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Interactive Comment

Interactive comment on "Global-scale modeling of groundwater recharge" *by* P. Döll and K. Fiedler

P. Döll and K. Fiedler

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We thank the three referees for their thoughtful reviews of our manuscript which helped us to improve our manuscript. We are glad that they found our manuscript interesting and well written. Below find our responses to their specific comments and how the manuscript has been revised (action).

Response to comments of anonymous referee 2

1 Referee 2 comments: *p.4078: It becomes not clear how the factors for calculating fg are estimated; just guessed, calibrated etc.? Also the linearity of the approach is not very reasonable. One idea for improvement of a later version would be to use thresholds similar as applied for the semi-arid areas which need to be exceeded to produce groundwater recharge. This would also reduce the occurrence of abrupt changes at the boundaries between the different climates.*

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With respect to thresholds, we think that if there is runoff (surface or subsurface) at all in humid areas, it is likely that there is some groundwater recharge even at low total runoff, and the introduction of a threshold might not be indicated.

Action: The following text was added on p. 4078: The values for the four factors fr, ft, fh and fpg are expert guesses that have been adjusted iteratively by comparing the resulting spatial distribution of groundwater recharge and base flow indices with the global map of Lvovich (1979) as well as regional maps for the Elbe basin (Haberlandt et al. 2001), Southern Africa (Bullock et al., 1997) and Southwestern Germany (Bernhard Lehner, personal communication).

2. Referee 2 comments: *p.4080, l.18/19: Where comes the rule Precipitation <= Potential Evapotranspiration for the definition of semi-arid/ arid region from?*

Please note that the definition we use and provide on p. 4080 is precipitation less or equal half potential evapotranspiration. It is the definition of UNEP and the United Nations Convention to Combat Desertification, who use the aridity index (long-term average precipitation/potential evapotranspiration) to identify areas prone to desertification. According to the UNCDD definition, an aridity index of less or equal to 0.5 indicates semi-arid and arid regions.

Action: The sentence Semi-arid/arid grid cells are those with long-term average (1961-90) precipitation less or equal to half the potential evapotranspiration. on p. 4080 was modified and now reads: Following the definition of UNEP and the United Nations Convention to Combat Desertification (UNEP, 1992), semi-arid/arid grid cells are those with long-term average (1961-90) precipitation less or equal to half the potential evapotranspiration. The reference UNEP (1992) World Atlas of Desertification has been added.

3. Referee 2 comments: *p.4082, l.10: The unique distribution of precipitation for all wet days is a very simple approach and might suffice with this linear approach. However, if the groundwater recharge algorithm is modified in the future to a non-linear approach*

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e.g. using thresholds a non-unique distribution of daily precipitation should be applied to avoid biased estimation.

We agree that a nonhomogeneous distribution of monthly precipitation to wet days would more appropriate.

4. Referee 2 comments: *Fig.4: This figure seems to show the ratio of CRU to GPCC mean annual precipitation. The description in the figure caption is not clear here.*

Action: The caption of Fig. 4 now reads: Difference between the two available 0.5 degree global data sets of time series of gridded observed precipitation: ratio of CRU 19618211;1990 mean annual precipitation to GPCC 19618211;1990 mean annual precipitation.

5. Referee 2 comments: *Equations 2 and 3: Those equations seem unrealistic. Assuming the following values: P0=100mm, T=10C, Tmean=13C, CR=0.90 using Eq. (2) and (3) would lead to a correction of Pc=265mm which seems much too high?*

The Equation in our manuscript 2 was not correct and did not represent what we compute in our model. Eq. 3 is correct.

Action: Equation 2 is replaced by Pc = P0 [(1/CR-1)*(R(T)/R(Tmean))+1]

For the values assumed by the reviewer we would obtain Pc = 127 mm.

However, we found in the meantime that this correction is too high, given that at these temperatures a correction for snow effects does not make sense. In the current version of the model, we therefore set the correction factor R(T)/R(Tmean) to 1 if mean monthly temperature is higher than 3 degree C, as this correction factor is only supposed to account for the different snowfall fractions in different years. We found that this change in precipitation correction does not significantly affect the computed long-term average groundwater recharges.

