There is minimal discussion of the results, to enable the reader to understand the causes of the simulated changes and thereby their significance. Section 4 is called "Results and Discussion" but there is no discussion, merely description of Results. Process-based explanations for the impacts observed must be provided for the paper to have any wider value beyond this Belgium catchment

Authors' response: Indeed in this paper we focused primarily on the impact of the climate change scenarios on the groundwater system (recharge). We extensively described the observed changes but put less emphases on what is the importance of other hydrological processes causing the observed changes. We agree on adding ad-

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ditional analyses of the impact on the climate changes on the actual evapotranspiration, runoff and recharge (spatial) which will allow to assess more in depth which processes are the main drivers for the changes in groundwater recharge. Furthermore, as mentioned in the response to the comments made by Mr. Stoll the additional analyses will provide further information on the spatial differences in observed groundwater head changes.

specific comments:

Comment 4: P10200, L16 – what is “TAW”?

Authors’ response: TAW is the abbreviation of "Tweede Algemene Waterpassing", which is the height to which elevation measurements are referred to in Belgium. An explanation will be added in the text.

Comment 5: P10199, L26 –are the Quaternary and Tertiary sediments actually “confined” (aquitards above and below; groundwater under pressure) or merely underlain by a low permeability clay layer as described in the text

Authors’ response: The Quaternary and Tertiary sediments are not confined but below them an aquitard is present. Indeed there could be some confusion in our formulation because the aquifers are not confined, therefore we will change the sentence to: The subsurface of the model area is limited to the Quaternary and Tertiary sediments which are deposited on the Boom clay aquitard during the Oligocene epoch.

Comment 6: Why were the A2 and B2 scenarios, only, chosen?

Authors’ response: All scenarios applied in this study are based on the simulations included in the PRUDENCE database. Because all scenarios in the PRUDENCE project are based on A2 and B2 emission scenarios also the scenarios of this study are based on the same emission scenarios.

Comment 7: P10201, L14 – describes the analysis done on the RCM data. What about the GCM data?

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Authors' response: The perturbations for rainfall and potential evapotranspiration applied in this study are derived based on the time scale and the intensity level or return period. For the rainfall variable, perturbations are derived separately for the number or frequency of rainfall events (i.e. storm events) and the mean intensity per event. Both perturbations combined lead to perturbations in the mean intensity for a given aggregation level. The applied methodology consists of comparing the complete frequency distribution between the RCMs reference and scenarios simulations. A full description of the applied perturbation technique is described in Ntegeka et al. (2008). The description of the applied perturbation technique in the paper will be extended.

Ntegeka V., Baguis P., Boukhris O., Willems P., Roulin E., 2008. "Climate change impact on hydrological extremes along rivers and urban drainage systems. II. Study of rainfall and ETo climate change scenarios", Belgian Science Policy – SSD Research Programme, Technical report CCI-HYDR project by K.U.Leuven – Hydraulics Section & Royal Meteorological Institute of Belgium, May 2008, 112 p. Available from http://www.kuleuven.be/hydr/cci/reports/CCI-HYDR_II-ClimateChangeScenarios.pdf

Comment 8: Was there a baseline assessment done on the GCM data to see if the GCMs adequately represented the baseline climatology, or required re-scaling?

Authors' response: Baseline assessments have be performed for the RCM scenarios. The tests involved calculation of error, bias, correlation and trends for the different time series under consideration. In the three spatial performance tests that were performed for the control simulations of the models (bias, RMS and correlation), two simulations showed consistently poor performance on every test: GKSS-CTL and ICTP-ref (Ntegeka et al. 2008). Consequently, we did not included the GKSS-CTL and ICTP-ref simulations in this study.

Comment 9: P10201, L20-24 – given the importance of this approach to the methodology, as it produces your changed daily time series, some description is required.

Authors' response: We agree to include more information on the perturbation method-

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ology.

Comment 10: P10202, L1 – is WetSpa a distributed model? Equation 1 appears to have no grid-to-grid routing i.e. soil doesn't receive runoff from upslope. From the description, the model would appear to be a grid-based conceptual model

Authors' response: Because the WetSpa model calculates the water balance components referred to in equation 1 for every grid cell the model is a distributed model. However, runoff, interflow and groundwater flow are indeed routed directly from the grid cell to the watershed outlet. Although there is a direct routing, essential in the routing scheme is that slope, soil and landuse distributed characteristics along the flow path are taken into account. Inherently, all hydrological models make considerable simplification towards the description of the hydrological processes. We believe that therefore all available hydrological models, including the WetSpa model could be considered more or less conceptual. However, in contradiction to traditional conceptual hydrological models that apply empirical derived descriptions of the hydrological processes we believe the WetSpa model could be considered physically and distributed based.

