Response to Referee #1 comments on HESS-D paper

(Sutanudjaja et al., 2011, doi:10.5194/hessd-8-2555-201)

Response to overall/general comments:

First of all, we would like to thank Referee #1 for her/his kind appraisal of our paper and valuable suggestions and comments.

Referee #1 suggests condensing Section 2 ("Model concepts, parameterization and forcing data"). As we are of the opinion that a detailed model description of the "PCR-GLOBWB-MOD land surface model" (Section 2.2) is useful to readers who are unfamiliar with the model and to highlight the changes that were necessary to couple the land surface model to the groundwater model, we would like to include the current detailed description as an appendix of the paper. This publication may then also serve as a base for upcoming changes to the model, either by us or others, and be cited as such, rather than referring to the existing unpublished description of PCR-GLOBWB (see Van Beek and Bierkens, 2009), which is detailed but not always pertinent to the coupling of the models.

Therefore, we suggest that the current version of Section 2.2 will be included as the appendix of the paper. In this way, about 10-12 pages can be taken from the main text and replaced by one or two paragraphs summarizing the general description of the land surface model. As suggested by Referee #1, we will include a table summarizing the difference between the original and the modified versions ("PCR-GLOBWB-ORI" and "PCR-GLOBWB-MOD"). The information of Section 2.3 ("Climatological forcing data") and Section 2.4 ("Groundwater model"), which is not documented in other references, will be preserved, but in a much condensed way.

Regarding the Referee #1 second issue about why we ignored the global lithological map of Dürr, et al. (2005) and the derived global permeability map of Gleeson, et al. (2011): we found that at the resolution of 1 km the map of Dürr, et al. (2005) is too imprecise. We show this here (not in the original paper) for an important aquifer, such as the Upper Rhine Graben area (Figures 1a-1b and Figure 2). Figure 1a and 1b are the lithological map of Dürr, et al. (2005) and the digital elevation map of HydroSHEDS (Lehner et al., 2008), while Figure 2 is the UNESCO international hydrogeological map of Europe (http://www.bgr.de/app/fishy/ihme1500/). It is shown that the geographical position of the Upper Rhine Graben in Dürr, et al. (2005) is not consistent with the HydroSHEDS digital elevation map, which was used in our study. Moreover, the map of Dürr, et al. (2005) does not capture small aquifer structures located near most major rivers as suggested in the hydrogeological map of Figure 2.

Therefore we developed an alternative methodology in Section 2.4.1 of the paper to derive an aquifer classification map. Briefly stated, the method in Section 2.4.1 made use of a steady state groundwater model to calculate steady-state groundwater heads, a digital elevation map (DEM) to calculate groundwater depths and a drainage direction (LDD) map to incorporate the influence of river networks, that are closely related to the occurrence of groundwater bodies in their surroundings. The main steps of this method are summarized as follows:

1. First, we classified all cells with shallow groundwater depths (less than 25 m), mainly located in valleys, as the "sedimentary pocket/basin" cells that contain permeable and productive aquifers. Note that the resulting steady-state groundwater depth map presented in Figure 3 of our discussion paper (Sutanudjaja et al., 2011) is generally consistent to the UNESCO hydrogeological map of Europe presented in Figure 2 of this document.

2. Then, to avoid the occurrence of isolated cells due to errors and limitations in the DEM (such as rivers in narrow valleys that are missed in the DEM), we used the LDD to assure that downstream cells of a sedimentary basin cell are also classified as sedimentary basin cells. Moreover, because MODFLOW uses a discretization that does not allow diagonal flow across the corners, we made sure that a sedimentary basin cell must have at least one neighbor in its left, right, upper or lower extents. Finally, the remaining cells (which were not categorized as the sedimentary basin cells) were as "mountainous area" cells, where groundwater bodies are less permeable and most likely located at greater depths.

Referee #1 also questioned why we used KD = 100 m^2/day as a base case transmissivity value, while the global permeability (symbolized as p) mean of Gleeson, et al. (2011) is about 5E-14 m^2. If we assume the gravity acceleration g = 9.81 m/s^2, water density ρ = 1000 kg/m^3 and water dynamic viscosity μ = 1.0E-3 $N.s/m^2$, the global hydraulic conductivity of Gleeson, et al. (2011) is $K = p\rho g/\mu$ = ~4E-2 m/day, suggesting KD = ~4 m^2/day for 100 m thick aquifer.