To clarify further the performed precipitation correction, the following sentences have been added to the section:

In some areas, extremely high values of CR in the data of Adam and Lettenmaier (2003), which are likely due to the interpolation algorithm, were smoothed.

Correction of P0 was limited to a range between 1 and 2.3. Correction by R(T)/R(Tmean) overestimates the impact of interannual variability of monthly temperatures on the necessary precipitation correction if catch ratios are not affected by snow, i.e. at high temperatures. If this correction is only applied at mean monthly temperatures below 3 degree C, computed long-term average groundwater recharge is not significantly changed. The global value (ensemble mean using GPCC and CRU precipitation data) decreases by only 0.5%, and for 83.3% and 99.77% of all grid cells, long-term average groundwater recharge changes by less than 1 and 5 mm/yr, respectively.

6. Referee 2 comments: *Fig.5b: It becomes not clear which difference is shown here between CRU data and mean values or between GPCC data and mean values? I would guess it is the maximum of both differences. This should be made clear in the figure caption.*

As the mean is only computed as the average of GPCC and CRU values, the differences GPCC 8211; mean are equal to CRU 8211; mean everywhere. Thus, we think that no change in the figure caption is required.

7. Referee 2 comments: *p.4088, l.23-25; p4089, l.17-18: How is model efficiency defined? I would assume the Nash-Sutcliffe efficiency criterion is meant here? If yes, please call it that way or provide an equation or a reference. The Nash-Sutcliffe efficiency measure is independent of scaling of the target variables. So, the result should be identical no matter if mm/yr or if km3/yr are used as flow units.*

When looking at groundwater recharge of areas of different sizes, like countries, the modelling efficiencies (as well as the correlation coefficients) are not identical for mm/yr or km3/yr. In the case of km3/yr, large countries (with therefore large groundwater recharge values in km3/yr) dominate the modeling efficiencies, and we would consider that the evaluation of groundwater recharge per unit area, in mm/yr, is a more indicative of model performance with respect to groundwater recharge computation.

Action: In the revised version of the paper, the reference to Janssen and Heuberger (1995) who defined modelling efficiency has been provided and the equivalence to the Nash-Sutcliffe coefficient is given: Modeling efficiency (or Nash-Sutcliffe coefficient; Janssen and Heuberger, 1995) remains low, 8230;. The reference Janssen, P.H.M., Heuberger, P.S.C., 1995. Calibration of process-oriented models. Ecol. Model. 83, 558211;66. has been added.

Response to comments of anonymous referee 3

1 Referee 3 comments: *My general concern is about the different uncertainties in the simulation results. The authors have used two precipitation datasets as precipitation uncertainty is a major source uncertainty in these types of models. They then take the average of the simulation results with these two datasets as the best estimate. This is reasonable, but instead of stating that, e.g., the global groundwater recharge is 12666km3/yr I would like to see a 180;sxxx after this number, reflecting the two results with the different precipitation datasets. This is not the full uncertainty in the results, but at reasonable estimate. I do not think the readability of the paper will decrease by adding these numbers to the text.*

The uncertainty due to the two precipitation data sets is given in Tables 1 and B1, and also described at the end of the abstract. We prefer not to write the deviations as +- in the text, also because some people might think of it as representing standard deviations.

Action: In the abstract, we added the deviation for the global value: Regarding the uncertainty of estimated groundwater resources due to the two precipitation data sets, the deviation from the mean is 1.1% for the global value and

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2 Referee 3 comments: *WGHM is a conceptual hydrological model, where the simulated runoff is divided into fast surface and subsurface runoff Rs and groundwater recharge Rg (p. 4076). It is not explained what differs the subsurface runoff from the groundwater recharge.*

Fast subsurface runoff refers to interflow. The reader may refer to Döll et al. (2003) for details.

