Bachelorarbeit

zum Thema

Global groundwater recharge:

Evaluation of modeled results on the basis of independent estimates

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Abstract Long-term average groundwater recharge representing the sustainable groundwater resources is modeled as a 0.5° by 0.5° grid on global scale by the WaterGAP Global Hydrology Model. Due to uncertainties of estimating groundwater recharge, especially in semi-arid and arid regions, independent estimates are used for calibrating the model. This work compiled a new set of independent groundwater recharge estimates based on a work of Scanlon et al. (2006). The 59 independent estimates, together with an already existing independent estimates compilation, are used for the evaluation of two WGHM variants; one variant is modeling with an improved more realistically distributed daily precipitation dataset.

The objective of this thesis is the evaluation of the modeled data of the WaterGAP Global Hydrology Model (WGHM). The analysis of the impact of the new Watch Forcing Data (WFD) precipitation dataset on the modeled groundwater recharge tends to result in lower values in humid and higher values in (semi-)arid regions compared to the WGHM standard variant. Comparing both WGHM variants to the independent estimates compilations, representing (semi-)arid regions, the WGHM variant shows over- and underestimations especially of the low values and the WGHM WFD variant shows a bias toward overestimation especially for values below 4 mm/yr. The analysis of texture, hydrogeology and vegetation/ land cover could not give satisfying explanations for the discrepancies, but derived from the groundwater recharge measurement methods analysis indirect/ localized recharge seems to be a significant factor causing underestimations, as resulted in the comparison of the independent estimates based on Scanlon et al. 2006 with the WGHM variants.

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1 Introduction

Generally groundwater recharge can be defined as the downward flow of water, originating from precipitation, rivers, canals or lakes, reaching the water table and forming an addition to the groundwater aquifers (Lerner et al. 1990: 6). This amount of water, which is added to reservoirs, is an important part of the global water supply. "*Groundwater recharge is the major limiting factor for the sustainable use of groundwater because the maximum amount of groundwater that may be withdrawn from an aquifer without irreversibly depleting it, under current climatic conditions, is approximately equal to long-term (e.g. 30 years) average groundwater recharge. Therefore, long-term average groundwater recharge is equivalent to renewable groundwater resources*" (Döll & Fiedler 2007: 863).

The question of a sustainable use is therefore how much water is recharged and according to that how much water can be withdrawn. This question can be analyzed on several scales depending on the issue of research. The most common way is to analyze on a national or watershed scale, according to the borders of the authorities. But today there are scientific and political reasons requiring global-scale approaches. There is a rising global interest in researching global changes and the resulting impacts. One example for such an eminent change is the anthropogenic climate change. International financing or funding organizations are seeking for information about future developments, with a special focus on the problem of freshwater scarcity (Döll et al. 2003: 105f.).

The need for information about sustainable groundwater resources is especially apparent in arid and semiarid (hereinafter (semi-)arid) regions. According to the United Nations Environment Programme (UNEP) and the United Nations Convention to Combat Desertification (semi-)arid regions are defined as areas where the long-term average precipitation is less or equal to half the potential evapotranspiration (Fig. 2) (UNEP 1992; qtd. Döll & Fiedler 2008: 868). In (semi-)arid regions "groundwater is often the only water source, [it] is vulnerable to contamination, and is prone to depletion." (de Vries & Simmer 2002: 5). Hence, the above mentioned problem of freshwater scarcity, which requires global-scale approaches of estimating groundwater recharge have highest impact on (semi-)arid regions and reliable knowledge of groundwater recharge is especially needed in water scarce regions.

One method of estimating groundwater recharge on a global scale is the use of a groundwater recharge model. "A model is a *simplified* representation of a real-world system, and consists of a set of simultaneous equations or logical set of operations contained within a computer program" (Wheater 2008: 2).

The ” **Water** – **G**lobal **A**ssessment and **P**rognosis“ (WaterGAP) model is such a global-scale groundwater recharge model, which has been developed by the Center for Environmental Systems Research at the University of Kassel in Germany in cooperation with the National Institute of Public Health and the Environment of the Netherlands. “The overall aim is to investigate current and future world-wide water availability, water use and water quality” (Center of Environmental Systems Research, University Kassel 2010).

WaterGAP consists of two main components, a Global Hydrology Model and a Global Water Use Model. While the Global Water Use Model is modeling global water withdrawal and consumptive water use, the Global Hydrology Model models the global water availability. Hence, the WaterGAP Global Hydrology Model (WGHM) is the part of the WaterGAP model calculating global groundwater recharge.

The problem of groundwater recharge models is high uncertainties, which are due to ”erroneous input data (precipitation, in particular, as well as radiation), sub-grid spatial heterogeneity, uncertainty with respect to model algorithms (e.g. computation of potential evapotranspiration or discharge reduction by water use) and neglect of important processes like surface water groundwater interaction (river losses, capillary rise), the formation of small ponding after short lateral transport and artificial transfers” (Döll et al. 2003: 113). So why is groundwater recharge modeled? Groundwater recharge is a parameter whose spatially extended measurement is especially difficult, meaning that the existing methods only have a rather local representativeness. By modeling the groundwater recharge on a global-scale recharge values for every location can generated. But what is inexcusably needed is a good basis of input data and a good model algorithm – describing all important features of the groundwater recharge process. To evaluate a model algorithm, minimize uncertainties and to improve the model performance, a model has to be calibrated against independent estimates. In humid regions river discharge is a good parameter for calibrating groundwater recharge, because “in watersheds with gaining streams, groundwater recharge can be estimated from stream hydrograph separation (Meyboom 1961; Rorabough 1964; Mau and Winter 1997; Rutledge 1997; Halford and Mayer 2000). Use of baseflow discharge to estimate recharge is based on a water-budget approach (…) in which recharge is equated to discharge” (Scanlon et al. 2002: 22). In (semi-)arid regions gaining stream generally do not occur but rather loosing streams, hence for (semi-) arid regions river discharge is not so reliable. “Tuning is likely to lead to an underestimation of runoff generation, as river discharge at a downstream location is likely to be less than the runoff generated in the basin, due to evapotranspiration of runoff and leakage from the river” (Döll & Fiedler 2008: 866). Therefore in (semi-)arid regions other methods for calibrating groundwater recharge are needed. Field studies using groundwater recharge measurement methods (e.g. tracer-techniques) provide independent groundwater recharge estimates, which can be used for comparison.

Previous WGHM results were compared with 51 independent estimates; as result of the analysis it was found that the groundwater recharge results in the (semi-)arid regions inhabited a systematic overestimation. It turned out that groundwater recharge in (semi-)arid regions with coarse texture and especially below 20 mm/year was overestimated. To solve this problem an additional algorithm was added, only causing groundwater recharge in (semi-)arid regions where the soil texture is coarse or medium (10 till 20), if the precipitation exceeds 10 mm/day (Döll & Fiedler 2008: 868). The groundwater recharge algorithm eliminated the bias of overestimation and the accordance of the results was improved, these WGHM results are the current WGHM standard variant.

As improvement to the data input, a new climate dataset “Watch Forcing Data” (WFD) (Weedon et al. 2010) is to be introduced to the model. The influence of the new dataset on the groundwater recharge results will be analyzed in this work. The new dataset might change the correctness of the current groundwater recharge algorithm, of other adjustments of factors or parameter in the model.

Next to the introduction of the new climate dataset, the focus of this study lies on a new compilation of independent estimates which are supposed to help to improve both variants, the WGHM standard and the WGHM WFD variant using the new precipitation dataset. The objective of this work is creating a compilation of independent estimates for the evaluation of modeled results of the WGHM variants. On a next step possible reasons for explaining discrepancies will be analyzed and in which way they would need to be corrected to improve the modeled results of the WGHM.

This leads us to three main questions of this work:

- How does the performance of the WGHM changes when introducing the new precipitation dataset?
- How effective is the performance of WGHM variants compared to independent estimates from (semi-)arid regions?
- What factors are possibly causing discrepancies between the independent estimates and the WGHM result?

2 Data and methods

2.1 WaterGAP Global Hydrology Model

2.1.1 Description of the model

The WaterGAP Global Hydrology Model (WGHM), models the average long-term annual direct groundwater recharge on a global scale with a grid of 0.5° geographical latitude by 0.5° geographical longitude, with the exception of Antarctica (Fig. 1). The computational grid consists of 66896 cells; and for each grid cell exist climate information and information about the slope characteristics, soil texture, vegetation/ land cover, hydrogeology and occurrence of permafrost and glaciers. A detailed description of the WGHM is given by Döll & Fiedler (2008). In this work only the groundwater recharge algorithm will be explained in more detail.

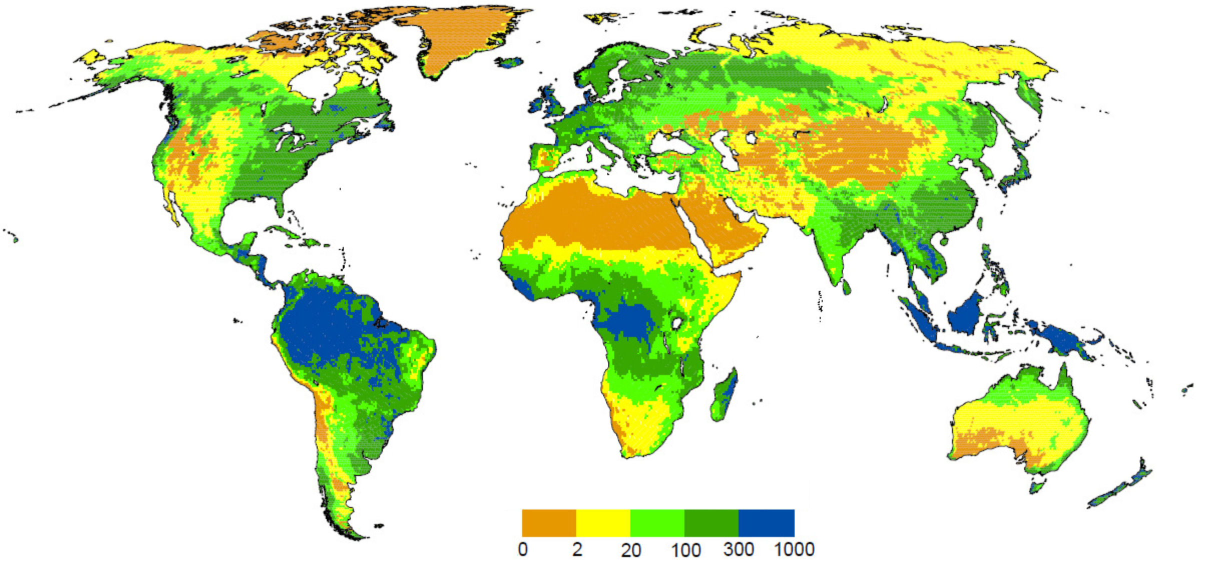

Figure 1. Long-term average groundwater recharge [mm/yr] modeled by the WGHM standard variant.

Groundwater recharge algorithm description Important for this work is the groundwater recharge algorithm which is used in the model (Eq. 1). This work will evaluate the current adjustment of the algorithm, which is based on a former compilation of independent estimates (comp. 2.2.2), on the basis of new independent estimates.

