Global depletion of groundwater resources

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[1] In regions with frequent water stress and large aquifer systems groundwater is often used as an additional water source. If groundwater abstraction exceeds the natural groundwater recharge for extensive areas and long times, overexploitation or persistent groundwater depletion occurs. Here we provide a global overview of groundwater depletion (here defined as abstraction in excess of recharge) by assessing groundwater recharge with a global hydrological model and subtracting estimates of groundwater abstraction. Restricting our analysis to sub-humid to arid areas we estimate the total global groundwater depletion to have increased from 126 (±32) km^3 a^{-1} in 1960 to 283 (±40) km^3 a^{-1} in 2000. The latter equals 39 (±10)% of the global yearly groundwater abstraction, 2 (±0.6)% of the global yearly groundwater recharge, 0.8 (±0.1)% of the global yearly continental runoff and 0.4 (±0.06)% of the global yearly evaporation, contributing a considerable amount of 0.8 (±0.1) mm a^{-1} to current sea-level rise. **Citation:** Wada, Y., L. P. H. van Beek, C. M. van Kempen, J. W. T. M. Reckman, S. Vasak, and M. F. P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.*, *37*, L20402, doi:10.1029/2010GL044571.

1. Introduction

[2] Increasing population numbers, expanding areas of irrigated agriculture and economic development are drivers for an ever-increasing demand for water worldwide. Although globally such demand can be met by surface water availability (i.e., water in lakes, rivers and reservoirs), regional variations are large, leading to water stress in several parts of the world. Examples of regions experiencing recurrent water stress are the Sahel, South Africa, the Central U.S., Australia, India, Pakistan, and North-East China [*Hanasaki et al.*, 2008]. It is estimated that over 2 billion people (35% of the world population) suffer from severe water stress [*Alcamo et al.*, 2000].

[3] In regions with frequent water stress and large aquifer systems groundwater is often used as an additional water source. If groundwater abstraction exceeds groundwater recharge for extensive areas and long time, overexploitation or persistent groundwater depletion can occur [*Gleeson et al.*, 2010]. The resulting lowering of groundwater levels can have devastating effects on natural streamflow, groundwater fed wetlands and related ecosystems. Also, in deltaic areas, groundwater depletion may lead to land subsidence and salt water intrusion.

[4] Here we provide a global overview of groundwater depletion by assessing groundwater recharge with a global hydrological model and subtracting estimates of groundwater abstraction. Hence, in this study we define groundwater depletion as the rate of groundwater abstraction in excess of natural recharge rate. To limit problems related to increased capture of discharge (i.e., the water budget myth as explained by *Bredehoeft* [2002]) and increased recharge due to groundwater pumping, we restrict our analysis to sub-humid to arid areas (see auxiliary material for further elaboration).[1] Our overview provides an additional dimension to the analyses of global water resources such as the UN World Water Development Reports [*World Water Assessment Programme*, 2009].

2. Estimating Groundwater Recharge

[5] We used the global hydrological model PCR-GLOBWB [*van Beek and Bierkens*, 2009; *Bierkens and van Beek*, 2009] to estimate global groundwater recharge. PCR-GLOBWB calculates for each grid cell (0.5° × 0.5° globally) and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evaporation and snow melt). The model also calculates canopy interception and snow storage. Sub-grid variability is taken into account by considering separately tall and short vegetation, open water, different soil types and the area fraction of saturated soil and the frequency distribution of groundwater depth based on the surface elevations of the 1 × 1 km Hydro1k data set. Fluxes between the lower soil reservoir and the groundwater reservoir are mostly downward, except for areas with shallow groundwater tables, where fluxes from the groundwater reservoir to the soil reservoirs are possible (i.e., capillary rise) during periods of low soil moisture content. The total specific runoff of a cell consists of saturation excess surface runoff, melt water that does not infiltrate, runoff from the second soil reservoir (interflow) and groundwater runoff (baseflow) from the lowest reservoir. To calculate river discharge, specific runoff is accumulated along the drainage network by means of kinematic wave routing including storage effects and evaporative losses from lakes, reservoirs and wetlands. PCR-GLOBWB was forced with 44 years (1958–2001) of daily fields of precipitation, temperature, and reference crop potential evaporation calculated first on a monthly basis with the CRU TS 2.1 [*New et al.*, 1999] and CRU CLIM 1.0 [*New et al.*, 2002] data sets and downscaled to daily fields by ERA40 re-analysis data [*Uppala et al.*,

