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# Global Modeling of Groundwater Recharge

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**Abstract.** Global-scale assessments of freshwater availability can be improved by estimates of groundwater recharge. With the global water quantity model WaterGAP 2, groundwater recharge is simulated with a spatial resolution of 0.5°. The model is calibrated against measured discharge in 724 drainage basins which cover about 50% of the Earth's land surface. Recharge is computed by partitioning total runoff based on information about relief, soil, hydrogeology and permafrost/glacier. The global 1961-90 long-term average groundwater recharge is estimated to be almost 14,000 km$^3$/yr (36% to the total runoff). The quality of the modeling results is difficult to judge because independent estimates of groundwater recharge are highly uncertain.

## 1 INTRODUCTION

Freshwater availability has been recognized as a global issue, and its consistent quantification not only in individual river basins but also at the global scale is required to support the sustainable use of water. Water availability cannot only be estimated based on river discharge (even though river discharge is often taken as an approximate measure of the total available water resources) because groundwater is an important source of water. If the water availability in two river basins with the same total annual runoff is compared, the water availability in the basin with the higher fraction of groundwater recharge is very probably better. One reason is the natural interseasonal storage that is provided by aquifers, which for surface water would need to be created artificially, and costly, by reservoirs. Besides, groundwater is better protected from evapotranspiration (and contamination) than water in surface reservoirs. Thus, it is important to estimate not only total runoff and river discharge in a drainage basin but also groundwater recharge.

The global model of water availability and water use WaterGAP was developed to assess the current water resources situation and to estimate the impact of global change on the problem of water scarcity. With a spatial resolution of 0.5°, the raster-based model is designed to simulate the characteristic macro-scale behavior of the terrestrial water cycle, including the human impact, and to take advantage of all pertinent information that is globally available. To the authors' knowledge, WaterGAP is the only global model that simulates both water availability – as surface runoff, groundwater recharge and river discharge – and water use in drainage basins (and not only in countries). WaterGAP consists of two main parts, the Global Hydrology Model and the Global Water Use Model. The Global Water Use Model itself is composed of four submodels, one for each of the water use sectors households, industry, irrigation and livestock. The Global Hydrology Model of WaterGAP 2 (WGHM) is calibrated against discharge measured at 724 gauging stations, the drainage areas of which cover about 50% of the global land area excluding Greenland and Antarctica, taking into account the reduction of natural discharge by consumptive water use. A concise description of the most recent version of WaterGAP 2 is provided by Döll et al. (2001).

The partitioning of total runoff into fast surface and subsurface runoff and groundwater recharge, which is modeled in WGHM for each of the 67000 grid cells world-wide, is relevant for calculating river hydrographs and for deriving improved water availability indicators. A difficulty of modeling groundwater recharge with a macro-scale model is that different from river discharge, no direct measurement data are available for comparison at the appropriate scale. River discharge integrates over the whole drainage basins, while groundwater recharge estimates are generally local. Unfortunately, for almost no country or river basin there are reliable estimates of groundwater recharge, and in the most recent compilation of country values of groundwater recharge (WRI, 2000), many values stem from Margat (1990) which again compiled results of the global-scale baseflow analysis of L'vovich (1979). Baseflow analysis of river hydrographs, i.e. the analysis of streamflow recession, is generally considered to provide an integral estimate of groundwater recharge, but results are very dependent on the applied analysis method (Bullock et al., 1997, Tallaksen, 1993). Besides, groundwater recharge is likely to be larger than the baseflow observed at a downstream location, in particular in arid and semiarid regions, where groundwater recharge might evapotranspirate at some location upstream of the gauging station (Margat, 1990). Finally, baseflow analysis is not possible at river gauging stations downstream of large reservoirs, lakes or wetlands upstream (L'vovich, 1979). In the following sections, we present the methodology of estimating groundwater recharge at the global scale that is used in WGHM, show the resulting global groundwater recharge map and compare the computed values with independent estimates.

