A High Resolution Global Scale Groundwater Model

Response to review

We wish to thank the tree reviewers for their positive review and the useful comments and suggestions on our manuscript. We have modified the manuscript accordingly. Detailed responses to their comments and corrections are listed below. In the following the reviewers' comments are given in italics and our replies in regular font.

Reviewer #1 Nir Krakauer

The authors have satisfactorily addressed my substantive comments. The manuscript however needs extensive copyediting prior to publication, as there are numerous word and syntax choices that make parts of this work difficult to read and render the authors' valuable scientific contribution less clear to the prospective audience than it can be. As an illustration, here is the abstract marked up.

- We understand the concerns of this reviewer, thank him for his suggestions and revised our manuscript to improve grammar, syntax, and hopefully readability.

Reviewer #2 Mary Hill

A high resolution global scale groundwater model
By IEM deGraaf, EH Sutanudjaja, LPH van Beek, MFP Bierkens

1. Scientific Significance: Does the manuscript represent a substantial contribution to scientific progress within the scope of Hydrology and Earth System Sciences (substantial new concepts, ideas, methods, or data)?

The study is good to excellent. The global simulation of groundwater flows is very interesting and potentially has important consequences; for example, countries trying to peacefully cope with boundary water issues may be able to use global models to achieve a plan with which all can live in peace. Model have played that role in many circumstances, such as the Klamath and Republican River basins in Oregon and Kansas, USA.

In this first of type study, clear presentation of methods is critical for the future utility of the work. The present study is mostly clear, though some things need additional explanation. Specific suggestions are provided below. A general comment is that the presentation of methods without reference to the figures, and reserving reference to the figures in the results section is does not work well. Using the figures to explain the methods and their consequences and saving the results and/or discussion section to discuss bigger consequences and possibly highlight briefly one situation for which the global model results are likely to be important would be much more interesting. Using a trans boundary water example seems like an obvious choice, but the authors may have other ideas. In this article the example would be quite superficial – just used existing figures to point out a situation of interest. One zoomed in figure might be useful as well.

- We made sure that references to the figures are now also included in the methodology section, improving the readability for the reader. The figures are now used better to support the explanation of the methodology.

- We focused are discussion concerning the flow paths more on the relevance and importance of inter-basin flow paths. We do agree that this was not yet discussed in sufficient detail. Nevertheless, we do not give specific examples, as we think this does not contribute to this study's main goal: showing global scale results. Zoomed figures of flowpahts for Europe and Africa are given in Figure 9. The specific additional discussion we provided on this topic is mentioned below, were this point Is raised.

2. Scientific Quality: Are the scientific approach and applied methods valid? Are the results discussed in an appropriate and balanced way (consideration of related work, including appropriate references)?

As far I as can tell the methods seem ok. Some are poorly enough explained that it is not possible to tell for sure.

- We clarified methods in agreement to the referee's comments listed below.

3. Presentation Quality: Are the scientific results and conclusions presented in a clear, concise, and well-structured way (number and quality of figures/tables, appropriate use of English language)?

Clarification for some methods is required. Referring to the figures in the methods section and possibly including one or two small additional explanatory figures would help a great deal.

- As mentioned earlier, we clarified the methods according to the comments and included an additional figure explaining the model concept (Figure 1). This figure supports the explanation of the difference between the simulated regional scale groundwater levels and (likely) sampled perched water tables. This figure also helps to understand the results of the groundwater head comparison.

The following are more specific suggestions.

- We adopted the suggested textual corrections throughout. Below we reply to the specific comments pertaining to the contents of our manuscript.

a) There are some typos. E.g. page 3 line 16. positivity. This same part of the text is repetitive. P. 4 first full paragraph is also repetitive.

- We rewrote this paragraph and removed the repetition; p. 3 , l. 12-17.

c) Page 7.
a. Line 1. There are 15 lithology classes in table 1. Expending should be expanding? This paragraph describes a situation much easier to understand if table 1 is referenced. You don't need to talk about everything in a table or figure when it is first referenced.
b. Line 22. Item 1. First sentence. Does this sentence refer to elevations within on cell? This description is not clear.