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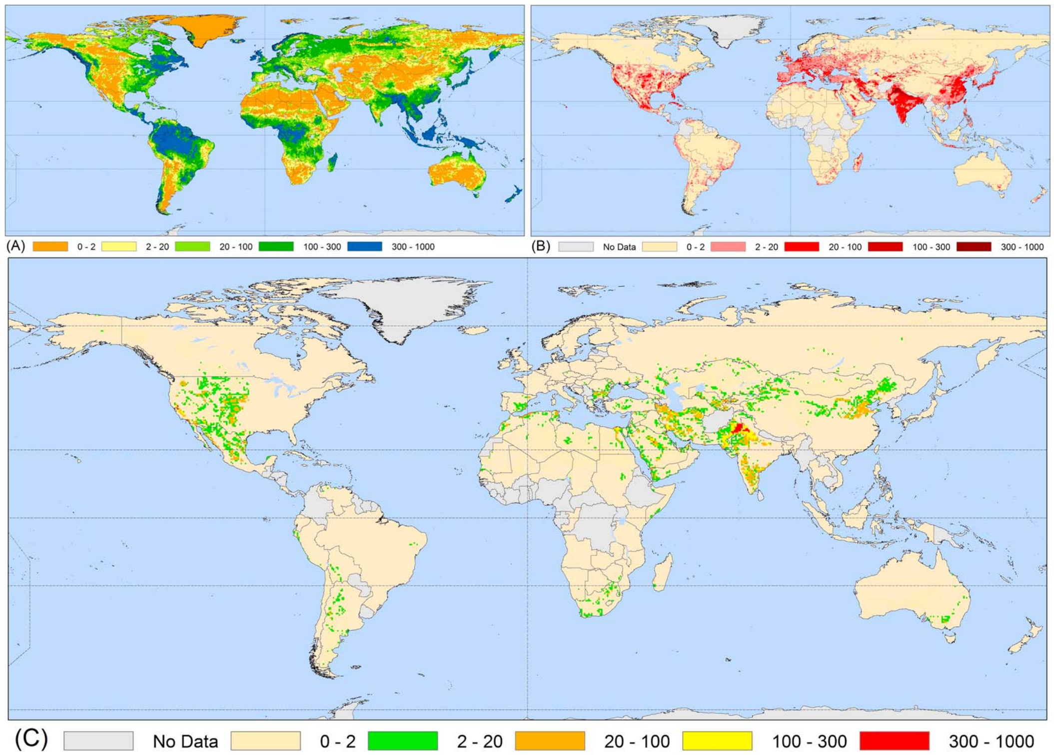

Figure 1. (a) Simulated average groundwater recharge by PCR-GLOBWB, (b) total groundwater abstraction for the year 2000 and (c) groundwater depletion for the year 2000 (all in mm a^{-1}).

2005]. Based on these simulations the average yearly flux between the lowest soil reservoir and the groundwater reservoir was calculated as an estimate of the groundwater recharge. Note that this does not explicitly include recharge from streams, although such effects may be implicitly included when calibrating soil characteristics to reproduce observed low flow properties. Figure 1a shows the result in the same scale as used in paper of *Döll and Fiedler* [2008]. The auxiliary material also contains a map of groundwater recharge in km^3 a^{-1} (Figure S1). Although our map of groundwater recharge shows very similar patterns as their study, our estimated total groundwater recharge ($15.2 \cdot 10^3$ km^3 a^{-1}) is higher than that of *Döll and Fiedler* [2008] ($12.7 \cdot 10^3$ km^3 a^{-1}). Simulated global runoff in our model ($36.2 \cdot 10^3$ km^3 a^{-1}) is smaller than that of *Döll and Fiedler* [2008] ($39.4 \cdot 10^3$ km^3 a^{-1}), who also used CRU but with an additional correction for under catch of snow (a similar correction in our case led to a poorer fit to the discharge data so we reverted to the original CRU). This shows that the main difference is the partioning between surface runoff/interflow and baseflow, which is larger in our study. Differences between the two studies as well as runoff data have been used to perform an uncertainty analysis of recharge estimates (see auxiliary material, with Figure S5a providing a map of estimated error standard deviations).