## 2 METHODOLOGY

### 2.1 Overview

Based on a gridded data set of monthly climate variables between 1901 and 1996 (New et al., 2000), WGHM computes the daily vertical water balance of each 0.5° grid cell and the lateral transport of water between grid cells. Land cover and soil characteristics are taken into account as well as the influence of lakes, reservoirs and wetlands. From the vertical water balance of the land fraction of each cell, the total runoff from land is computed, which is then partitioned into fast surface and subsurface runoff and slow groundwater runoff (or base flow) using information on the cell-specific slope characteristics, soil texture, hydrogeology and the occurrence of permafrost and glaciers. Outflow from the groundwater (base flow) is simulated as being proportional to groundwater storage, and it is then transported together with the fast runoff component through the surface water units in each cell before it is routed to the downstream cell. Thus, it is assumed that all groundwater recharge returns to the river at the outlet of the cell. This simplifying assumption must be made because of the lack of knowledge on groundwater flow directions (or levels) at the global scale.

The hydrological model is calibrated against time series of annual discharge measured at 724 stations (data from GRDC, Koblenz) such that the long-term average modeled discharge is within 1% of the observed value (Döll et al., 2001). This is achieved by adjusting a parameter in the vertical water , the runoff coefficient, in the respective upstream areas (however, for many basins, one or two additional correction factors had to be introduced to achieve a 1% correspondence to measured discharge, e.g. in snow-dominated areas where actual precipitation is known to be underestimated by measurements). The runoff coefficient is regionalized to the remaining uncalibrated drainage basins by multiple regression to independent characteristics of the calibration basins. Döll et al. (2002) discuss the capability of WGHM to compute water availability indicators by comparing simulated and observed discharge at the calibration and other stations with respect to long-term average discharges, interannual variabilities and monthly $Q_{90}$ values.

### 2.2 Groundwater Recharge Modeling

In order to estimate groundwater recharge with WaterGAP 2, the total runoff from the land area of each cell is partitioned into fast (surface and sub-surface) runoff and groundwater recharge. This is done following a heuristic approach which is based on qualitative knowledge about the influence of certain characteristics (for which global data sets are available) on the partitioning of total runoff: slope characteristics (G. Fischer, IIASA, personal communication, 1999), soil texture (FAO, 1995), hydrogeology (Canadian Geological Survey, 1995) and the occurrence of permafrost and glaciers (Brown et al., 1998; Hoelzle and Haeberli, 1999). Land cover characteristics are not included; in their study on base flow indices in the Elbe river basin, Haberlandt et al. (2001) found that the proportion of forest and arable land in subbasins of or below the size of 0.5° grid cells only had a weak influence on the groundwater recharge index GWI (groundwater recharge as a ratio of total runoff). Groundwater recharge $R_g$ is computed as

$$R_g = \min(R_{g\max}, f_g R_l) \quad \text{with} \quad f_g = f_s f_t f_a f_{pg} \tag{1}$$

$R_{gmax}$ = soil texture specific maximum groundwater recharge [mm/d]
$R_l$ = total runoff of land area [mm/d]
$f_g$ = groundwater recharge factor ($0 \leq f_g < 1$)
$f_s$ = slope-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 ($0 \leq f_g \leq 1$)

The cell-specific value of all four factors and the maximum groundwater recharge rate are defined by 1) assigning values to property classes of the global data sets (compare as an example the table of the slope-related factor) and 2) upscaling to 0.5° x 0.5°. The assignment of values was done in an iterative manner by using expert guesses and checking the results, i.e. the resulting groundwater recharge rates against independent estimates (see discussion in section 4).

The slope-related groundwater recharge factor $f_s$ does not represent the average slope between two cells but the relief within the cell. The more mountainous the terrain, the lower is the fraction of total runoff that recharges the groundwater. Based on the GTOPO30 DEM with a resolution of 0.5 min (USGS EROS data center), a map of slope classes with a resolution of 5 min was provided by G. Fischer which includes the fraction of each 5 min cell that is covered by a certain slope class. Seven slope classes are distinguished; the values of $f_s$ assigned to each slope class are given in Table 1. The factor $f_s$ of each 0.5° cell was calculated by areal weighing of the sub-grid scale slope classes.