3 Referee 3 comments: *I also miss a discussion on the representatively of the simulated groundwater recharge to actual measured recharge.The division into fast runoff and groundwater recharge in conceptual models is rather made to get a good fit to the measured hydrograph but not to mimic the actual flow paths. A comparison with measurements is made in Fig. 3 for semi-arid areas, but what about the humid?*

When choosing the specific values for fr, ft, fh and fpg, maps of groundwater recharge or base flow indices also for humid areas have been considered. The validation in humid areas against base flow is limited 1) due to the uncertainty in deriving baseflow components from hydrographs, as discussed in the third section of the Introduction, and 2) the fact that most discharge stations on large rivers have upstream lakes or wetlands which determine the low flow behaviour.

Action: The following sentence has been added on p. 4078: The values for the four factors fr, ft, fh and fpg are guesses that have been adjusted iteratively by comparing the resulting spatial distribution of groundwater recharge and base flow indices with the global map of L8217; vovich (1979) as well as regional maps for the Elbe basin (Haberlandt et al. 2001), Southern Africa (Bullock et al., 1997) and Southwestern Germany (Bernhard Lehner, personal communication).

4 Referee 3 comments: *It surprises me that Fig 8 show rather few areas with a groundwater recharge share of the total runoff above 50%, while I had expected humid areas to have a groundwater share of 60-90%. Do you have any explanation to this? How come that e.g. Finland and Sweden has a lower groundwater recharge in Fig. 8 than*

Germany/Poland/Denmark and that such small areas of North America have a groundwater recharge higher than 50%?

Values of 60-90% are expected in flat terrain. Finland and Sweden have a lower groundwater recharge than Northern Germany/Northern Europe/Denmark because of the type of aquifer (low porosity, fissured). An indication that we do not underestimate the fraction of groundwater recharge in humid areas is that our global value is 10

5 Referee 3 comments: *On p. 4072 is the scale dependence mentioned, but it would also be interesting to know how you consider that in connection to the measurements in Fig. 3.*

On p. 4078, lines 24-28, it is explained in our discussion paper that only measurements were chosen for comparison that are assumed to be representative for an area of at least 25 km x 25 km. However, that does not solve the scale dependency related to groundwater recharge reappearing as river discharge. In this sense, for Fig. 3, we assume that there is no reappearance of groundwater within each cell.

6 Referee 3 comments: *In table B1 I suggest an additional column, stating the percentage of cells of the country belonging to calibrated basins where the estimates can be expected to be somewhat more certain, at least when no correction factor is applied to the calibration. I also miss a discussion of the latter, i.e., the influence on the groundwater recharge ratio to the total runoff in areas where the correction if the total runoff is applied.*

It cannot be determined whether groundwater recharge estimates are less certain in basins where a correction factor had to be applied. Thus, we do not think that such an additional column fits well into a (n already large) table the objective of which is to show water resources per country.

There are two types of correction factors, CFA, which corrects areal runoff generation and CFS, which corrects directly station discharge. It is the runoff as corrected by CFA that is partitioned into groundwater recharge and fast surface and subsurface runoff. So a correction by CFA should improve the computed groundwater recharge (as compared to no correction) if, for example, the need to use CFA is caused by wrong input data.

Altogether, we think it is not useful to discuss in this paper the relation between the uncertainty of groundwater recharge and the necessary application of correction factors, as 1) that would require a rather extensive presentation of the correction factors and 2) we cannot say anything conclusive about this relation.

7 Referee 3 comments: *Earlier groundwater recharge studies with WGHM are mentioned on p. 4073-74, but no comparison with these values is given in the discussion. It would be interesting to know if the new algorithm for arid areas and the updated dataset of gauged stations cause large or small deviations to the earlier results.*

Fig. 9 and its discussion on p. 4088 of the discussion paper shows the impact of the new algorithm for semi-arid/arid regions on groundwater recharge of countries. There is a reduction from 3690 to 3305 km3/yr of gw recharge in the semi-arid countries. The effect of the additional stations has not been determined as in the new version 2.1f (with 1235 stations) also other model and input changes have occurred. In Döll and Flörke (2005), the global value was 12882 km3/yr (with semi-arid/arid regions tuning) as compared to 12666 km3/yr in this manuscript, the difference being similar to the effect of the two different precipitation data sets.