The daily direct groundwater recharge in each grid cell is computed as a fraction of the total runoff. And total runoff results from the balance of precipitation (GPCC Full data version 3 (Fuchs et al. 2007)), evapotranspiration from canopy, soil and surface waters, and water storage changes. The total runoff, which results from the described balance, is further divided into surface/subsurface runoff and groundwater recharge. While the surface/subsurface runoff runs quickly into lakes, rivers and wetlands, groundwater recharge is the fraction of the runoff which is added to the groundwater aquifer and will only leave the grid cell as baseflow. This represents a simplification of groundwater recharge processes for the model; in reality it is also possible for groundwater to rise up, back to the surface. The partitioning of the total run-off is calculated with the groundwater recharge algorithm, which calculates the amount of recharge on the basis of five factors. These groundwater recharge factors decide what amount of the total runoff in a cell will infiltrate into the ground. The groundwater recharge is calculated as described in (Eq. 1) by multiplying the total runoff with the groundwater recharge factor. But the infiltration and therefore the groundwater recharge can only reach a certain maximum (infiltration capacity; R_{gmax}), which is soil texture specific. If the amount of groundwater recharge that results from the product of the factors and the total runoff is higher than the infiltration capacity, this surplus which occurs can not infiltrate and will turn into surface runoff; groundwater recharge will be R_{gmax} (Döll & Fiedler 2008).

$$R_g = min(R_{gmax}, f_g * R_l) \text{ with } f_g = f_r * f_t * f_h * f_{pg} \qquad (1)$$

R_{gmax} = *soil texture specific maximum groundwater recharge [mm/d]*
R_l = *total runoff of land area [mm/d]*
f_g = *groundwater recharge factor* ($0 \leq f_g < 1$)
f_r = *relief-related factor* ($0 < f_s < 1$)
f_t = *texture-related factor* ($0 \leq f_t \leq 1$)
f_a = *aquifer-related factor* ($0 < f_a < 1$)
f_{pg} = *permafrost/glacier-related factor* ($0 \leq f_{pg} \leq 1$)

Algorithm for (semi-)arid regions The current version of the WGHM has an additional assumptions for groundwater recharge in (semi-)arid regions, saying that groundwater recharge in (semi-)arid areas with a medium to coarse texture (meaning < 21) will only occur if there is a minimum precipitation of 10 mm/day (P_{crit}). This aridity-adjustment was introduced to compensate a systematic overestimation of the results in (semi-)arid regions. This overestimation was found when comparing the modeled results to 51 independent estimates (Döll & Fiedler 2008: 867 f.). This algorithm for (semi-)arid regions is in better accordance to groundwater recharge processes occurring in (semi-)arid regions, “recharge does not occur continuously and regularly, but is confined to periods of exceptionally heavy rainfall” (Vogel and Van Urk 1975: 34). So if P_{crit} is increased, this will create a more realistic groundwater recharge process and small precipitation amounts do not lead to groundwater recharge.

2.1.2 WGHM standard and WGHM WFD variant

In this work two variants, calculated by the WGHM, will be evaluated. The first is the WGHM standard variant which is computed as described by Döll & Fiedler (2008) and the second is called WGHM Watch Forcing Data (WFD) variant, differing from the WGHM standard variant by the precipitation dataset that was used.

The WGHM WFD variant is called like this after a new precipitation dataset called The Watch Forcing Data (WFD) 1958-2001, a meteorological forcing dataset for land surface- and hydrological-models (Weedon et al. 2010), which is part of WATCH an Integrated Project Funded by the European Commission under the Sixth Framework Programme, Global Change and Ecosystems Thematic Priority Area.

With this improved data input the model performance of WGHM should be improved. While the monthly and yearly sums of precipitation in the WFD precipitation data are the same as in the GPCC precipitation dataset, used in the WGHM standard version, the new dataset has a more realistic distribution of precipitation amounts for each day. Next to the change in the precipitation dataset, also the land cover dataset is different in the WGHM WFD variant.

2.2 Independent estimates

The independent estimates in this study have the aim to represent one grid cell of the WGHM. The new compilation of independent estimates was taken from the work of Scanlon et al. (2006) and the other part are independent estimates from M. Edmunds compiled for a former evaluation in Döll & Fiedler (2008). The locations of the independent estimates are situated in semiarid and arid regions of the United States of America, northern and southern Africa, the eastern Mediterranean, the Arabic Peninsula, India, China and Australia (Fig. 2). There are 59 independent estimates based on Scanlon et al. (2006) and 25 based on M. Edmunds; some locations appear in both compilations. In total there are 72 WGHM grid cells, which have a corresponding independent estimate.

Independent estimates are defined as data which was observed and not modeled, originating from field studies and are measured with different methods, like tracer techniques (e.g. chloride-mass-balance, isotope-tracer), physical methods (e.g. water balance, lysimeter) and GIS applications. The independent estimates therefore are not based on the datasets of the WGHM.

Because the independent estimates are observed values, it is assumed that the independent estimates give more reliable values, than the results which are modeled by the WGHM. This assumption leads to evaluating how good the modeled data are compared to the independent estimates. Independent estimates for river discharge, which are commonly used for comparisons in humid regions are reliable and relatively easy accessible. Independent groundwater recharge estimates have uncertainties in their spatial representativeness to exactly one grid cell of the model. To improve the representativeness additional information about area size and precipitation deviation from the modeled results are evaluated.

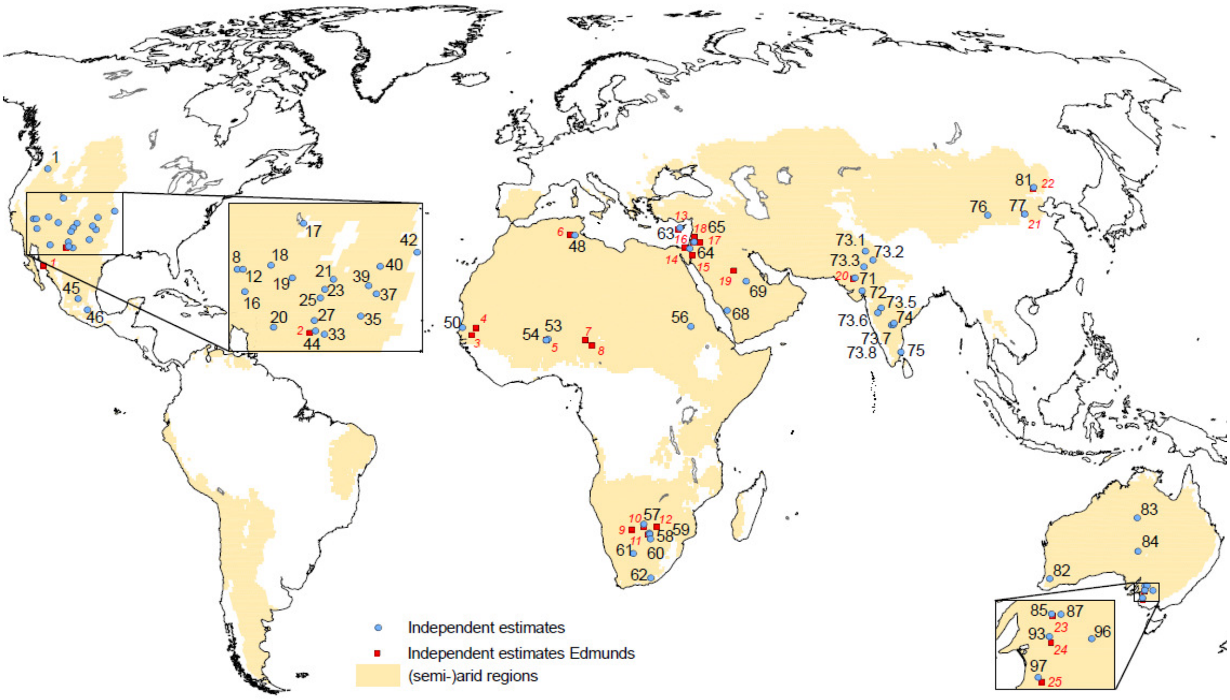

Figure 2. Global distribution of the independent estimate locations from Scanlon et al. 2006 (blue) and Edmunds (Döll & Fiedler 2008).

2.2.1 Description independent estimates based on Scanlon et al. 2006

The independent data used for the evaluation is based on a compilation that was made in the work of Scanlon et al. (2006). This work had the objective of a global synthesis of groundwater recharge in semiarid and arid regions. Those groundwater recharge estimates are an ideal basis for a comparison with recharge values from global scale models; for they are a compilation of recharge estimates of studies of arid and semiarid region on a global scale (Scanlon et al. 2006: 3336). The work of Scanlon et al. (2006) contains 105 recharge study location in arid and semiarid regions. The original works of the independent estimates compiled in Scanlon et al. (2006) were analyzed with the result that from those 105 locations only 59 locations will be used in this evaluation for reasons of representativeness to the WGHM.

The compiled studies were undertaken with different aims; therefore the information given in the studies vary. Nevertheless, ever study location contains (1) groundwater recharge values, (2) precipitation values and (3) the groundwater recharge measurement method that was used. Further more some contain information about (4) the size of the area in which the recharge value was estimated, and if the value is a regional average or a rather local value. Almost all study areas give information about the underground, which means mainly about (5) the type of soil, but some also about (6) the geology (and about clay contents). Not all study areas give information about (7) vegetation or land cover.

Selection of representative independent estimates As already mentioned independent data in my work means that the data is not modeled, because Scanlon et al. (2006) also contains a number of study locations, whose data were estimated by modeling, these study locations do not appear in this study. As it was explained in the description of the WGHM, in the model only direct recharge is modeled. Because this study wants to evaluate how good the model and the used algorithm is, only data were used for the survey, which is representative for one grid cell. (1) This excluded recharge values whose estimates represent recharge of impermanent water reservoirs, like ephemeral streams or playa lakes; these estimates can not be representative for a WGHM grid cell. But the study will contain values that have some influence of ephemeral streams and playa lakes, because indirect/ localized recharge processes are part of the groundwater recharge process for this location. (2) The WGHM only models natural groundwater recharge, which means, that the recharge was not induced artificially, so study areas in which irrigation takes place are not representative. (3) Data which clearly do not represent the current recharge situation are not representative; this means groundwater recharge rates that are clearly not occurring in the Holocene, for example Pleistocene recharge values. (4) It was found that the concept of groundwater recharge and the way it is estimated in the studies can differ. One study from Scanlon et al. (2006) was found in which the concept of the groundwater recharge was not to be compared to the concept of the WGHM and the other independent estimates. Here the groundwater recharge was reduced during the year by massive evaporation from the aquifer, which was lying very shallow under the surface (10 cm). This value had to be taken out, because the representative recharge could not be ascertained. This sorting reduced the total number of studies to 73 locations with representative groundwater recharge values.

Additional information about the independent estimates In the different works of the independent estimates groundwater recharge is given in several kinds; some recharge estimates represented a regional average, other contained groundwater recharge estimates from several profiles, others give a groundwater recharge range and some the arithmetic mean of several estimates. For the evaluation of the groundwater recharge a independent estimate values representing one WGHM grid cell as best as possible are needed. Therefore regional averages or the arithmetic mean is needed; if the arithmetic mean was not given, it was calculated from the values given in the works, which in some cases were several samples and in some cases it was minimum and maximum; in both cases the arithmetic mean was calculated.