3. Estimating Groundwater Abstraction

[6] The International Groundwater Resources Assessment Centre (IGRAC) compiled a large database of global groundwater resources (Global Groundwater Information System, GGIS). The database has been filled with publicly available information from the internet (e.g., World Resources Institute), publications, reports and maps, complemented with information obtained from contacts with groundwater experts from many countries. GGIS (www.igrac.net) contains 77 different attributes per country, including groundwater abstraction in mm a^{-1}. Groundwater abstraction was first indexed to a common year 2000, based on population statistics (most records of groundwater abstraction in GGIS are from before 2000). Next, using a map of the groundwater regions of the world (regions with common geological and physiographic features, distinguishing large aquifer systems (see www.igrac.net)), abstraction rates per country were attributed to the groundwater regions per country. The exact locations of abstraction wells are not known for many countries, in particular in agricultural areas where thousands of individual land owners have developed private wells. Otherwise, information about well locations is often classified. Therefore, based on the assumption that groundwater is abstracted close to where it is most needed, we use a global map of yearly total water demand as a proxy for groundwater use to further downscale groundwater abstraction to a $0.5° \times 0.5°$ resolution. Yearly total water demand was calculated as part of a global water stress study [*Wada*, 2008], where total water demand is calculated from irrigation, livestock, domestic and industrial water demand [cf. *Alcamo et al.*, 2000]. The resulting $0.5° \times 0.5°$ map of groundwater abstraction is shown in Figure 1b (see Figure S1b of the auxiliary material for a map in km^3 a^{-1}). The estimated total global groundwater abstraction is 734 (±82) km^3 a^{-1} for the year 2000. Notice the large abstraction rates in Europe, North-East China, United States, Iran, India and Pakistan (see also Table S1). It should however be noted that no abstraction rates have been reported for

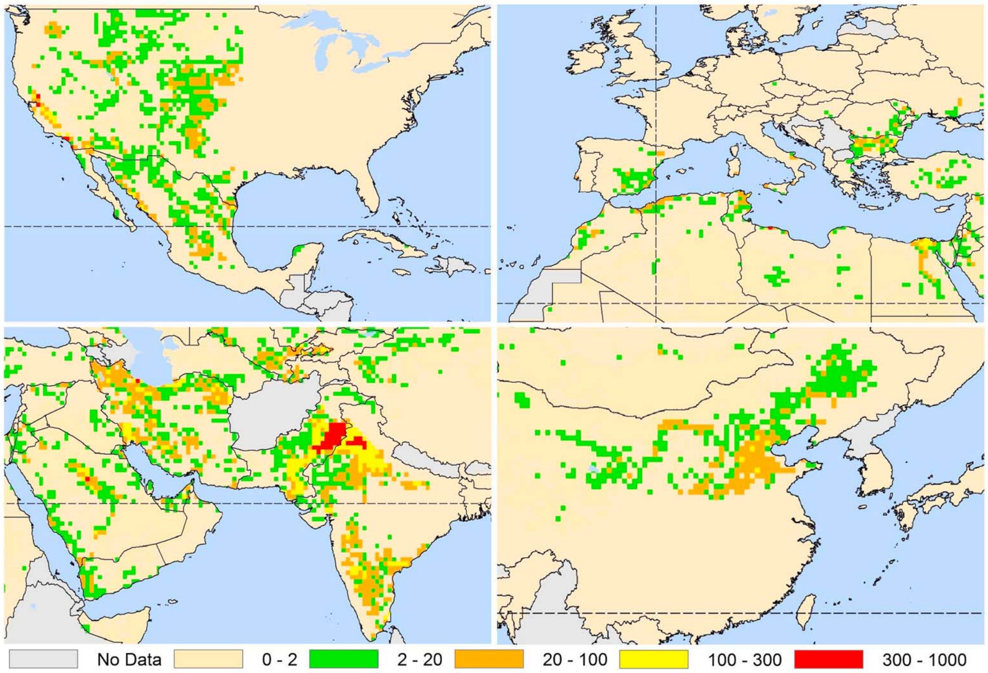

Figure 2. Groundwater depletion in the regions of the U.S.A., Europe, China and India and the Middle East for the year 2000 ($mm \cdot a^{-1}$; clockwise from top-left).

countries for which no data are available in GGIS, e.g., North-Korea, Afghanistan, Sri Lanka, Colombia, several central African countries.