- A reference to Table 1 is added. Elevations of the surface and floodplain are evaluated within a cell, this is added to the text ; p. 7 , l. 21.

d) Page 8. Item 2. How does the depth referred to compare to the thickness referred to on p. 9? Is this depth from land surface? Eq. for F'. What is the range for F'? Next page refers to a Gaussian distribution, so F' goes from minus to plus infinity? Does 0 to 50 apply everywhere? In general this is not clear.

- Aquifer depth should be aquifer thickness; p. 9, l. 9.
- We acknowledge that this part of the methodology was still not completely clear at some points. A short explanation is given here as a response, we clarified this aspects in our manuscript on p. 8, in point 2.
- F'(x) can be seen as the likelihood of finding a thick aquifer at a particular location, and is calculated using eq. 1.: $F'(x) = 1 - \frac{F(x)-Fmin}{Fmax-Fmin}$. Fmin and Fmax are the minimal and maximal value, corresponding to the difference between the land surface elevation and the floodplain (p. 7 l. 23-24). We delineated sediment basins by having an elevation of equal or less than 50 m above the current river position, so Fmin = 0 m and Fmax = 50 m. The associated z-score of F'(x) is calculated using the inverse of the standard normal distribution, calculated by eq. 2: $Z(x) = G^{-1}(F'(x))$.

e) Page 9. Item 3. How many studies were used? Two are mentioned. In this item is the thickness of the unconsolidated deposits from land surface or water table?

- In total six studies area used, this information is added to the text p. 9 l. 4. As an example we only mention the most extensive ones.
- The thickness is estimated from the land surface, this is clarified in the text p. 9, l. 6-8 : "We assume that the thickness of the delineated sediment basins corresponds with the total thickness of the upper aquifer and that this thickness is log-normally distributed."

g) Page 11. The recharge is corrected for changing cell sizes. It is not clear to me why conductances were also not corrected. There was a comment about a full K tensor being needed, but there is an intermediate correction method that could have at least accounted for the changing length of flow. Whatever you did is fine, but be clear.

- Indeed a correction of conductance is need to account for the spatial dimensions of model cells. However, in the current MODLFOW model we are using this is still not possible. We acknowledge this is one of the limitations of the model, discussed at p. 10, l. 23-25. We will include this correction in near future versions of the model.

h) P. 12. Line 2. "Factor" is too vague. At least cite the purpose of the factor.

- 4.8 is an empirical factor derived from the relationship between discharge and channel geometry. This is added to the manuscript p. 12 l.2-3.

i) Page 12. Line 13. There is no thickness of the riverbed allocated, although a riverbed conductance is assigned, right. Again, no problem, but be clear.

- A thickness is not needed here as only a conductance should be provided to the RIV package. We assumed this is 1 day. We extended our explanation on this point in the manuscript p. 13, l. 1.

j) Page 12. Eq. for Qriv suggests an original MODFLOW sign convention, while a previous discussion for pumpage suggested a reversed sign convention. Be clear about the model sign convension. If it differs within the model and in the input files, be very, very clear.

- Indeed for the RIV and DRN packages we have used the original MODFLOW sign convention; water flowing into the aquifer is positive water flowing out of the aquifer is negative. The package outputs Qriv and Qdrn are thus negative when water is drained and positive when water infiltrates, explained p. 12, l. 20 and following from eq. 11 and eq 13. If pumpage would be implemented in the model it will use the same sign convention; negative when pumped, positive when infiltrated. However we do not implement pumpage in our model yet

m) Page 13. Eq. 14. This equation is calculated on a cell-by-cell basis, right? Qriv and Qdrn are negative for flow out of the gw and into the sw, based on earlier descriptions. This is consistent with the MODFLOW convention. It there is flow out the drains and river, the first term of the equation is thus positive. Let's day the distance L is very large and T is small so the second term is small. This leaves a Qbj value that is a positive number equal to the absolute value of (Qriv + Qdrn). As a positive number the sign convention would suggest this is flow to the gw system. The argument behind the magnitude and the sign do not make any obvious sense at all. Please provide a rationale and simple example such as I used here to clarify what was done.