To classify the representativeness of the recharge estimates, information about the size of the area of the study was needed. This information was in some studies derived directly and for others it was estimated from maps displayed in the studies. Unfortunately some studies do not contain any information about the size of the area. There are also locations, whose area is larger than a ~55km by ~55 km grid cell. For those locations, the groundwater recharge of several cells was summed up. The cells chosen were either around the center cell or they were chosen so the shape of the map seen in the original work was achieved.

Like the groundwater recharge, also the precipitation data from the studies is given in different kinds. Some precipitation values were given as arithmetic means, some as a range from maximum to minimum and some contained the both information. For this evaluation like for the groundwater recharge the arithmetic mean of precipitation is needed, therefore in cases where no arithmetic mean was given it was calculated.

The verbal soil texture information available in the studies (gravel, sands, loams, clays), was classified into the texture classification system used in the WGHM, where 10 stands for coarse textures, 20 for medium textures and 30 for fine textures, with interim values varying according to the tendency towards an other category.

The vegetation and land cover information is derived from the studies and usually contains descriptions about typical plant types. From these information about typical plant types a classification was made according to the vegetation/ land cover system used for WGHM standard variant.

The verbal information about geology was also classified into the geohydrology categories of the WGHM; 100 meaning a high hydraulic conductivity for Cenozoic and Mesozoic sedimentary rocks, 70 for low hydraulic conductivity for Paleozoic and Precambrian sedimentary rocks and 50 for very low hydraulic conductivity for non-sedimentary rocks.

Allocation of independent estimates to the WGHM results Information containing the geographic coordinates of the study sites for the independent estimates based on Scanlon et al. (2006) was available from B. Scanlon. The coordinates were taken from the papers of the studies, from maps used in the papers or from other sources (e.g. internet); I assumed that for larger areas the coordinates represent the centre of the location.

In the GIS program ArcMap the locations were displayed over a layer of the WGHM 0.5° by 0.5° grid cells. The ID of the grid cell, which contained an independent estimate location, was allocated to the accordant independent estimate. This resulted in the allocation of all independent estimates to one WGHM grid cell. There are now some WGHM grid cells containing more than one independent estimate with different groundwater recharge estimates. The independent estimates are not equally representative to the values of the WGHM. Therefore in cases where more than one study with independent estimates for one WGHM grid cell was available, the most representative study was chosen. Which is the study having the smallest precipitation difference towards the GPCC precipitation value, the largest area size or most additional information. This selection led to the final 59 groundwater recharge estimates and their additional information used for the evaluation (Appendix 1a-3a).

Comparability criterions To asses the representativeness of the final 59 estimates, a weighting represented by "comparability criterions" was created. The additional information of the independent estimates is compared to the WGHM information. Precipitation, area size, vegetation/ land cover, texture and geohydrology were categorized (Tab. 1).

Table 1. Comparability criterions - representativeness of the independent estimates compared with the modeled results.

Precepitation			
Class	Meaning	No. of indep. Estimates	
1	Indep. differs less than 25% from modeled	44	
2	Indep. differs less than 50% from modeled	12	
3	Indep. differs more than 50% from modeled	3	
Area			
Class	Meaning	No. of indep. Estimates	
1	Area size is bigger than 500 km²	21	
2	Area size is bigger than 1 km²	14	
3	Area size is smaller than 1 km²	7	
4	No area size available	17	
Soil texture			
Class	Meaning (deviation from less then 5 points)	No. of indep. Estimates	
1	Texture from indep. is comparable to model data	36	
2	Texture from indep. is not comparable to model data	8	
3	No information about texture	15	
Vegetation/ Land cover		WGHM standard	WGHM WFD
Class	Meaning	No. of indep. Estimates	
1	Veg/LU from indep. is comparable to model data	21	10
2	Veg/LU from indep. is not comparable to model data	17	28
3	No information about vegetation and landuse	21	21
Geohydrology			
Class	Meaning	No. of indep. Estimates	
1	Geohydrology is comparable to model data	24	
2	Geohydrology is not comparable to model data	4	
3	No information about geohydrology	31	

2.2.2 Additional independent estimates (Edmunds and Hevesi et al. 2003)

The compilation of 51 independent estimates used for calibrating the WGHM in Döll & Fielder (2008) are also available for this evaluation. It is a compilation containing 25 independent estimates complied by W. Michael Edmunds from the Oxford Center for Water Research, Oxford University Center for the Environment. The independent estimates from this compilation contain information about groundwater recharge and precipitation (Appendix 1b-2b). Some of locations 59 estimates based on Scanlon et al. (2006) appear also in the 25 independent estimates from Edmunds, this is the case for 13 estimates. If analyses with both compilations of independent estimates are made, for the doubled estimates the values from Edmunds are used.

Next to the estimates compiled by M. Edmunds, the compilation of 51 independent estimates also contains a set of 26 estimates generated by Hevesi et al. 2003, representing 26 bordering WGHM grid cells with a size of 25 km by 25 km in the Death Valley Region in Nevada and California, USA. The model is “estimating the temporal and spatial distribution of net infiltration and potential recharge” (Hevesi et al. 2003: 1).

3 Results

3.1 Analysis of the WGHM WFD variant

3.1.1 Comparison with WGHM standard variant

At first the influence of the new precipitation dataset onto the WGHM is evaluated by comparing the WGHM WFD to the WGHM standard variant. When comparing the difference of the two WGHM variants, by subtracting each grid cell of WGHM standard from WGHM WDF, groundwater recharge is differing within a small range of ±5 mm/year in large parts of the global land area (Fig. 3). But in large parts of South America, eastern USA and central Africa the WGHM standard results are up to 250 mm/year higher than the WGHM WFD results. There are only few parts for example in eastern Europe, where the WGHM WFD estimates are with more than 25 mm/year higher than WGHM standard. The areas with little difference (± 5 mm/year) are especially the (semi-)arid regions where also groundwater recharge is low with values mainly under 20 mm/year.

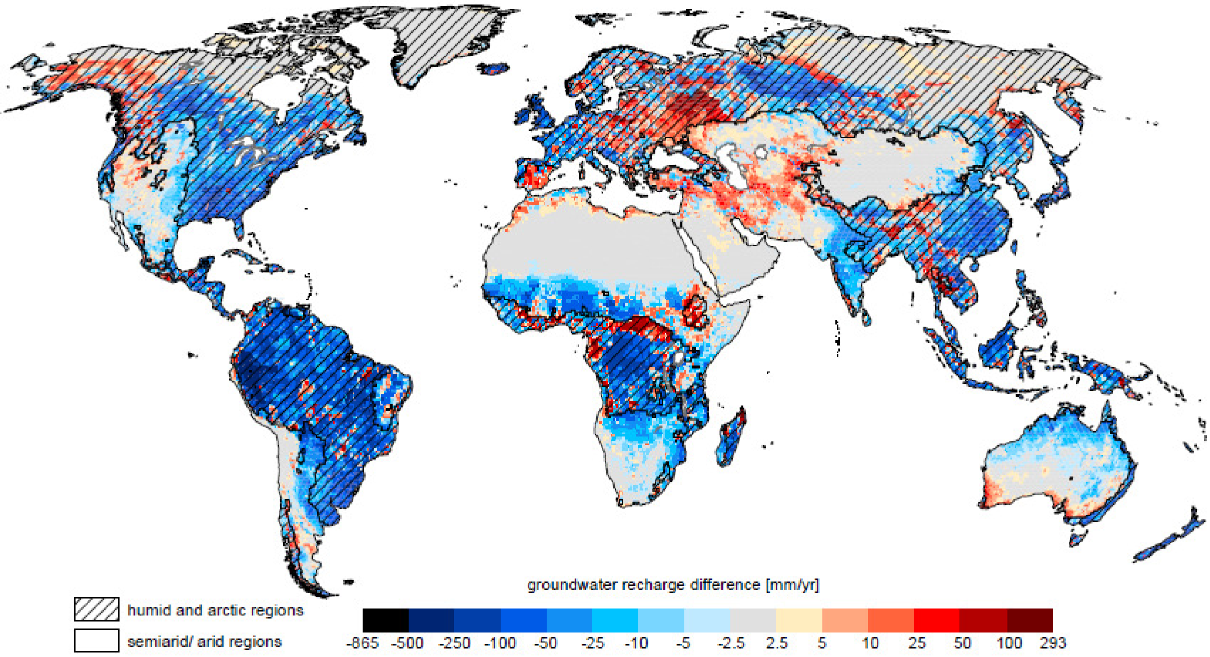

Figure 3. Global distribution of differences [WGHM diff = WGHM WFD – WGHM standard] between the WGHM variants.

Comparing the WGHM standard variant and the WGHM WFD variant using the percent deviation of each grid cell (Fig. 4). In humid regions the deviation of groundwater recharge has a deviation within a range of ± 25% in most of the area. In humid regions WGHM standard estimates are generally higher than the WGHM WFD estimates, examples are South America and the eastern USA; here the WGHM standard variant is up to 100% higher than the WFD variant. But there are also a few northern humid regions Siberia, north Canada or in eastern Europe, in which not the WGHM standard, but the WFD variant is up to about 100%

higher. In most (semi-)arid regions the groundwater recharge of the WGHM WFD is higher than the WGHM standard estimates. The WGHM WFD variant values exceed the standard variant by more than +1000% in central Asia, some parts of northern Africa, south-east of Australia and the east-north USA. But there are also (semi-)arid regions that show that WHGM standard exceeds the WFD variant by up to 100%.

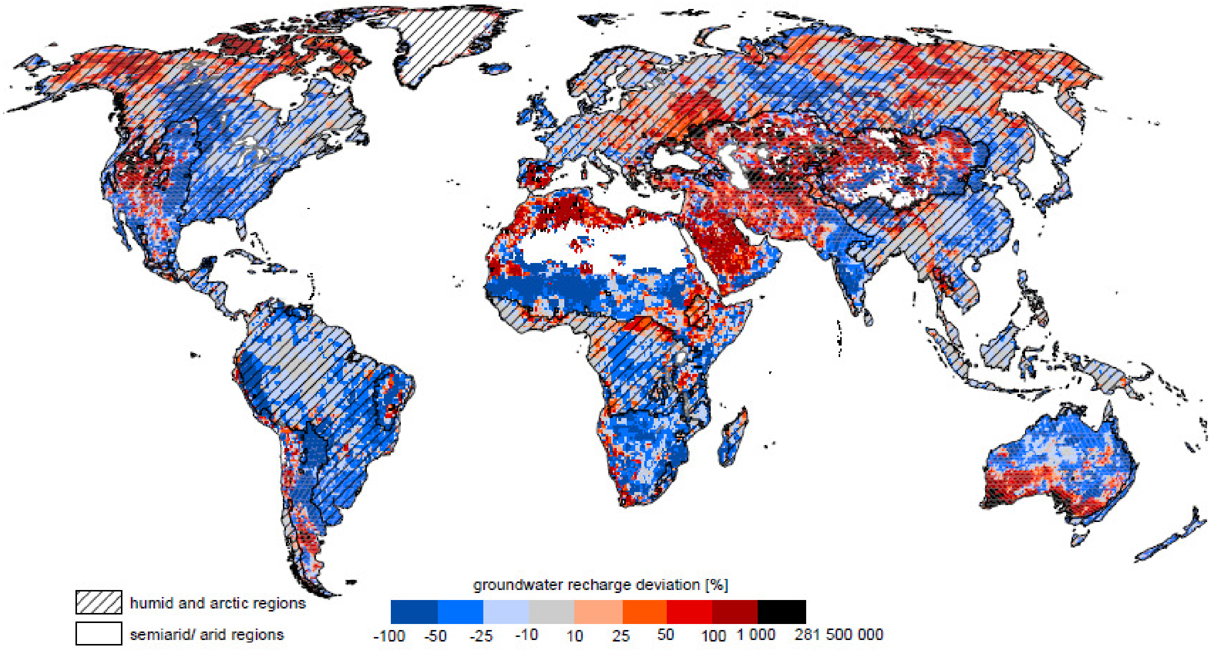

Figure 4. Global distribution of the percent deviation [WGHM perc. dev. = (WGHM WFD – WGHM standard)/ WGHM standard * 100] (areas with WGHM values of 0 are white).