8 Referee 3 comments: *Is it the results of this manuscript that will be included in WHYMAP (p. 4074) or some further developed results?*

Results as obtained with GPCC precipitation input will be included after being smoothed for cartographic reasons and setting groundwater recharge in two karst areas in former Yugoslavia and in Mexico to higher values.

Action: A paragraph on the review process of the WHYMAP map including the WGHM estimates of groundwater recharge (and its results) are added in the revised manuscript as last paragraph of section 4 on map quality: Groundwater recharge computed by WGHM using GPCC precipitation data as input has been included in WHYMAP Global Map of Groundwater Resources (with some smoothing for cartographic reasons). During the map development process, the groundwater recharge values were commented on by more than 30 groundwater experts from all around the globe (Wilhelm Struckmeier, personal communication, 2008). As a result, the depicted groundwater recharge was increased in two karst areas in former Yugoslavia and in Mexico. Otherwise, the experts did not identify, in the regions they are familiar with, any divergences from the groundwater recharge values they consider plausible.

9 Referee 3 comments: *The explanation of the catch ratios (p. 4082, row 10-12) is not clear. Did you use the data by Adam and Lettenmaier, or did you do this analysis yourself? In the latter case: - What was the source of the climatic stations? - Was both measured and actual precipitation provided at these climatic stations, or was it the wind that you used to calculate a correction factor? Did you use the temperature too, or was it only used in eq. (3)?*

We agree that we did not express clearly that we used data on catch ratios as provided by Adam and Lettenmaier.

Action: The introducing sentence to Eq. 2 now reads: We developed the following equation to correct the time series of gridded observed monthly precipitation Po, using catch ratios of Adam and Lettenmaier (2003):

10 Referee 3 comments: *The Method part should state that the model is calibrated against the runoff with both precipitation dataset. Right now I found that information in the Results part at first.*

Action: The following sentence was added as the last sentence of the methods section: WGHM was tuned separately with each of the two precipitation data sets.

11 Referee 3 comments: *What was the source of the country border data? This is*

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especially interesting as you exemplify with several countries which sovereignty too my understanding is not internationally totally clear (Falkland Islands, Svalbard, Western Sahara) while another discussed country, Taiwan, is not included table B1. Hydrological papers are not about diplomacy, so I have no problems with your list, but I would like to know the source of your country borders. More interesting, scientifically, is the exemplification with these rather remote countries, where you have used a regionalised model parameter instead of calibration. As I assumed earlier, that makes the results less reliable for those countries.

The country border data are from Environmental Systems Research Institute (ESRI)ő Data and Maps 2004 and represent the situation in January 2004. In B1, only countries larger 10,000 km2 are included.

Action: The following sentence is added . (borders of countries and subnational units are taken from ESRI, 2004). The reference ESRI: Data and Maps 2004, 2004. is added.

12 Referee 3 comments: *p. 4084, row 5-6 says: except for the dry Australia and Oceania. What is the size of Australia and Oceania in your continental division compared to Europe? Could it be a size effect too?*

No, we think this is due to the high precipitation uncertainty high there (as compared to Europe)

13 Referee 3 comments: *Are the B/A (when calculated for the two precipitation datasets, separately, and not on their average) very similar between the two precipitation datasets in Table 1 and B1, or can you see any effect of the absolute limit for groundwater recharge in semi-arid areas between the two precipitation datasets?*

They are very similar in most countries including semi-arid countries (e.g. South Africa: GPCC 0.294, CRU 0.295, Uzbekistan: GPCC 0.266 CRU 0.245) except when total water resources A are smaller than groundwater resources due to evapotranspiration of open water bodies (e.g. Chad: GPCC 1.97, CRU 1.44), which is due to strongly different estimates of A.

14 Referee 3 comments: *Can you please discuss why the deviation is 1.1precipitation datasets, used in the current paper, small, while they differ a lot from the old precipitation dataset in the ungauged areas?*

This is just due to averaging out (or not, depending on the specific values). Please have a look at the example below, which shows that large deviations can sum up to a zero deviation between methods.