Regarding to this question, we acknowledge that we did not describe clearly enough each aquifer class that we introduced. Here we think that the main source of the difference is in the definitions used. For our groundwater model simulation, we mean real groundwater bodies (excluding their upper soil layers) that are most likely constituting permeable materials. For our "sedimentary pocket/basin" class, we adopted K = 2 m/day and assumed 50 m aquifer thickness, suggesting KD = 100 m^2/day, while Referee #1 concentrated on the global K values of Gleeson, et al. (2011), ~4E-2 m/day, which is the average value calculated based on most lithological units defined by Dürr, et al. (2005). Therefore, for the latter, we may expect a relatively lower value because of the influence of silty, peat, clay soils and unfractured and unweathered rocks.

It should be also understood that our chosen K value (2 m/day) is actually not too far from the mean value reported by Gleeson, et al. (2011) for the "coarse grained unconsolidated sediment" class for their North America map, where they reported mean p = ~1E-11 m^2, suggesting K = ~10 m/day. However, besides of all afore-mentioned arguments, we realize that, for our future studies, we should consider to include the global mean p and K values of Gleeson et al. (2011) as suggested by Referee #1.

Referee #1 suggested that we should better explain and discuss the potential non-uniqueness in our model results. We indeed agree that non-uniqueness is an issue. We recognize this problem as one of our model performance indicators, R (a measure of timing agreement), is not sensitive to the variation in aquifer properties. To make this clear, we plotted the pareto space of the basin scale values of [1-R] and QRE_{7525} (a measure of amplitude error) in Figure 3 (of this document) that we have also included in the revised paper. Please note that, to plot Figure 3, we used the basin scale values of Table 3 of our paper. Thus, we encounter that different parameter combinations may lead to similar performance of R. We also see a pareto optimal front developing while looking multiple objective functions or performance indicators. It implies that the performance indicators, R and QRE7525, behave oppositely, in the sense that, moving through parameter space, performance indicator improves whereas the other deteriorates. This condition can regarded as an inability of the model to reproduce simultaneously different aspects of the model behaviors, which may be related to model structural limitations. Related to this last issue, we acknowledge that the current study cannot tackle it. However, we hope that we have shown that we aware with this problem and have addressed this issue now more substantially by means of Figure 3 (of this document) and in this discussion.

Response to specific comments:

Note: The bold sentences shown below are comments or questions from the Referee #1.

- **Referee #1 asked us to explain why the models were run uncoupled.**
  Response: This first, uncoupled model is the first step into developing a fully coupled one. One of its purposes was to evaluate computational loads and identify weaknesses and possibilities in the modeling structure. On a single PC with AMD Athlon Dual Core Processor 5200B 2GB RAM, the run time of this uncoupled version is about 1.0 hours for one year simulation, while with a preliminary version of the coupled version it may take up to 7 hours.

- **Page 2, Line 1: I am not sure that it is just lack of hydrogeological data that limits large models – it is also model platforms**
  Response: We agree that lack of large scale groundwater models -- whose main objective to calculate spatio-temporal groundwater head distribution and fluctuation -- is not only due to lack of hydrogeological data. As pointed by Referee #1, most of large-scale hydrological models (e.g. the original version of PCR-GLOBWB), do not have ability to calculate spatio-temporal groundwater heads.

- **Hydraulic conductivity should be capital K and Sy should be called specific yield.**
  Response: We will change the symbol for hydraulic conductivity to the capital *K* and we agree that the better definition of *Sy* is the specific yield (not the porosity).

- **Section 2.3.2 is strange – Van Beek should not be listed as pers. comm. if he is a co-author.**
  Response: We have removed the reference to Van Beek, pers. comm. in Section 2.3.2, as suggested by the reviewer.

- **Pg. 23, Line 13: dgw should be described as depth to water table**
  Response: We agree that the proper definition of d_{gw} should not have been "groundwater depth". However, we have an objection to use "depth to water table" as its definition, because the term of "water table" is only suitable for phreatic aquifers, not for confined aquifers. On this ground, we propose to maintain the definition of d_{gw} as "groundwater depth", but with an extra description: "groundwater depth, difference between the surface level elevation and groundwater head".

- **Pg. 25 "Big Lake" is colloquial – change to large lake.**
  Response: We have changed "big lake(s)" to "large lake(s)".

- **Add a map of Europe with basins shown on it to Figure 1.**
  Response: We have included the map of Europe to help the readers to identify the study area.