This analysis did not show a clear pattern of the difference between the WGHM standard and WGHM WFD variant; some of the discrepancies might also be caused due to the differences in the land cover datasets. The analysis led to the conclusion that there is a tendency of the WGHM WFD variant to calculate lower groundwater recharge in humid regions and higher groundwater recharge in (semi-)arid regions than the WGHM standard variant.

The statistics of the WGHM variants show that the arithmetic mean of groundwater recharge of the WGHM WFD variant in humid regions is lower than arithmetic mean of the WGHM standard, with a reduction of 17.96 % supporting the results of the spatial comparison. But in (semi-)arid regions contrary to the results found in the spatial comparison, where the WGHM WFD variant is higher than WGHM standard variant, the statistic results show less groundwater recharge for the WGHM WFD variant in (semi-)arid regions, with a reduction of 24.41 % (Tab. 2).

3.1.2 Comparison with independent estimates representing (semi-)arid regions

In the comparison of the statistics of WGHM and the 51 independent estimates, which are representing (semi-)arid regions and were used for calibrating the WGHM in Döll & Fiedler (2008), the results of both WGHM variants have a slightly higher arithmetic mean (28.90 % WGHM standard & 13.29 % WGHM WFD) than the independent estimates. Because the arithmetic mean gives no information about the accordance between single values of the WGHM and independent estimates, the distribution of the estimates around the 1:1 line is taken into account. While the distribution of the WGHM standard results have deviations towards both sides of the 1:1 line, the results of WGHM WFD show a bias towards being overestimated, especially for independent estimates below 4 mm/yr (Fig. 4). So other than the arithmetic mean, which shows overestimation for both WGHM variants in (semi-)arid regions, the graphic only shows a significant bias for the WGHM WFD results.

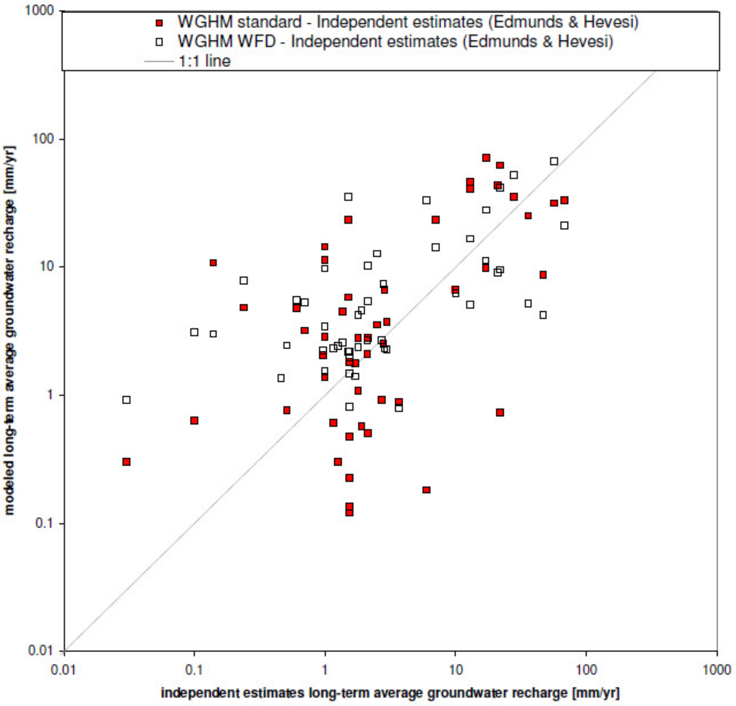

Figure 5. Distribution of the modeled long-term average groundwater recharge results of the WGHM standard and WGHM WFD variant compared to 51 independent estimates based on Edmunds (Döll & Fielder 2008).

3.1.3 Groundwater recharge algorithm analysis to adjust the WGHM WFD variant

After those previous analyses a groundwater recharge algorithm analysis is supposed to find out how the WGHM WFD values will react to a change of the soil texture specific maximum groundwater recharge (infiltration capacity; R_{gmax}) and changes of the critical precipitation (P_{crit}), which has to occur to generate groundwater recharge in (semi-)arid regions with coarse texture. The aim was to increase groundwater recharge for the WGHM WFD variant in humid regions and to reduce it in (semi-)arid regions.

When increasing the R_{gmax} parameter groundwater recharge will increase. To decrease the groundwater recharge in the (semi-)arid regions, P_{crit} has to be increased. With a higher P_{crit} more precipitation on a day is needed to create groundwater recharge. The new precipitation dataset is expected to bring more days with high precipitation amounts, being more realistic than an equal distribution of precipitation amounts.

Table 2. Statistical results of the groundwater recharge estimates of the WGHM including the results from the groundwater recharge algorithm analysis.

	Independent estimates	WGHM standard	WFD standard	WFD* 10 mm/d	WFD* 12.5 mm/d	WFD* 15 mm/d	WFD* 17.5 mm/d	WFD* 20 mm/d
humid and arctic regions (44,100 cells)								
Minimum:		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum:		959.58	894.12	1188.57	1188.57	1188.57	1188.57	1188.57
Mean:		**133.48**	**109.51**	**133.91**	**133.91**	**133.91**	**133.91**	**133.91**
Stand. Dev.:		151.48	126.84	166.68	166.68	166.68	166.68	166.68
(semi-)arid regions (22,796 cells)								
Minimum:		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum:		305.42	171.68	241.36	228.34	228.34	228.34	228.34
Mean:		**20.56**	**15.13**	**18.66**	**16.93**	**15.46**	**14.24**	**13.24**
Stand. Dev.:		32.90	21.76	27.39	25.94	24.80	23.98	23.42
(semi-)arid cells with independent estimates based on Scanlon et al. 2006 (59 cells)								
Minimum:	0.00	0.00	0.90	0.90	0.35	0.18	0.01	0.01
Maximum:	350.00	94.23	94.80	100.44	100.44	100.44	100.44	100.44
Mean:	**31.90**	**19.10**	**15.30**	**18.57**	**17.26**	**16.14**	**15.39**	**14.64**
Stand. Dev.:	52.90	22.48	18.79	22.82	22.55	22.59	22.73	22.91
(semi-)arid cells with independent estimates based on Edmunds and Hevesi et al. 2003 (51 cells)								
Minimum:	0.03	0.00	0.80	0.89	0.76	0.37	0.29	0.16
Maximum:	68.00	71.03	67.03	74.73	74.73	74.73	74.73	74.73
Mean:	**8.58**	**11.06**	**9.72**	**11.84**	**10.15**	**8.87**	**7.84**	**7.11**
Stand. Dev.:	14.71	16.81	13.64	16.26	15.47	15.12	14.84	14.76

*Rgmax is increased and Pcrit is on written value [mm/d]

As expected, when increasing R_{gmax}, the groundwater recharge was increased in humid and in (semi-)arid regions (Tab. 2). The analysis of P_{crit} showed that by increasing P_{crit} from 10 mm/day to 12.5 mm/day groundwater recharge can be decreased from a mean of 18.66 mm/yr to the mean of 16.93 mm/yr, this is more or less the amount of groundwater recharge which was increased befor by increasing R_{gmax}. For humid and (semi-)arid regions together this results in a smaller reduction of the arithmetic mean from 94.63 mm/yr to 94.05 mm/yr.

In the statistical comparison of the WGHM grid cells with the 51 independent estimates, like seen in the comparison of the all grid cells in arid regions, a reduction can be achieved by increasing P_{crit} to 15 mm/d, resulting in good accordance of WGHM WFD variant to the 51 independent estimates. But if comparing the WGHM variants to the 59 independent estimates, which were compiled in this study, the arithmetic mean of those estimates is with 31.90

mm/yr much higher than the arithmetic mean of the 51 independent estimates with 8.58 mm/yr.

Hence, when comparing with the new independent estimates the aim, to improve the WGHM WFD variant by reducing groundwater recharge in the (semi-)arid regions, can not be maintained. According to those independent estimates groundwater recharge in (semi-)arid regions has to be increased in both WGHM variants.

3.2 Comparison of the WGHM variants with the independent estimates

For the following analyses the 26 estimates from Hevesi et al. (2003) which were used in Döll & Fiedler (2008) will no longer be taken into account. They are not in accordance to the criterions for independent estimates the way they have been defined in chapter 2.2, because they are not purely observed estimates.

3.2.1 Statistical and efficiency coefficient evaluation

Comparing the remaining 25 old independent estimates based on M. Edmunds to the 59 new independent estimates compilation, the independent estimates based on Scanlon et al. (2006), according to the arithmetic mean (31.90 mm/yr), give distinctively higher groundwater recharge than the estimates based on Edmunds (15.66 mm/yr). This leads to the result that WGHM is underestimated when compared to the independent estimates based on Scanlon et al. (2006) and overestimated when compared to the estimates based on M. Edmunds. Combining the two independent estimates compilations the arithmetic mean is 27.42 mm/yr, it will still result in an underestimation of the WGHM variants with 19.88 mm/yr (standard) and 14.50 mm/yr (WFD) (Tab. 3).

Table 3. Arithmetic mean, Nash-Sutcliffe coefficient (E) and coefficient of determination (R²) of the WGHM variants and the results of the groundwater recharge algorithm analysis.

	independent estimates	WGHM standard	WFD standard	WFD* 10 mm/d	WFD* 12.5 mm/d	WFD* 15 mm/d	WFD* 17.5 mm/d	WFD * 20 mm/d
	Scanlon							
mean	**31.90**	**19.10**	**15.30**	**18.63**	**17.27**	**16.10**	**15.29**	**14.50**
E		0.366	0.231	0.329	0.333	0.326	0.317	0.307
R²		0.506	0.411	0.456	0.490	0.501	0.501	0.497
	Edmunds							
mean	**15.66**	**20.50**	**16.38**	**19.98**	**17.67**	**15.83**	**14.40**	**13.38**
E		-0.421	-0.030	-0.340	-0.162	-0.098	-0.063	-0.063
R²		0.141	0.135	0.163	0.200	0.220	0.236	0.244
	all							
mean	**27.42**	**19.88**	**14.50**	**17.68**	**16.25**	**15.04**	**14.10**	**13.29**
E		0.352	0.246	0.334	0.340	0.336	0.329	0.321
R²		0.407	0.377	0.420	0.452	0.464	0.471	0.471

*Rgmax is increased and Pcrit is on written value [mm/d]

The parameter for modeling efficiency the coefficient of determination (R²) was used (Eq. 2) for a general value of the goodness of the results; the closer R² to 1.0 the better the representativeness. Taking all independent estimates the coefficient of determination gives a slightly better result of R² = 0.41 for WGHM standard than for WGHM WFD with R² = 0.38. When looking at the coefficient of determination for the compilations of independent estimates separately, we find significantly better accordance for the independent estimates based on Scanlon et al. (2006).