Table 1. Sub-grid scale slope classes and the slope-related groundwater recharge factor.

| slope class[%] | $f_s$ |
|---|---|
| 0-2 | 1.00 |
| 2-5 | 0.95 |
| 5-8 | 0.90 |
| 8-16 | 0.75 |
| 16-30 | 0.60 |
| 30-45 | 0.30 |
| > 45 | 0.15 |

FAO (1995) provides information on the average soil texture of the uppermost 30 cm of the soil in each 5 min grid cell as well as on the occurrence of bare rock. The coarser the soil, the higher the groundwater recharge fraction, i.e. the texture-related factor $f_t$ and the maximum daily groundwater recharge $R_{gmax}$. In the fraction of each 0.5° cell that is covered by bare rock, groundwater recharge is assumed to be zero. With respect to the influence of the hydrogeology on groundwater recharge, the more permeable the subsurface, the higher is the fraction of the total runoff that can recharge the groundwater. However, there is no global hydrogeological map but only a digital geological map (Canadian Geological Survey, 1995). A comparison of the rock type and age layers of the geological map with hydrogeological maps of Europe and Africa suggested to classify the geological map into three classes only: 1) Cenozoic and Mesozoic sediments with high hydraulic conductivity, 2) Paleozoic and Precambrian sediments with low hydraulic conductivity, 3) non-sedimentary rocks with very low hydraulic conductivity. Besides, the permeability of the subsurface is assumed to be higher in warm and humid climates due to weathering. Where there are permafrost and glaciers, we assume that there is no groundwater recharge. Therefore, the factor $f_{pg}$ is equal to the areal fraction of permafrost and glaciers in the cell.

## 3 RESULTS AND DISCUSSION

Figure 1 presents a global map of the 1961-1990 long-term average groundwater recharge computed by WaterGAP 2. Obviously, the spatial distribution of groundwater recharge is similar to the distribution of precipitation and runoff, with the highest values in the tropics. Figure 2 shows a GWI map, i.e. groundwater recharge as a fraction of total runoff from land. Very low GWI-values occur in the permafrost areas, mountainous regions like the Alps or Western Norway and in the monsoon regions of Asia where most of the annual precipitation falls within a short period of time and therefore cannot infiltrate. Very high GWI-values are simulated for flat areas with permeable soils and aquifers like the plains in the northern part of Central Europe.

1961-1990 global groundwater recharge is computed to be 13,826 km$^3$/yr, which amounts to 36% of the total discharge into the oceans (Döll et al., 2002). This value is 20% larger than the value estimated by L'vovich (1979) by a global-scale baseflow analysis for almost 1500 rivers (800 of them in the former Soviet Union), which certainly is still the best continental or global scale analysis that exists up to today. However, no discharge data had been available for 80% of South America, 20% of Africa (not counting the Sahara and the Kalahari), 60% of Australia (not counting the desert), and some parts of Asia and Canada. Figure 3 shows a comparison of the modeled total groundwater recharge of countries with values compiled in WRI (2000). The problem with these independent estimates of groundwater recharge is that they must be considered to be highly unreliable. Here again we observe a certain overestimation by WGHM, except for countries with a high per unit area groundwater recharge like New Zealand (Figure 3, right). In particular, the country values of large countries like Brazil, Russia and the USA are overestimated. However, the average of the per unit area groundwater recharge values of the countries listed in WRI (2000), 143 mm/yr, is very close to the modeled value of 137 mm/yr. Independent estimates of groundwater recharge in Germany range from 125 mm/yr to 300 mm/yr (WRI, 2000; Neumann and Wycisk, 2002), with the currently best estimate of 161 mm/yr, as compared to 201 mm/yr from WGHM.