- Indeed Qriv and Qdrn are negative when water is flowing out of the aquifer. The total baseflow is calculated as the sum of river drainage (big and small rivers, calculated by RIV and DRN) and local springs presented by the storage-outflow relationship (third term eq. 14). However the latter term does not use the sign conversion, that is why in eq 14 a minus sign is used; in this equation a positive baseflow means drainage. We acknowledge that this is confusing and decided to introduce a negative sign for the storage outflow relationship, meaning water is flowing out of the aquifer. Eq 14 is improved to: $Qbf = (Qriv + Qdrn) - JS3$, and discussed on p. 13, l. 18-19.

n) Page 14. In section 2.4 refer briefly to fig. 5. Discussing it later is fine, but being introduced at this point makes it a lot easier for the reader.
o) Page 14. This paragraph says in one place that gw depth is evaluated and then that heads are evaluated instead of depth. This is confusing. 65.303 cells are mentioned. How many are there in total.

- Groundwater heads are evaluated, calculated from groundwater depth data; this is now mentioned in the text p. 14 l. 26 , as well as the total amount of cells (6,480,000 cells)

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p) Page 15. Refer to figures 6 and 7. What are "flux densities"?

- Flux density is the specific discharge per unit of cross-sectional area. This is added on p.15, l. 7-8.

Reviewer #3

Review of "A high resolution global scale groundwater model by Inge de Graaf et al.
I would like to thank the author for considering carefully all the previous comments. The paper has significantly improved, but there are still a couple of things that I would like to point out.
1) I was a bit surprised that in the previous version there was a quite long discussion about the results of the model in mountainous regions (perched GW table) and that this now almost disappeared. My previous comments were not going into the direction of discarding completely those results, but I just thought that a better explanation was needed.
2) The discussion is still very limited and a bit confused. There are some inconsistency about over estimation and/or under-estimation of the results. What I feel is missing is a more structured summary of the results obtained grouping them by geographical area, or by similar characteristic. For example, where and why is the model over (or under) estimating GW levels? Is this expected? And so on.
3) In figure 5 it is really hard to notice any difference between the two maps. Maybe show just one of them?

Answer:

- 1, 2) Indeed we reduced the discussion on perched water tables (accordingly to suggestions of other reviewers). We acknowledge part of the discussion required more focus so we rewrote parts of the paragraph discussing the scatter plot of figure 6, and histograms of figure 7, p 17 l. 7-12 and 18-26. We also added an extra figure (F1b) showing a cross-section which illustrates the difference between the simulated regional scale groundwater table and the (often) sampled perches water tables to make our model concept more clear.

- We agree with the reviewer to move Figure 5B to the supplementary material .

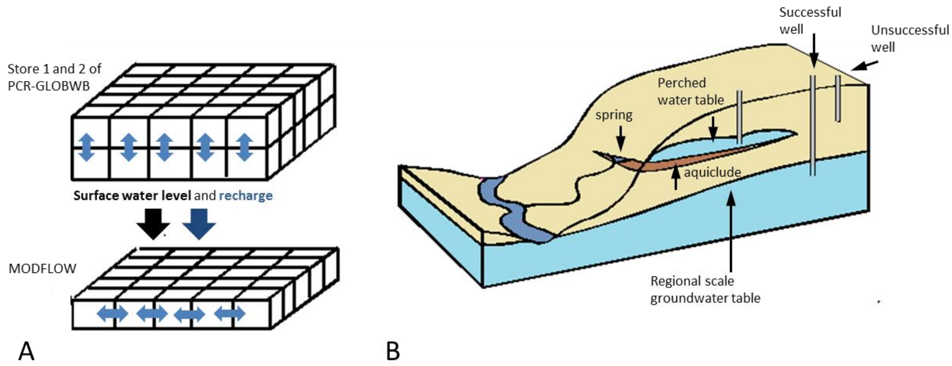

Figure 1: A) Model structure used to couple the land-surface model PCR-GLOBWB with the groundwater model MODFLOW: first average annual net recharge and average annual channel discharge is calculated with PCR-GLOBWB. The latter is translated into surface water levels. Both recharge and surface water levels are used to force MODFLOW (after Sutanudjaja et al. 2011). B) Cross-section illustrating the difference between the simulated regional scale groundwater level and often sampled from perched groundwater levels.