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2 \sum_{i=1}^{n} (S_i - \overline{S})^2}} \right\}^2 \qquad (2)$$

When looking at the quite good representativeness of results according to R² it has to be taken in to account that “the R coefficient estimates the concentration of (Qo, Qc) points [observed, computed] along an arbitrary line on the (Qo, Qc) plane, not along the 1:1 line which is of the only interest to the modeller. This means that the correlation coefficient is insensitive to the whole bias of the model” (Weglarczyk 1998: 100). To evaluate the results also with regard to the bias, the Nash-Sutcliffe coefficient (Eq. 3) is used, which “represents model success with respect to the mean as well as to the variance of the observations” (Hunger & Döll 2008: 848). While a value of 1 would stand for high accordance, a value of zero would indicate that the modeled results are as good as the arithmetic mean of the independent estimates and values below zero indicate that the arithmetic mean of independent estimates would be a better estimation than the model.

$$E = 1.0 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \qquad (3)$$

Taking all the independent estimates the Nash-Sutcliffe coefficient is E = 0.35 for the WGHM standard variant, which is not very high, but higher than E = 0.25 of the WGHM WFD variant. Similar values are achieved for the independent estimates based on Scanlon et al. (2006), while for the independent estimates based on M. Edmunds the Nash-Sultcliffe coefficient is below zero, indicating no representativeness of the WGHM with the independent estimates. The bad result may partly be caused due to the very low amount of values. For the WGH WFD results, as analyzed in the groundwater recharge algorithm analysis, when reducing the groundwater recharge of (semi-)arid regions, by increasing R_{gmax} and setting P_{crit} to 20 mm/day, it leads to an improvement of R² and E.

3.2.2 Graphical comparison of the independent estimates and modeled results

Next to the mathematical analysis a graphic comparison of the distribution of the values around a 1:1 line is conducted for a better determination of the bias. Looking at the distribution around the 1:1 line, better accordance for the higher groundwater recharge values than for the low values is found (Fig. 6). The WGHM standard variant gives a high variation of low recharge estimates to both sides of the 1:1 line. About the same amount of values that have a deviation of more than 100% towards either side of the 1:1 line, it means that the WGHM standard results are over- and underestimated. This is bias to both sides occurs for the independent estimates of Scanlon et al. and M. Edmunds, whereas the Edmunds estimates are slightly more overestimated.

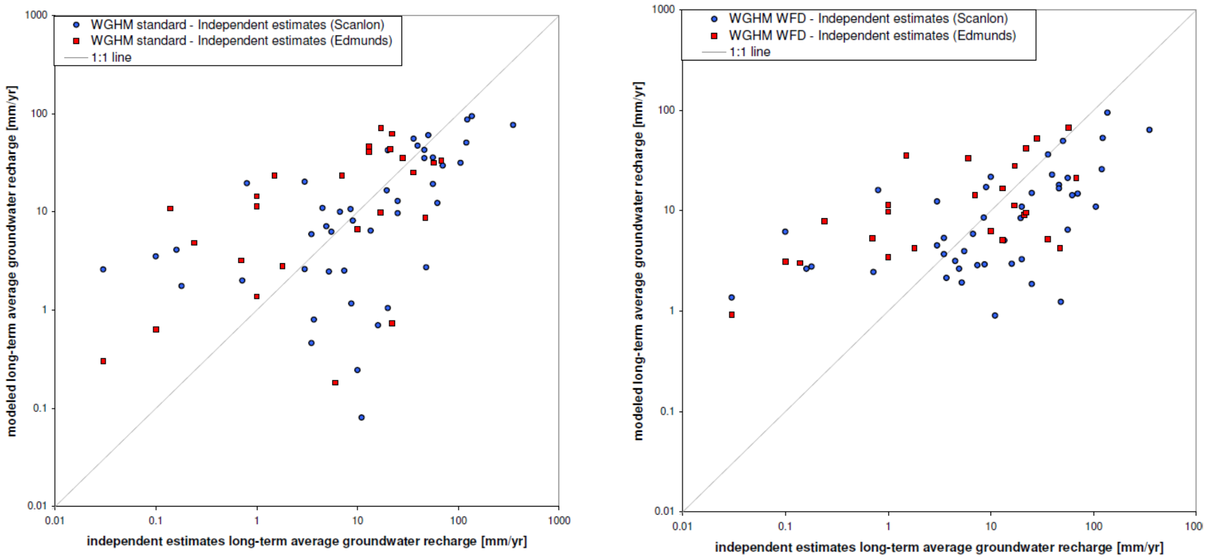

Figure 6. WGHM standard (left) and WGHM WFD (right) compared to 72 independent estimates.

The already described discrepancy of the arithmetic mean of the two independent estimates compilations is also visible when looking at the distribution around the 1:1 line for the WGHM WFD values (Fig. 7). While the Scanlon et al. (2006) estimates are slightly underestimated, the Edmunds estimates are overestimated. The distribution shows a bias towards overestimation especially for independent estimates below 4 mm/yr.

The result of this graphical comparison is that the WGHM standard variant has deviations from the 1:1 line to both sides, especially for low groundwater recharge values, and that the WGHM WFD variant has a bias towards overestimation for estimates below 4 mm/yr, supporting the results from the statistical analysis.

3.3 Analysis of possible factors causing discrepancies in (semi-)arid regions

3.3.1 Groundwater recharge factors analysis

The groundwater recharge factors (texture & geohydrology), occurring in the studies of the independent estimates, are possible factors for the deviations between the independent estimates and the modeled results.

Comparing the **soil texture** of the independent estimates and the modeled results, 36 grid cells are in good accordance and only 8 are not (Tab. 1). It was reviewed if for a certain soil texture range the modeled results have a bias, but no clear indication was found. Only one grid cell (ID 73.1) showed a significant discrepancy between the independent and modeled textures which is also visible in the groundwater recharge values. When adjusting the fine WGHM texture value (24) to the coarser independent estimate value (10), due to a coarser texture groundwater recharge of the WGHM is expected to increase and this would lead to a better accordance. All in all, independent and modeled values are in good accordance and the analyses of the soil textures could not bring significant explanations for an over- or underestimation.

The groundwater recharge factor of **geohydrology** shows good accordance for 24 grid cells and no accordance for only 4 grid cells (Tab. 1). Of the 4 grid cells with no accordance to the independent estimates, 2 grid cells according to the independent estimates have rocks with higher conductivity. This means if the hydraulic conductivity of the WGHM would be adjusted towards higher conductivity, WGHM results would increase. For the grid cell with ID 17 this could bring better accordance to the independent value, even though we have to take into account here, that the precipitation difference is 73 %, which already gives an explanation for the higher independent recharge value. The second grid cell (ID 20) is in no need for improvement. Two other locations (ID 68, 69) show lower conductivity according to the independent estimates, meaning that groundwater recharge is expected to be reduced when adjusting to the independent estimates. But this would cause an even higher difference between independent estimate and WGHM result. A further discrepancy is that precipitation here is higher for the WGHM and has lower groundwater recharge than the independent estimate. It can be concluded that the geohydrology values are in quite good accordance and no explanations for groundwater recharge discrepancies can be found in geohydrology.

3.3.2 Vegetation/ land cover analysis

The **vegetation/ land cover information** show little accordance; compared to the WGHM standard variant, 21 grid cells have good accordance and but almost the same amount, 17 grid cells have no good accordance and for the WGHM WFD variant only 10 show good accordance and 28 show no accordance (Tab. 1). It was reviewed if a bias is inhabited to a certain vegetation/ land cover type, but no clear evidence was found.

The difference between WGHM and independent estimates vegetation/ land cover, could be interpreted as a land cover change resulting in a change of groundwater recharge. Scanlon et al. (2006) analyzed the impact of land cover changes on groundwater recharge. For example the "conversion of grassland and shrubland to crops also has significant impacts on recharge" (Scanlon et al. 2006: 3351). While in the study of Scanlon et al. (2006) an increase of groundwater recharge was found, comparing independent estimates and modeled results for 4 results (out of 5) less recharge was found, if the land cover is mainly cropland. Another example of land cover change impacts is that "changing LU/ LC [land use/ land cover] from non-vegetated to vegetated conditions reduces recharge to zero" (Scanlon et al. 2006: 3350). Comparing independent estimates and modeled results, in 6 cases (out of 10) groundwater recharge was higher for barren or no vegetation. Two examples from China (ID 76 & 81) show high recharge (47-48 mm/yr) for the independent estimates with no-vegetation. Shrubland or cropland is assumed in the WGHM results and groundwater recharge is between 1.24 and 8.76 mm/yr.

The vegetation/ land cover analysis shows that vegetation/ land cover data from the independent estimates studies and the modeled results are in no good accordance. But in this study it can not be determined whether groundwater recharge discrepancies are in correlation to a certain land cover type not being modeled correctly or land cover changes not yet being displayed by the land cover data of the WGHM or independent data.

3.3.3 Groundwater recharge measurement methods analysis

The different groundwater recharge measurement methods were analyzed to explain what might be a reason for over- or underestimation of the recharge. Both WGHM variants have best accordance, if the independent estimate is derived from the average of more than one method (Fig. 7). If the chloride mass balance (CMB) method of the saturated and unsaturated zone was used, modeled groundwater recharge over- and underestimation occurs. When applying the Tritium (^3H) and Chloride (Cl disp.) tracers almost all modeled results, especially in the WGHM standard variant, are underestimated (Fig. 7). "Tritium transport appears to become dominated by vapour transport when fluxes decrease below 10 mm/yr. Therefore, systematically higher flux rates are found when applying the tritium method for uncorrected tritium activities than when the chloride mass balance method is used" (Selaolo et al. 1996:

46). The tracer methods could explain underestimations for some of the modeled results, especially for the WGHM standard variant.