Besides, comparisons with the results of regional-scale groundwater recharge studies (Haberlandt et al., 2001, for the German Elbe river basin; Bullock et al., 1997, for Southern Africa) show a good agreement of the spatial patterns of GWI. Only in the case of the rather dry parts of Southern Africa, the base flow analysis of Bullock et al. results in much lower values than WGHM, which could be tentatively interpreted as being due to the evaporation of baseflow in ponds upstream of the gauging station. It is interesting to note that in the case of the Elbe basin, there is a strong negative correlation between the GWI-Index and precipitation (where more rain falls in the mountainous areas), while the opposite is true in the Southern Africa (where more rain falls in the norhern flat parts). This shows that precipitation, unlike relief, is not a good predictor of GWI.

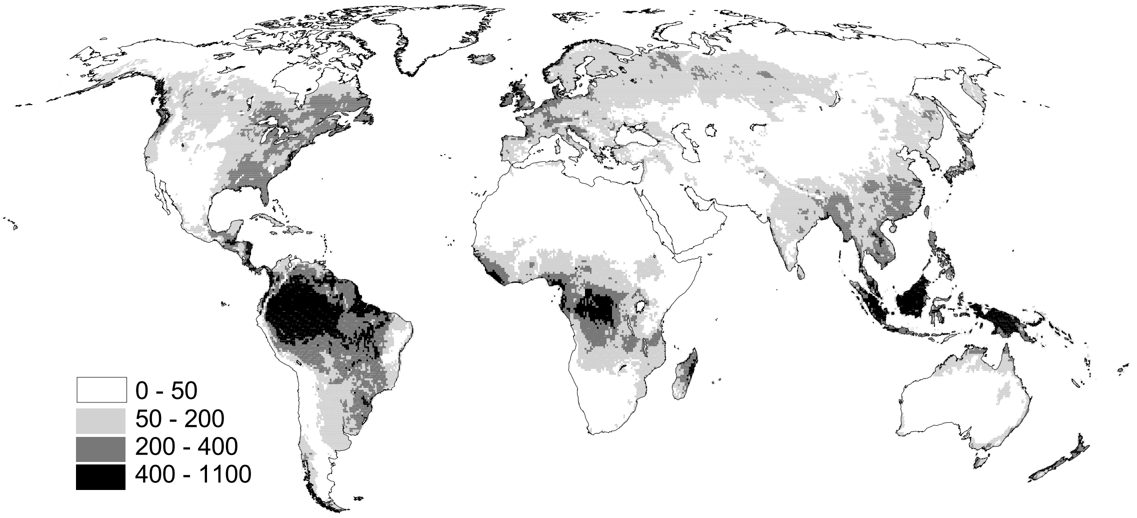

Figure 1. Long-term average groundwater recharge, in mm/yr (climate normal 1961-90).