Comment 11: P10203, L2 – MODFLOW is set-up so that the top layer represents an amalgamation of multiple aquifers and aquitards, presumably with parameterisation representing neither (as they are means of the multiple layers). This approach needs to be justified, and the significance for the results of groundwater heads, discharge etc discussed later

Authors' response: The models top layer indeed represents all Tertiary sediments. This is a common approach for these sediments since it constitutes one aquifer. Because most Tertiary sediments do not cover the whole basin the top layer is subdivided into different zones in which the vertical and horizontal conductivity is calibrated separately. As mentioned in the text the initial horizontal and vertical hydraulic conductivity are calculated using respectively the weighted arithmetic and harmonic mean of the hydraulic conductivities of the individual aquifers and aquitards. There are three main reasons to combine the top layers into one layer in the model. First of all applying one top layer increases the models numerical stability. The numerical stability of the MODFLOW model with an increased number of layers fails especially during the dry climate change scenarios. Secondly reducing the number of layers also significantly reduces the calculation time, which is important because the model has to be run for all the different climate change scenarios. Thirdly, because the Campine clay-sand-complex occurs scattered around the basin it is difficult to delineate a separate layer for this aquitard.

Comment 12:P10203, L23 – what is the "calibration period" – months, years.

Authors' response: As shown on the graph, the calibration period ranges from the 1st of January 1992 until the 31st of December 2001. We will add the dates also in the text.

Comment 13: If I have understood correctly, the potential recharge outputs from WetSpa are used as Inputs to MODFLOW? Are there any other linkages? Figure 5 shows that both WetSpa and MODFLOW provide independent estimates of baseflow. It is unclear how the two are related, and whether the baseflow from MODLFOW has been calibrated (given that no error statistics for the baseflow are given).

Authors' response: Besides the groundwater recharge also the river heads are, although indirectly, based on the river discharge simulated by WetSpa. These simulated river discharges at the outlet are linked to an upstream river head profile. The baseflow simulated by WetSpa and MODFLOW are indeed both driven by the recharge output of WetSpa. In the MODFLOW model the recharge and the river leakage are the input to the groundwater system. The wells, drains and groundwater discharge to the rivers are outputs. The MODFLOW baseflow represented in Figure 5 is calculated as the difference between the river leakage from the groundwater system towards the river minus the river leakage from the river towards the groundwater system. The baseflow in WetSpa is calculated using a linear reservoir method for each sub-basin. The calibration of the MODFLOW was based only on the groundwater heads. The NSE of the baseflow calculated by MODFLOW compared to the filtered baseflow is 0.76 [-].

Comment 14: P10204, L5 – are these errors for Layer 1 and/or 2? Given that no groundwater heads are presented, it is difficult to judge these head errors.

Authors' response: The observation wells are located both in layer 1 and layer 2. Groundwater heads are shown in Figure 6d.

Comment 15: P10204, L8 – initial time step are "not used" – for what? How many?

Authors' response: This is to reduce the effect of the initial conditions, primarily the initial groundwater head. Because the results show that groundwater heads stabilize relatively quickly only 3 months are excluded. The sentence will be adapted to:" In order to reduce the effect of the initial conditions, the results of the first six time steps are not integrated in the analyses."

Comment 16: Section 4.1 – the focus on PET is not necessarily helpful as it is AET that is important. PET can increase significantly, with almost no impact on AET or recharge in the situation of low Available Water (i.e. sandy) soil. The results presented in this section on PET, precipitation and recharge do not balance as a result – Precipitation decreases by 50mm; PET increases by 180mm and recharge decreases by only 20mm!! Also, there is no mention of runoff – why? This section should be re-analysed to present and describe what is actually controlling recharge/

Authors' response: As mentioned previously we will include additional analyses of the WetSpa output, including AET and runoff.

Comment 17: P10205, L17 – why are the groundwater levels being given relative to the ground surface and not to a datumn such as sea level? A spatial change in groundwater head (with no change in the mean) could lead to a change in this metric.

Authors' response: One of the important aims of this paper is to assess what the impact of climate change could be on groundwater dependent vegetations. Therefore,

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most of the analyses made in this paper are based on variables that are important for vegetation. Groundwater depth is relevant, while the absolute groundwater level is not a relevant parameter for vegetation. Spatial changes are shown in maps such as Fig. 7a-d.

Comment 18: The authors average the results of their ensemble across the A2 and B2 scenarios. The authors should say why this is appropriate, given that A2 and B2 are separate Worlds – in other words, that the future impacts of climate change on groundwater is given by the average of two mutually incompatible worlds

Authors' response: The inclusion of both A2 and B2 scenarios merely gives an indication of the uncertainty on the future greenhouse gas emission that will affect the climate change. The scenarios indeed indicate the trend of the greenhouse gas emission based on different socio-economic assumptions however it is also likely that in reality the emissions will fall somewhere in between of those different assumptions. Recently for example Holman et al. (2011) point out that groundwater impact studies should span a range of emission scenarios.