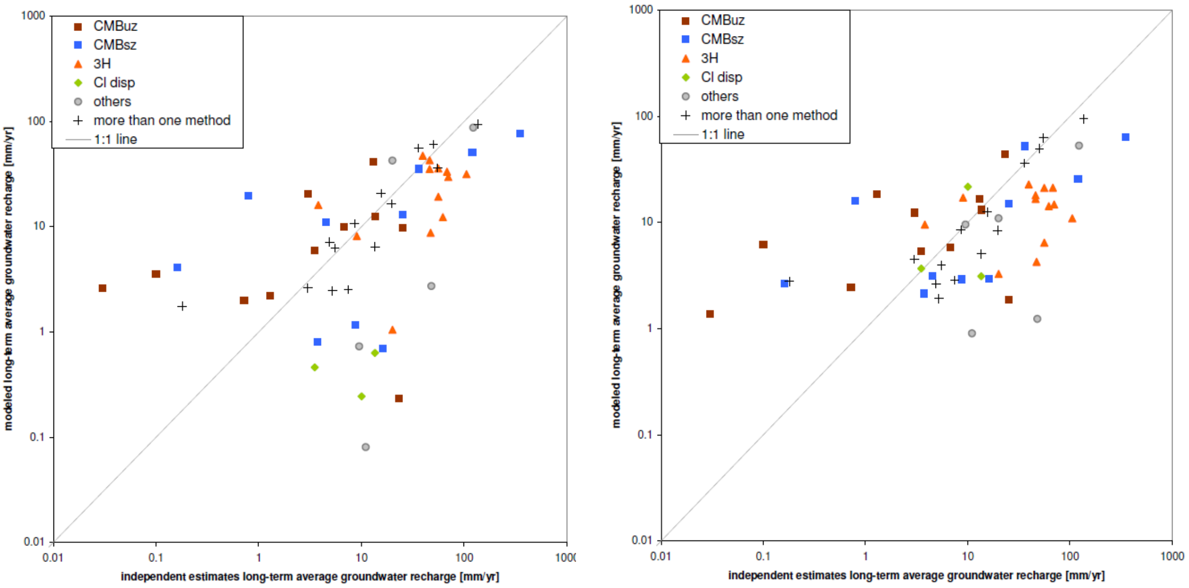

Figure 7. Groundwater recharge measurement method analysis of the independent estimates when compared to WGHM standard (left) and WGHM WFD (right).

“Historical tracers, such as bomb-pulse tritium an chlorine-36, have proved useful in delineating preferential flow in many regions (Nativ et al.,1995; de Vries et al., 2000; Flint et al., 2002)” (Scanlon et al. 2006: 3352). This allows the conclusion that a reason for underestimations can be preferential flow, which is a form of indirect recharge not being modeled by the WGHM. Indirect recharge or more specific localized recharge, “results from percolation to the water table following runoff and localization in joints, as ponding in low-lying areas and lakes, or through the beds of surface water courses” (Sophocleous 2004).

4 Discussion

4.1 Influence of new precipitation dataset

In the comparison of the WGHM standard variant with the WGHM WFD variant with the new precipitation dataset, it was found that in the WGHM WFD variant the global arithmetic mean of groundwater recharge is reduced. But taking into account the results from the analysis of the distribution around the 1:1 line, it shows that the modeled results have a tendency towards underestimating groundwater recharge in humid regions and to overestimate it in (semi-)arid region. An explanation of the decrease of groundwater recharge in humid regions is the higher amounts of precipitation, which are expected to occur in humid regions due to the new precipitation data. In the old precipitation dataset the monthly precipitation amount was equally distributed over the days with precipitation events during the month. The more realistic distribution of precipitation amounts resulted in a total runoff which is on more days than before likely to be higher than the texture specific infiltration capacity (R_{gmax}) and therefore more potential groundwater recharge can turn into surface runoff, because the soil has reached the maximum infiltration capacity. When increasing the infiltration capacity in the groundwater recharge algorithm analysis, the modeled groundwater recharge in humid regions can increase.

Also in (semi-)arid region typically higher amounts of precipitation in a single precipitation event occur. But total runoff amounts are still expected to be so low, that the infiltration capacity is usually not exceeded. The increase of groundwater recharge with the new precipitation dataset resulted from precipitation amounts being higher than the critical precipitation amount ($P_{crit;}$ 10 mm/day) in more days than before; and therefore more often the precipitation can be added to the groundwater recharge. By increasing P_{crit} in the groundwater recharge algorithm analysis the number of days reaching total runoff amounts which are higher than P_{crit} are reduced; and with it also the modeled groundwater recharge amounts in (semi-)arid regions. Comparing the arithmetic mean of the modeled results to arithmetic mean of the 51 independent estimates the adjustment led to a better accordance of the arithmetic mean of the results.

This means changing of R_{gmax} and P_{crit} can improve the groundwater recharge results if there is a bias towards one direction, for humid and (semi-)arid regions separately. But if within the humid or (semi-)arid region a bias towards both over- and underestimation occurs, the performance can not be improved by adjusting R_{gmax} and P_{crit}.

4.2 Evaluation of model performance compared to independent estimates

The statistical and coefficient evaluation stated a better performance for the WGHM standard than for the WGHM WFD variant. While the WGHM WFD suffers from overestimation with results below 4 mm/yr, the WGHM standard variant shows over- and underestimation. Comparing the two independent estimates compilations by the arithmetic mean showed that there is a clear discrepancy between the Scanlon estimates and the Edmunds estimates. The mean of the independent estimates based on Scanlon (31.90 mm/yr) have an arithmetic mean about double as high as the mean of Edmunds independent estimates (15.66 mm/yr). This discrepancy is clearly visible in the statistical and coefficient evaluation, but not in the distribution around the 1:1 line. However, it seems that M. Edmunds in his compilation only selected independent estimates that exclusively resulted from direct recharge. This seems to have lead to a very low arithmetic mean of those independent estimates. On the contrary the compilation based on Scanlon et al. (2006) also contains influences of indirect/localized recharge, which is not simulated in the model.

The indirect/localized recharge can explain underestimations for some results (this will be analyzed in Chapter 4.3), but it is not the explanation for all discrepancies between independent estimates and modeled results.

4.3 Possible factors for the improvement of the model performance

Analyzing the influence of the **groundwater recharge factors** derived from the new independent estimates (texture & geohyrology) no indication of significant discrepancies of the WGHM data compared with the independent data from the additional information given. Therefore it can be conclude that, compared to the independent estimates, texture and geohydrology information used in WGHM are of good quality and do not cause wrong results.

The discrepancies of **vegetation/ land cover information** occurring between independent estimates and modeled results, could not be explained by the vegetation/ land cover analysis. No land cover types causing a clear pattern of deviation to the groundwater recharge was found. Taking into account that changes towards cropland land cover can cause a reduction of recharge, next to the influences of the new precipitation dataset, might explain partly the reduction of groundwater recharge from WGHM standard towards WGHM WFD. While for WGHM standard only 18 of the 59 grid cells (compared to the independent estimates) have cropland land cover, 38 grid cells have cropland land cover in the WGHM WFD variant. Wherefrom the conclusion may be drawn that the WGHM WFD vegetation/ land cover dataset shows a land cover change in (semi-)arid regions towards more agricultural use, reducing the groundwater recharge. Not all independent estimates were derived from studies from this decade and therefore some land cover data may not be up to date and would have to be re-checked, if they represent the current vegetation/ land cover situation.

Influence of indirect/ localized recharge on the performance of the modeled results in (semi-)arid regions The WGHM only calculates direct recharge, but "mounting evidence suggests that in arid and semiarid regions recharge likely occurs in only small portions of the basin where flow is concentrated, such as depressions and ephemeral stream channels; elsewhere little recharge occurs [Heilweil and Salomon, 2004; Plummer et al., 2004; Scanlon et al., 1997, 1999 & 2003; Scott et al., 1999; Walvoord, 2002; Walvoord et al., 2002]" (Goodrich et al. 2004: 77). This means "as aridity increases *direct* recharge is likely to become less important than *localized* and *indirect* recharge, in terms of aquifer replenishment" (de Vries & Simmers 2002: 7). The underestimations which occurred for the WGHM standard variant are likely to result from indirect/ localized recharge processes, also indicated by the groundwater recharge measurement method analysis. Also Döll & Fiedler (2008) pointed out that "in semi-arid and arid regions, outside the mountainous headwater regions, neglecting groundwater recharge from surface-water bodies may lead to a significant underestimation of total renewable groundwater resources" (Döll & Fiedler 2008: 863f.).

This study showed that the WGHM modeled results show over- and underestimation in (semi-)arid region especially for the very low values (Fig. 6). It seems that a significant improvement of the modeled results in (semi-)arid regions could be achieved when introducing the groundwater recharge process of indirect/ localized recharge which would increase groundwater recharge of the modeled results, and reduce the underestimation. To reduce over-estimation the (semi-)arid algorithm of the groundwater recharge algorithm can be adjusted by increasing the critical precipitation amount per day (P_{crit}) which will lead to less modeled groundwater recharge.

The reason that indirect recharge was not taken into account in the WGHM model so far is that "groundwater recharge from surface water bodies cannot be estimated at the macro-scale" (Döll & Fiedler 2008: 863). Meso-scale topography data for (semi-)arid regions, displaying depressions and ephemeral stream riverbeds, is needed to analyze where indirect recharge occurs. An algorithm could be generated describing that "the combination of topographic concentration of water, coarse-textured soils and desiccation features at the soil surface allows (…) deep infiltration of limited precipitation" (Tyler et al. 1992: 180), and therefore indirect recharge.

5 Conclusions

The introduction of the new, more realistic, precipitation dataset led, according to the arithmetic mean, to a reduction of global groundwater recharge. This result could be differentiated by the use of spatial distribution maps into a reduction of recharge in humid regions and an increase of recharge in (semi-)arid regions. The comparison to independent estimates approved the overestimation of the WGHM WFD modeled results. Adjustments of the groundwater recharge and (semi-)arid regions algorithm were able to improve the overestimation.

In comparison with a set of new independent estimates based on Scanlon et al. (2006), the WGHM standard and WGHM WFD variants showed underestimations as well as overestimations. The significant discrepancies between the arithmetic mean of the independent estimates based on Scanlon et al. (2006) and Edmunds (Döll & Fiedler 2008), led to the assumption that Edmunds exclusively used independent estimates without any indirect recharge influences. The compilation from this study also used independent estimates with influences of indirect recharge. This was indicated by a significantly higher arithmetic mean of the new independent estimates compilation.

Pointing out possible factors for improvement was extremely difficult; precipitation, soil texture and hydrogeology from the independent estimates seem to be in good accordance to the data from the WGHM. Vegetation/ land cover on the other hand did not bring good accordance. Even though influences on groundwater recharge of the different vegetation/ land cover types were visible, deriving conclusions of influences from the land cover on groundwater recharge was not definitely possible.

The results of the groundwater measurement method analysis, showing underestimation when using Tritium-tracer and Chlorine displacement methods, which can display preferential flow recharge, a form of indirect recharge. Including indirect recharge seems to be a necessary improvement of the WGHM, wherefore a global dataset displaying indirect flow influences in (semi-)arid regions it needed. Further analyses are necessary to gain knowledge about the relation between meso-scale topography, soil texture and groundwater recharge. This may lead to a new algorithm for (semi-)arid regions describing the process of indirect/ localized recharge on a very basic level, using topography data, displaying depressions and ephemeral stream riverbeds.

Appendix

Table A1a. Locations and references of the independent estimates (based on Scanlon et al. 2006).