References:

Dürr, H. H., Meybeck, M., and Dürr, S. H.: Lithologic composition of the Earth's continental surfaces derived from a new digital map emphasizing riverine material transfer, Global Biogeochem. Cy., 19, GB4S10, doi:10.1029/2005GB002515, 2005.

Gleeson, T., L. Smith, N. Moosdorf, J. Hartmann, H. H. Dürr, A. H. Manning, L. P. H. van Beek, and A. M. Jellinek: Mapping permeability over the surface of the Earth, Geophys. Res. Lett., 38, L02401, 2011.

Lehner, B., Verdin, K., and Jarvis, A.: New global hydrography derived from spaceborne elevation data, EOS, 89, 2008.

Sutanudjaja, E. H., van Beek, L. P. H., de Jong, S. M., van Geer, F. C., and Bierkens, M. F. P., Large-scale groundwater modeling using global datasets: a test case for the Rhine-Meuse basin. Hydrology and Earth System Sciences Discussions 8 (2), 2555-2608, 2011. http://www.hydrol-earth-syst-sci-discuss.net/8/2555/2011/

Van Beek, L. and Bierkens, M.: The Global Hydrological Model PCR-GLOBWB: Conceptualization, Parameterization and Verification, Tech. rep., Department of Physical Geography, Utrecht University, The Netherlands, 2009. http://vanbeek.geo.uu.nl/suppinfo/vanbeekbierkens2009.pdf (last access: 28 Feb 2011).

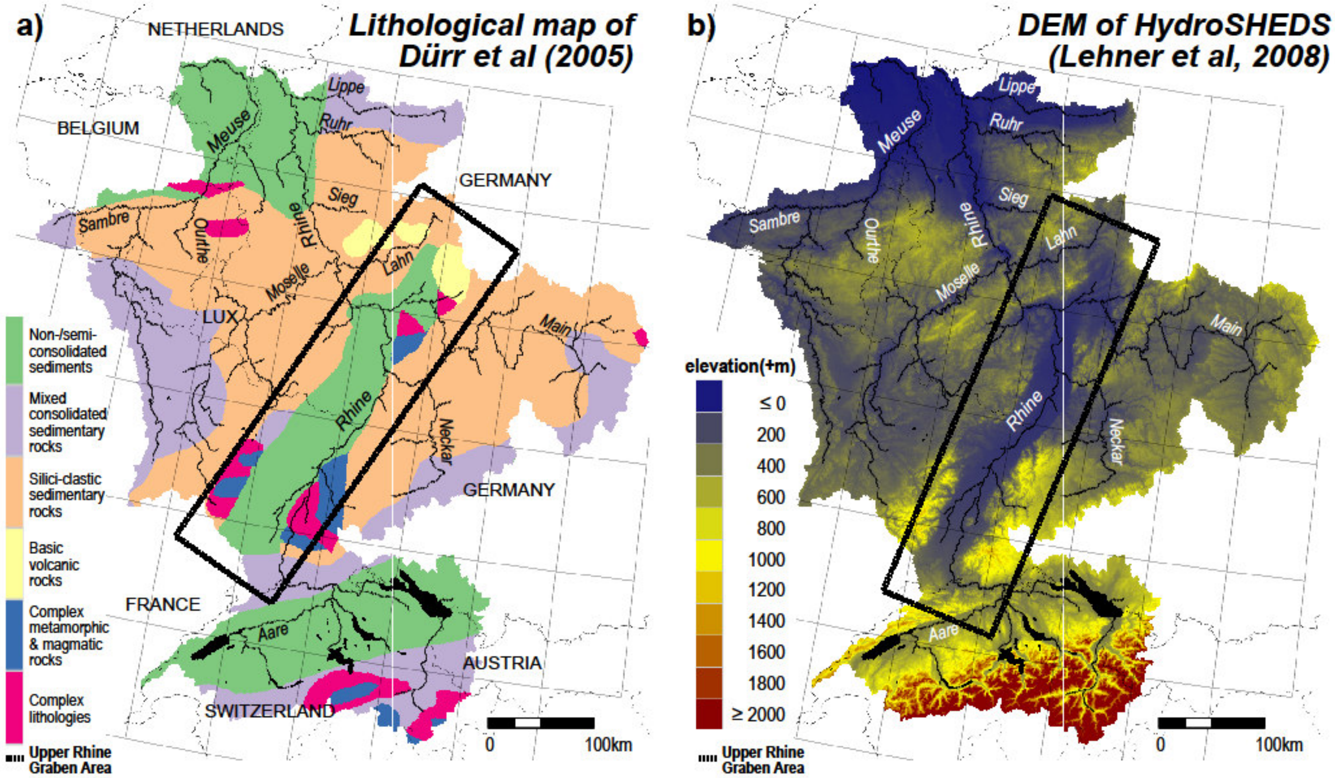

Figure 1 The global lithological map of Dürr et al. (2005) (1a) and the digital elevation map (DEM) of HydroSHEDS (Lehner et al., 2008) (1b) in the study area. It is clearly illustrated that there is mismatch of the position of the Upper Rhine Graben area in Dürr et al. (2005) map.