Holman I.P., Allen D.M., Cuthbert M.O. and Goderniaux P. Towards best practice for assessing the impact of climate change on groundwater. Hydrogeology Journal, DOI 10.1007/s10040-011-0805-3, 2011.

Comment 19: Section 4.2 – what is the reason for the spatial differences – is it merely distance from constant groundwater head cells or also a consequence of spatial recharge differences?

Authors' response: This is an interesting topic which was also raised by Mr. Stoll in his review. In order to answer this question we will perform additional spatial analyses on the groundwater recharge simulated under climate change circumstances.

Comment 20: P10207, L1-4 – relating buffering to ranges of discharge flux is interesting, but why should cells with recharge flux of between 1-10 mm/d be well buffered?

Authors' response: The cells with a small groundwater discharge flux (<1mm/day) are situated on the borders of the groundwater discharge areas. Due to climate change these areas will become smaller in most scenarios and as such lead to drastic changes in the groundwater discharge of this area. Within the center of wetlands groundwater discharge is higher, MODFLOW predicts a similar decrease of groundwater discharge for these cells. This is due to the fact that the changes in recharge of the upstream infiltration zones are spatially averaged. Closer to the river where the highest groundwater discharges are found the groundwater discharge is also influenced by the river heads. Therefore, the changes are more diverse. Hence, because of the relatively large recharge area of cells with a flux between 1-10 mm/d these cells will have a more moderate change.

Comment 21: L9-10 – groundwater discharge frequency – do you mean the number of days in which there is groundwater outflow?

Authors' response: Yes, the groundwater discharge frequency is calculated as the percentage of time steps in which a groundwater discharge to SEEPAGE and RIVER cells is simulated for every 50 by 50 m cell of the MODFLOW model. This is mentioned in section 3.3: P10204L14-16.

Comment 22: L12-14 – again an interesting observation, but why should zones with 40-90% frequency be highly sensitive?

Authors' response: The impact assessment of the groundwater discharge frequency due to climate change shows that the highest changes in frequency occur in cells that during the reference period change from groundwater recharge cells (generally during summer) to groundwater discharge cells (generally during winter). The majority of the cells that are infiltrating water during all time steps continue to stay groundwater recharge zones in the future. The same applies for cells that are groundwater discharge zones 100% of the time. From the question we notice that the figure is not understood correctly. The confusion is probably caused by the fact that the change in groundwater discharge frequency, represented on the y-ax, is represented in absolute % of the reference discharge and not the relative percentage. For example a decrease in groundwater discharge frequency of 10% means that the reference frequency of for example 50% changes to 40% and not to 45%. The sensitivity of the cells is therefore relatively constant for the cells with a reference frequency between 0 and 80% and decreases drastically from 80 to 100%. Between a reference frequency of 0 and 80% the frequency reduces on average with around 20%. Due to the higher discharge fluxes between 80 and 100% frequency it seems to be more difficult to change the higher frequencies.

Comment 23: Fig 2 – this does not show the "occurrence", as layers are much more extensive. Is it showing the outcrop areas?

Authors' response: Basically three Tertiary formations occur in the basin: the Pliocene clay layer (HCOV 0240), the Pleistocene and Pliocene aquifer (HCOV 0230) and the Campine clay-sand-complex (HCOV 0220). The Figure indeed might be somewhat confusing because the HCOV 0230 shown in white covers the whole basin (Fig. 3) including the areas where the HCOV 0240 and 0220 layers are shown. This will be added in the figure caption.

Comment 24: Figure 8 – I struggled to determine what each of the lines was showing-needs clearer explanation

Authors' response: Additional information on the lines shown in Figure 8 will be added.

Comment 25: Figure 9 – presumably all of the dots represent cells in groundwater discharge areas i.e. rivers, wetlands? It shows a lot of cells with low reference discharge frequency which increase – why? Where are these located?. Also shows a lot of cells with high discharge frequency which are insensitive – why? Where are these located?

Authors' response: The large number of cells with low reference discharge frequency that increase slightly are caused by the fact that the results are based on the aver-

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age discharge frequency simulated by the different scenarios. A few scenarios predict a significant increase in groundwater discharge area. Although after averaging the groundwater discharge frequency for the different scenarios the frequency becomes very small, the frequency is still larger than zero and is therefore included in this graph. Indeed, it seems that the frequency for cells that receive groundwater discharge throughout the year is less sensitive to the climate change. This is because these cells receive a relatively large amount of groundwater discharge which might increase or decrease but will always remain a minimum discharge and as such not influence the frequency.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 8, 10195, 2011.