	Method 1	Method 2	Average	Range (+/-) [%]
Region 1	5	3	4	25.0
Region 2	8	10	9	11.1
Sum	13	13	13	0.0

15 Referee 3 comments: *Can you please motivate further why you use the net cell runoff as a measure of the total water resources, instead of the total runoff (p. 4086 / Appendix B)? Why should the evaporation of water that is added from upstream cells be included, when not the runoff of these is included? To me, it seems more natural to use the total cell runoff, as you do in Figure 8.*

If you would use total runoff as a measure of water resources you would overestimate the water resources as these water resources would only be available if surface water bodies would be emptied to avoid the evaporation, or, to express it differently, one would have to use up the water flow before it reaches the water body. Useage downstream of the water body can only rely on inflow to lake minus evaporation.

16 Referee 3 comments: *Additionally, why does the number of total water resources for Germany differ so much between p. 490 (397 mm/yr) and table B1 (316 mm/yr). The evaporation from open waters of imported rivers cannot be 81 mm/yr, can it?*

You are correct. This was a typo. The WGHM value for total runoff from land is 315.6

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mm/yr, equal to the total water resources as given in Table B1.

Action: 397 mm/yr replaced by 316 mm/yr, and the base flow coefficient changed accordingly.

17 Referee 3 comments: *Comparing simulated groundwater recharge with the independent estimates in Fig. 9 (p 4088, row 15): I did not understand that it was the FAO estimate that was meant here as it is so much criticised in the sentence before and as you now consider it as a truth for the arid areas.*

The comparison is done as this is the most relied on global scale data on groundwater recharge in country, and we do not consider it as the truth but discuss extensively its uncertainty. We felt it useful to compare two uncertain estimates (FAO and WGHM). With respect to semi-arid regions, the point data that lead to the modified algorithm for semi-arid regions are rather taken as the truth (Fig. 3). Fig. 9 just shows that this tuning leads to results that are more compatible to FAO data (for the average of many countries).

18 Referee 3 comments: *How is the modelling efficiency (e.g. p. 4088) calculated?*

Action: In the revised version of the paper, the reference to Janssen and Heuberger (1995) who defined modelling efficiency has been provided and the equivalence to the Nash-Sutcliffe coefficient is given: Modeling efficiency (or Nash-Sutcliffe coefficient; Janssen and Heuberger, 1995) remains low, 8230;. The reference Janssen, P.H.M., Heuberger, P.S.C., 1995. Calibration of process-oriented models. Ecol. Model. 83, 558211;66. has been added.

19 Referee 3 comments: *Can you exemplify with some other countries on p. 4089 than Brunei and Réunion, as these are not included in Table B1?*

United Kingdom, Finland, and USA are already discussed, and Brunei and Réunion are included in Fig. 9.

20 Referee 3 comments: *Are the f values arbitrary set or have you tested several*

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different values? Are they the same throughout the earlier published WGHM results, or have you changed them over the years? Have you tested if the results are very sensitive to the selection of the f values?

The f values have changed between 2002 and 2005, but not since then. The results are very sensitive to the selection of the f values.

21 Referee 3 comments: *Table A1: I suppose that ravg here is if the whole cell has the same slope class, while eq. A1 describes the calculation of a more common ravg that do not have any of these distinct values, but it would be good if it could be clarified in the header of this table.*

Slope class and slope are characteristics evaluated at the 5 min scale, while ravg is for the 0.5 degree cell, and computed as given in Eq. A1 from 5 min values of the slope classes first, and then fr (at the 0.5 degree cell scale) is related to ravg. That might be confusing but we admit that we cannot think of a better heading.

22 Referee 3 comments: *What is meant with The coverage classes were related to the average areal coverage value Cpg. (p. 4097)?*

Action: The text has modified and now reads: Table A4 lists the five classes of permafrost extent according to Brown et al. To each of the five classes, an exact percentage of the area affected by permafrost Cpg was assigned, and fpg was set to (100-Cpg)/100.

23 Referee 3 comments: *Why did you need to rasterise the permafrost map when you write that you Brown (1998) provide digital data?*

The digital data were polygon data, not raster data.

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Referee 4 comments: *It would be interesting to further test the results and methods with smaller area groundwater estimates, where such estimates are of high reliability.*

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In the future, we plan to do this.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 4, 4069, 2007.

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