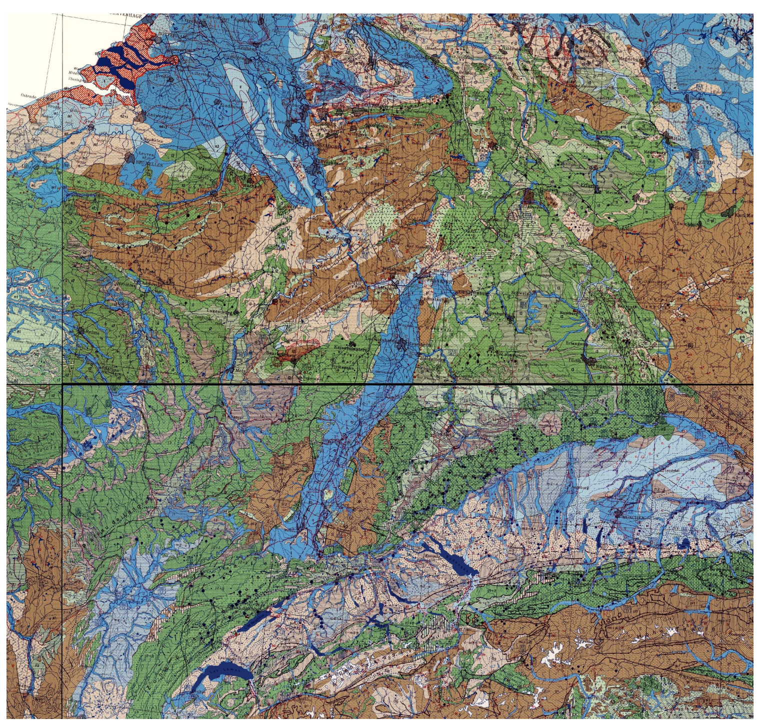

Figure 2 The UNESCO hydrogeological map of Europe (http://www.bgr.de/app/fishy/ihme1500/). The blue color indicates the location of permeable aquifer.

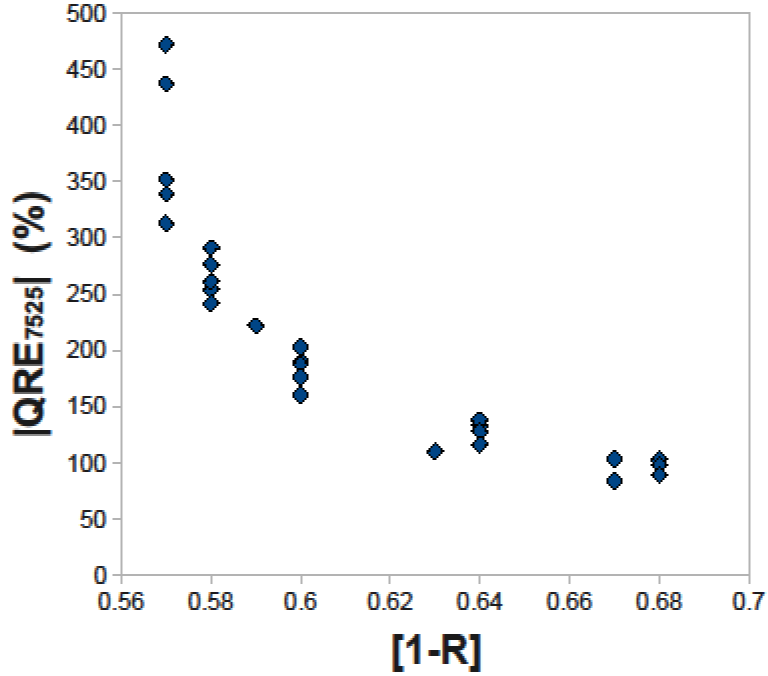

Figure 3 The scatter-plots of two model performance indicators (basin scale average values) from all scenarios with varying aquifer properties: QRE_{7525} (y-axis) and [1-R] (x-axis)