ID	Latitude [°]	Longitude [°]	Country	Location	Reference
1	46.5000	-119.5000	USA	WS, Hanford site	Fayer 1996
8	36.7647	-116.6925	USA	NV, Beatty Site	Prudic 1994
12	36.7500	-116.1100	USA	NV, Yucca Flat	Tyler et al. 1992
16	34.8333	-114.9833	USA	CA, Ward Valley Site	Prudic 1994
17	40.7600	-111.8900	USA	UT, Wasatch Mountains	Manning & Solomon 2004
18	37.1000	-113.3667	USA	UT, Sandy Hollow Basin	Heilweil et al. 2006
19	36.0000	-110.5833	USA	AZ, Black Mesa Basin	Zhu 2000
20	31.7167	-110.6833	USA	AZ, Walnut Gulch Experimental Watershed	Goodrich et al. 2004
21	35.9000	-106.2800	USA	NM, Pajarito Plateau	Newman et al. 1997
23	35.0000	-106.7500	USA	NM, E of Middle Rio Grande Basin	Anderholm 2001
25	34.2600	-106.9000	USA	NM, Sevilleta National Wildlife Refuge	Phillips et al. 1988
27	32.3100	-106.7500	USA	NM, NM State University Ranche Site	Phillips et al. 1988
33	31.1167	-105.2667	USA	TX, Eagle Flat	Scanlon et al. 1999, 2000
35	32.7100	-102.1400	USA	TX, Southern High Plains	Scanlon et al. 2005
37	34.6400	-101.2800	USA	TX, Southern High Plains	Scanlon et al. 2005
39	35.3333	-102.3667	USA	TX, Southern High Plains	Scanlon & Goldsmith 1997
40	37.0100	-101.8900	USA	KS, Cimarron National Grassland (CNG)	McMahon et al. 2003
42	38.2436	-98.5811	USA	KS, Great Bend Prairie	Sophocleous 1992
44	31.4000	-106.2800	Mexico	Chihuahua, El Parabien	Edmunds 2001
45	21.3000	-101.6167	Mexico	Altiplano	Mahlknecht et al. 2004
46	19.1667	-99.1667	Mexico	Valley of Mexico basin	Birkle et al. 1998
48	33.5600	8.8000	Tunisia	Tozeur	Edmunds 2001
50	15.7000	-16.3167	Senegal	NW Senegal, Louga	Edmunds & Gaye 1994
53	13.5000	2.5000	Niger	SW Niger	Leduc et al. 2001
54	13.2622	2.0586	Niger	S Niger	Bromley et al. 1997
56	15.9167	33.8333	Sudan	Abu Delaig, E of Khartoum	Edmunds et al. 1988
57	-22.2500	23.7500	Botswana	Central Kalahari	Selaolo et al. 1996
58	-24.0000	25.1167	Botswana	SE Botswana, Letlhakeng–Botlhapatlou	de Vries et al. 2000
59	-24.1900	25.1550	Botswana	SE Botswana, Molepolole and Letlhakeng	Gieske et al. 1995
60	-25.1200	25.4000	Botswana	SE Botswana, Nnywane-Pitsanyane	Selaolo et al. 1996
61	-27.9454	21.6943	South Africa	NW South Africa	Butler & Verhagen 2001
62	-32.6833	26.0833	South Africa	Great Fish River Basin	Sami & Hughes 1996
63	35.0000	33.0000	Cyprus	Akrotiri peninsula	Edmunds et al. 1988
64	31.0000	34.7500	Israel	Negev, Ramat Hovava	Nativ et al. 1995
65	32.2806	35.8953	Jordan	Jarash	Edmunds 2001
68	19.0000	42.0000	Saudi Arabia	W Saudi Arabia, Hijaz mountain area	Bazuhair & Wood 1996
69	24.6500	46.7333	Saudi Arabia	Dahna sand dunes, E of Riyadh	Dincer et al. 1974
71	25.3333	71.0833	India	N India, western Rajasthan	Navada et al. 2001
72	22.8000	72.3000	India	NW India, Gujarat	Sukhija et al. 2003
73.1	30.5000	74.5000	India	N India, Punjab (1)	Rangarajan & Athavale 2000
73.2	28.8000	75.8000	India	N India, Haryana (2)	Rangarajan & Athavale 2000
73.3	27.5000	73.5000	India	N India, Churu district, Rajasthan (4)	Rangarajan & Athavale 2000
73.5	19.5000	76.1000	India	C India, Godavari-Purna basin (16)	Rangarajan & Athavale 2000
73.6	18.6000	75.2000	India	C India, Kukadi basin, Maharashtra (17)	Rangarajan & Athavale 2000
73.7	16.2000	78.0000	India	S India, Aurepalle watershed (24)	Rangarajan & Athavale 2000
73.8	16.3000	78.4000	India	S India, Gaetec watershed (25)	Rangarajan & Athavale 2000
74	16.6000	78.5000	India	C India, Maheshwaram near Hyderabad	Sukhija et al. 2003
75	11.0000	79.5500	India	S India, Pondicherry	Sukhija et al. 2003
76	37.4500	104.9500	China	W China, Tengger desert	Wang et al. 2004
77	37.6833	113.6833	China	Shanxi prov., Yangquan City	Ruifen & Keqin 2001
81	42.8667	118.9333	China	Inner mongolia, Wudan county	Ruifen & Keqin 2001
82	-32.8333	117.1833	Australia	W Australia, Cuballing Catchment	Salama et al. 1993
83	-21.0646	132.9816	Australia	Ti-Tree Basin, Northern Territory	Harrington et al. 2002
84	-27.5000	135.0000	Australia	C Australia, SW to Great Artesian Basin	Love et al. 2000
85	-34.1667	139.6667	Australia	SE Australia, Murbko, NE Adelaide	Allison et al. 1985
87	-34.1809	140.0828	Australia	S Australia Western Murray Basin	Leaney & Allison 1986
93	-35.0333	140.0500	Australia	S Australia, Borrika site	Cook & Kilty 1992
96	-35.1167	142.0000	Australia	S Australia, Walpeup site	Allison & Hughes 1983
97	-36.5800	140.4500	Australia	S Australia, Naracoorte Ranges	Leaney & Herczeg 1995

N north, S south, E east, W west, C central
WS Washington State, NV Nevada, UT Utah, AZ Arizona, NM New Mexico, TX Texas, KS Kansas

Table A1b. Locations and references of the independent estimates from M. Edmunds.

ID	Latitude [°]	Longitude [°]	Country	Location	Reference
1	27.7500	-110.7500	Mexico	Sonora	
2	31.2500	-106.7500	Mexico	Mesilla Bolson	
3	14.2500	-14.2500	Senegal	Kaolack	
4	15.7500	-13.2500	Senegal	Louga	Edmunds & Gaye 1994
5	13.2500	2.2500	Niger	Say Plateau	Bromley et al. 1997
6	33.7500	7.7500	Tunisia	Tozeur	
7	13.2500	10.7500	Nigeria	Gashua	
8	12.2500	12.2500	Nigeria	Maiduguri	
9	-23.2500	21.2500	Botswana	Matsheng	Beekman et al. 1997
10	-22.7500	23.7500	Botswana	Central Kalahari	Beekman et al. 1997
11	-24.2500	24.7500	Botswana	Letlhakeng	
12	-22.7500	26.7500	Botswana	Serowe	
13	34.7500	32.7500	Cyprus	Akrotiri	Edmunds et al. 1988
14	31.2500	33.7500	Egypt	Northern Sinai	Hussein 2001
15	29.7500	35.2500	Jordan	Quwayra	
16	32.2500	35.7500	Jordan	Jarash	
17	32.2500	37.2500	Jordan	Azraq	
18	33.2500	36.2500	Syria	Damascus	
19	26.7500	44.2500	Saudi Arabia	Qasim	Sagaby & Moallin 2001
20	25.2500	70.7500	India	W Rajasthan	
21	37.7500	113.7500	China	Shanxi	
22	42.7500	118.7500	China	Inner Mongolia	
23	-34.2500	139.7500	Australia	Murbko	Cook et al. 1994
24	-35.2500	140.2500	Australia	Boorika	Cook et al. 1994
25	-36.7500	140.7500	Australia	Narracoorte	Cook et al. 1994

Table A2a. Independent estimates groundwater recharge and precipitation compared to WGHM results.

Groundwater Recharge						Precipitation			Area
ID	**WGHM stand.**	**WGHM WFD**	**In-dep.**	**method**	**Recharge information**	**GPCC**	**ind.**	**diff.**	
		[mm/yr]				**[mm/yr]**		**[%]**	**[km²]**
1	0.08	0.90	11.00	GIS	average regional, estimated using GIS and point recharge estimates	172	160	7	765
8	0.00	1.36	0.00	CMB$_{UZ}$	-	106	100	5	-
12	0.12	1.95	0.00	^{3}H	no significant recharge is occurring	130	125	4	-
16	2.60	1.36	0.03	CMB$_{UZ}$	-	123	150	-22	-
17	94.23	94.8	136.50	^{3}H/He$_{SZ}$	average volumetric RC of 176,000 m³/day	519	900	-73	300
18	8.14	17.16	9.00	^{3}H	Arithmetic mean of 11 boreholes	334	210	37	50
19	0.70[b]	2.96[b]	16.00	CMB$_{SZ}$	average of 8 snow samples	219	305	-39	14000
20	2.62	4.51	3.00	MG, CMB$_{UZ/SZ}$	Arithmetic mean of 3 methods	442	324	27	112
21	5.93	5.36	3.50	CMB$_{UZ}$	Arithmetic mean of 28 boreholes	368	490	-33	0.02[a]
23	1.17	2.92	8.70	CMB$_{SZ}$	average recharge rate	299	456	-53	1570
25	2.47	1.92	5.20	CMB$_{UZ}$,^{36}Cl,^{3}H	Arithmetic mean of the average of 3 methods	259	200	23	~2[a]
27	6.29	3.95	5.50	CMB$_{UZ}$,^{36}Cl,^{3}H	Arithmetic mean of the average of 3 methods	241	230	4	0
33	10.01	5.87	6.70	CMB$_{UZ}$	Arithmetic mean	281	320	-14	60
35	16.6	8.44	19.50	CMB$_{UZ}$, WTF	mean recharge rate of 4 boreholes	446	457	-3	3400
37	24.03	3.13	0.00	CMB$_{UZ}$	RC negligible in (semi-)arid rangeland	529	479	10	-
39	9.70	1.86	25.00	CMB$_{UZ}$	aerially uniform recharge	455	500	-10	~5000[a]
40	7.14	2.64	4.90	CMB$_{UZ}$, ^{3}H	Arithmetic mean of the averages of 3 methods	417	453	-9	~3[a]
42	55.59[b]	36.28[b]	36.00	WTF, GIS	area-weighted average recharge	626	562	10	10260
44	3.52	6.16	0.10	CMB$_{UZ}$	average of one borehole	260	230	12	350.0[a]
45	12.93[b]	15.00[b]	25.00	CMB$_{SZ}$	average of from 246 wells	607	600	1	6840
46	87.19[b]	52.95[b]	122.50	WB	Arithmetic mean	910	746	18	9600
48	2.20	18.36	1.30	CMB$_{UZ}$	average of one profile	130	100	23	-
50	10.70	8.53	8.55	CMB$_{UZ/SZ}$	arithmetic mean of mean of 12 profiles and mean of 119 dug wells	325	290	11	1600
53	42.42[b]	10.94[b]	20.00	WTF	average recharge rate	446	565	-27	8000
54	41.12	16.71	13.00	CMB$_{UZ}$	average recharge rate	548	564	-3	-
56	2.00	2.45	0.72	CMB$_{UZ}$	regional long-term average	153	200	-31	6
57	16.06	9.56	3.80	^{3}H	mean of 2 profiles	353	400	-13	0
58	20.28[b]	12.36[b]	3.00	CMB$_{UZ}$	average of ~50 profiles	464	~420	9	4875
59	20.70	12.60	15.50	CMB$_{UZ}$, ^{3}H	Arithmetic mean of both methods	460	420	9	2500[a]
60	6.45	5.06	13.50	CMB$_{UZ}$, ^{3}H	Arithmetic mean of both methods	508	500	2	0.04
61	2.52	2.87	7.40	CMB$_{UZ}$, ^{3}H	Arithmetic mean of both methods	262	336	-28	1[a]
62	10.95	3.15	4.50	CMB$_{SZ}$	area weighted mean of 12 profiles	505	472	7	665
63	36.11	62.68	55.00	CMB$_{UZ}$, ^{3}H	mean of mean of both methods on 12 profiles	699	406	42	6
64	60.49	49.48	50.34	^{3}H, Br	mean of mean of both methods on 7 profiles	290	200	31	~25[a]
65	35.42	52.41	36.00	CMB$_{SZ}$	average recharge rate	365	480	-32	-
68	0.80[b]	2.14[b]	3.70	CMB$_{SZ}$	regional mean recharge rate of 1422 profiles	197	160	19	135000
69	1.08[b]	3.29[b]	20.00	^{3}H	average recharge rate	120	70	42	25000
71	12.39	13.15	13.53	CMB$_{UZ}$	mean of four profiles	276	240	13	~1600[a]
72	47.32	22.81	39.50	^{3}H	average recharge rate	636	~740	-16	-
73.1	19.22	6.47	56.00	^{3}H	average recharge rate	400	460	-15	-
73.2	29.62	14.77	70.00	^{3}H	average recharge rate	389	470	-21	-
73.3	12.34	14.25	62.00	^{3}H	average recharge rate	272	491	-81	-
73.5	35.75	21.15	56.00	^{3}H	average recharge rate	805	652	19	-
73.6	42.71	18.07	46.00	^{3}H	average recharge rate	660	612	7	-
73.7	31.63	10.94	105.00	^{3}H	average recharge rate	685	750	-10	-
73.8	35.26	16.69	46.00	^{3}H	average recharge rate	713	445	38	-
74	50.76	25.84	120.00	CMB$_{SZ}$	average recharge rate	748	~725	3	-
75	75.78[b]	63.86[b]	350.00	CMB$_{SZ}$	average recharge rate	996	~1004	-1	~10000[a]
76	2.72	1.24	48.00	WB (lys.)	average recharge rate	204	191	6	-
77	33.30	21.27	68.00	^{3}H	average recharge rate	526	550	-5	0
81	8.76	4.26	47.00	^{3}H	average recharge rate	357	360	-1	0
82	0.24	21.74	10.00	Cl disp.	average recharge rate	447	409	9	2.3[a]
83	19.61[b]	16.03[b]	0.80	CMB$_{SZ}$	average recharge rate	385	290	25	5500
84	4.11[b]	2.65[b]	0.16	CMB$_{SZ}$	mean recharge of 21 profiles	191	200	-5	47000
85	0.63	3.12	13.50	Cl disp.	Arithmetic mean	278	300	-8	~16[a]
87	1.76[b]	2.77[b]	0.18	CMB$_{SZ}$, ^{14}C	Arithmetic mean of both methods of 163 profiles	257	275	-7	10000
93	0.73	9.57	9.50	EMI	Arithmetic mean of regional mean	362	340	6	32
96	0.46	3.69	3.50	Cl disp.	Arithmetic mean	325	335	-3	~0.09[a]
97	0.23	44.24	23.00	CMB$_{UZ}$	Arithmetic mean	563	545	3	1750