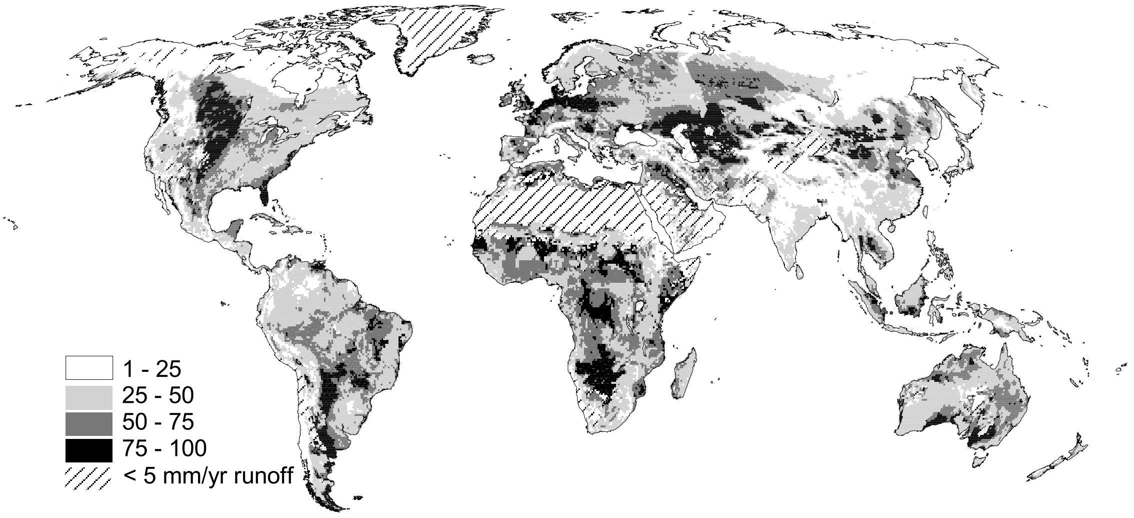

Figure 2. Long-term average groundwater recharge in percent of total runoff from land (climate normal 1961-90).

## 4 CONCLUSIONS

A first model-based estimate of global groundwater recharge at a resolution of 0.5° has been obtained based on information on climate, land cover, soil, slope, hydrogeology, permafrost/glacier as well as river discharge. The modeled groundwater recharge can be used to obtain water availability indicators that are more meaningful than those based on river discharges only. A comparison to independent data indicates that groundwater recharge might be somewhat overestimated by WGHM, but the uncertainty of the independent data is very high. In the future, a more detailed comparison of observed and modeled base flows as well as further analysis of basin-scale groundwater recharge studies will help to improve the groundwater recharge algorithm in WGHM. To achieve an estimate of actual groundwater availability, analysis of the exploitable fraction are required.

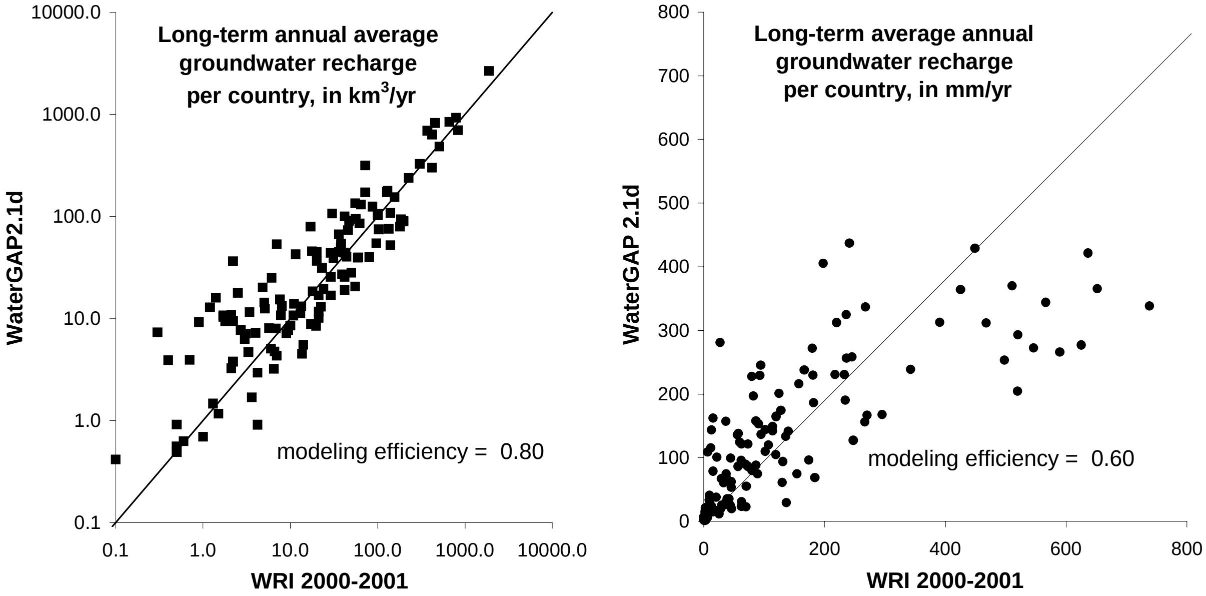

Figure 3. Comparison of simulated country values of long-term average groundwater recharge with independent estimates compiled by WRI (2000) (Left: in $km^3$/yr; right: in mm/yr)

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