^{14}C Carbon 14 tracer, ^{36}Cl Chlorine-36 tracer, ^{3}H Tritium tracer, ^{3}H/He tritium-helium dating, Br Bromide tracer, Cl disp. Chlorine tracer displacement, CMB$_{SZ}$ Chloride Balance Method saturated zone, CMB$_{UZ}$ Chloride Balance Method unsaturated zone, EMI Electromagnetic induction survey, GIS Geographic Information systems, lys. Lysimeter, MG micro-gravity, WB water balance, WC water content monitoring, WTF Water table fluctuations

[a] area was derived from a map

[b] arithmetic mean of more than one grid cell

Table A2b. Independent estimates groundwater recharge and precipitation compared to WGHM results.

		Groundwater recharge				Precipitation			
ID	**WGHM stand.**	**WGHM WFD**	**indep.**	**method**	**Recharge information**	**Ind.**	**GPCC**	**diff.**	**Area**
		[mm/yr]				[mm/yr]		[%]	[km²]
1	10.84	3.02	0.14		-	320	370	13	
2	4.82	7.86	0.24	-	-	230	196	-17	-
3	71.03	27.94	17.10	-	-	545	681	-20	-
4	46.21	5.11	13.00	-	-	290	351	-17	-
5	41.12	16.71	13.00	-	-	564	572	1	-
6	3.20	5.34	0.70	-	-	100	138	28	-
7	25.15	5.23	36.00	-	-	380	380	0	-
8	62.31	41.59	22.00	-	-	390	504	23	-
9	14.45	11.30	1.00	-	-	350	352	0	-
10	11.33	9.73	1.00	-	-	350	353	1	-
11	23.41	14.23	7.00	-	-	420	418	-1	-
12	6.69	6.29	10.00	-	-	440	428	-3	-
13	31.56	67.03	57.00	-	-	406	500	19	-
14	43.55	9.08	21.00	-	-	300	333	10	-
15	0.30	0.92	0.03	-	-	65	61	-7	-
16	35.42	52.41	28.00	-	-	480	435	-10	-
17	1.37	3.46	1.00	-	-	67	75	11	-
18	23.46	35.57	1.50	-	average of 5 profiles	220	361	39	-
19	2.79	4.24	1.80	-	-	100	61	-65	-
20	9.90	11.24	17.00	-	-	240	269	11	-
21	33.3	21.27	68.00	-	-	550	533	-3	-
22	8.76	4.26	47.00	-	-	360	395	9	-
23	0.63	3.12	0.10	-	-	260	269	3	-
24	0.73	9.57	22.00	-	-	340	374	9	-
25	0.18	33.03	6.00	-	-	575	550	-4	-

Table A3a. Additional information about independent estimates compared to WGHM results.

ID	Texture		Hydrogeology	Vegetation/ Landuse		
	WGHM	ind.	WGHM	Independent	WGHM standard	WGHM WFD
1	17	17	50	open shrubland	open shrubland	mixed cropland/ pasture
8	18	-	70	open shrubland	open shrubland	hot desert
12	17	12	70	-	open shrubland	hot desert
16	17	-	50[c]	open shrubland	open shrubland	hot desert
17	20	-	70	-	deceduous broadleaf forest	mainly cropland
18	20	20	100	open shrubland	open shrubland	grassland
19	20[b]	-	100	open shrubland	open shrubland	grassland
20	20	20	50[c]	open shrubland	grassland	scrubland
21	19	19	50	closed shrubland	open shrubland	grassland
23	20	-	100	-	open shrubland	grassland
25	20	20	100	open shrubland	open shrubland	grassland
27	19	19	100	open shrubland	open shrubland	hot desert
33	20	-	100	open shrubland	open shrubland	grassland
35	15	20	100	cropland	grassland	mixed cropland/ pasture
37	20	25	100	crassland	grassland	mainly cropland
39	20	20	100	cropland/ natural veg mosaik	grassland	mainly cropland
40	20	20	100	grassland	grassland	mainly cropland
42	20[b]	19	100	barren or sparsely vegetated	cropland/ natural veg mosaik	mainly cropland
44	15	15	100	open shrubland	open shrubland	mixed cropland/ pasture
45	21[b]	21	50	-	woody savanna	Scrubland
46	20[b]	-	50	cropland/ natural veg mosaik	mixed forest	mainly cropland
48	24	24	100	barren or sparsely vegetated	barren or sparsely vegetated	mixed cropland/ pasture
50	13	13	100	open shrubland	open shrubland	grassland
53	12[b]	-	100	cropland/ natural veg mosaik	grassland	mixed cropland/ pasture
54	12	15	100	open shrubland	grassland	mixed cropland/ pasture
56	24	21	100	barren or sparsely vegetated	open shrubland	mixed cropland/ pasture
57	16	16	100	grassland	grassland	mixed cropland/ pasture
58	15[b]	15	100	grassland	grassland	mixed cropland/ pasture
59	15	15	100	open shrubland	grassland	mixed cropland/ pasture
60	19	-	50	-	grassland	mixed cropland/ pasture
61	16	16	100	savanna	cropland/ natural veg mosaik	mixed cropland/ pasture
62	19	20	70	grassland	grassland	mainly cropland
63	23	15	50	closed shrubland	cropland/ natural veg mosaik	scrubland
64	23	20	100	barren or sparsely vegetated	open shrubland	hot desert
65	22	-	100	-	cropland/ natural veg mosaik	mainly cropland
68	18[b]	-	70[c]	-	barren or sparsely vegetated	mixed cropland/ pasture
69	18[b]	18	100[c]	-	barren or sparsely vegetated	mixed cropland/ pasture
71	13	13	100	cropland/ natural veg mosaik	open shrubland	hot desert
72	20	-	100	-	cropland	scrubland
73.1	24	10	100	-	cropland	mainly cropland
73.2	15	12	100	-	cropland	grassland
73.3	13	16	100	-	open shrubland	hot desert
73.5	28	24	50	-	cropland	mainly cropland
73.6	27	27	50	-	open shrubland	scrubland
73.7	28	28	50	-	cropland	mainly cropland
73.8	25	25	50	-	cropland	mainly cropland
74	23	-	50	-	cropland	mainly cropland
75	19[b]	-	100	-	cropland	mainly cropland
76	20	18	70	barren or sparsely vegetated	open shrubland	grassland
77	23	23	70	-	cropland	mixed cropland/ pasture
81	20	23	50	barren or sparsely vegetated	cropland/ natural veg mosaik	mainly cropland
82	18	-	50	cropland	cropland	mixed cropland/ pasture
83	15[b]	15	50	cropland/ natural veg mosaik	open shrubland	mixed cropland/ pasture
84	18[b]	15	100	-	open shrubland	mixed cropland/ pasture
85	19	15	100	barren or sparsely vegetated	savanna	mixed cropland/ pasture
87	15[b]	15	100	-	savanna	mixed cropland/ pasture
93	16	18	100	cropland	cropland	mixed cropland/ pasture
96	15	18	100	cropland	cropland	mixed cropland/ pasture
97	14	19	100	cropland	cropland	mainly cropland

[b] arithmetic mean of more than one grid cell

[c] hydrogeology of independent estimate differs

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Eigenständigkeitserklärung

Hiermit erkläre ich eidesstattlich gem. § 20 Abs. 12 PO, dass ich diese Bachelorarbeit zum Thema „Global groundwater recharge: Evaluation of modeled results on the basis of independent estimates“ selbstständig verfasst habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel verwendet und alle wörtlich oder sinngemäß aus anderen Werken übernommenen Aussagen als solche gekennzeichnet. Diese Arbeit war weder vollständig noch auszugsweise Gegenstand einer anderen Studienleistung oder eines anderen Prüfungsverfahrens.

Datum Unterschrift