4. Results: Global Groundwater Depletion

[7] A global map of groundwater depletion for the year 2000 was obtained by subtracting groundwater recharge from year 2000 groundwater abstraction. Abstractions in excess of recharge provide an estimate of the amount of groundwater depletion, while negative values occur in regions where abstraction rates are sustained by groundwater recharge. In the latter case, abstractions could still lead to reduced streamflow, but will not lead to ongoing depletion of groundwater reserves. As explained further in the auxiliary material, we restricted our depletion estimates to the sub-humid to arid zones of world, to limit over-estimation related to increased capture of discharge [*Bredehoeft*, 2002] and enhanced recharge due to groundwater pumping. To take account of uncertainty about recharge and abstraction rates, a Monte Carlo-type uncertainty analysis was performed (see auxiliary material), resulting in a grid-based estimate of groundwater depletion and an associated uncertainty map (Figure S5c). The grid-based global estimate is shown in Figure 1c (see Figure S1c for a map in $km^3 \; a^{-1}$), while details in four regions are shown in Figure 2. Many of the well-known hot spots of groundwater depletion appear: North-East Pakistan and North-West India [*Rodell et al.*, 2009], North-East China [*Konikow and Kendy*, 2005], the Ogallala Aquifer in the central U.S. [*Gutentag et al.*, 1984], the San-Joaquin aquifer in the Central Valley of California [*Reilly et al.*, 2008], Iran [*Karami and Hayati*, 2005], Yemen [*Al-Sakkaf et al.*, 1999] and the South-East of Spain [*Custodio*, 2002]. The total global groundwater depletion is estimated as 283 (±40) $km^3 \cdot a^{-1}$. Country estimates (Table S1 of the auxiliary material) of, e.g., the United States (32 ± 7 $km^3 \cdot a^{-1}$) and Saudi Arabia (10 ± 2 $km^3 \cdot a^{-1}$) are similar to estimates provided by *Sahagian et al.* [1994] of 35 $km^3 \cdot a^{-1}$ and 16 $km^3 \cdot a^{-1}$ respectively.

[8] Our global estimate is in line with estimates of "non-local or non-renewable blue water abstraction" as estimated by *Rost et al.* [2008] (730 $km^3 \cdot a^{-1}$) and *Hanasaki et al.* [2010] (703 $km^3 \cdot a^{-1}$), although these authors do not differentiate between renewable and non-renewable sources. *Vörösmarty et al.* [2005] suggest that 16 to 33% of agricultural water withdrawal is non-renewable (400–800 $km^3 \cdot a^{-1}$). Our own estimate of gross irrigation water demand amounts to 2057 $km^3 \cdot a^{-1}$ of which 1478 $km^3 \cdot a^{-1}$ can be met by locally available blue water (i.e., surface water from rivers, lakes and reservoirs) (Y. Wada et al., Global monthly water stress: II. Water demand and severity of water stress, submitted to *Water Resources Research*, 2010), leaving a gap to be filled from additional non-local or non-renewable water sources of 579 $km^3 \cdot a^{-1}$, similar to the estimate by *Vörösmarty et al.* [2005]. It can be expected that a considerable part of this additional demand is met by groundwater abstraction, which makes an estimate of 283 (±40) $km^3 \cdot a^{-1}$ realistic. Although our analysis is limited to the semi-humid to arid zones, total global groundwater depletion is quite substantial, totaling an estimated 39 (±10) % of the global yearly groundwater abstraction, 2 (±0.6) % of the global yearly groundwater recharge, 0.8 (±0.1) % of the global yearly continental runoff and 0.4 (±0.06) % if the global yearly evaporation. This makes groundwater over-abstraction a term of the global water balance that cannot be neglected.

[9] As a first-order estimate of development of groundwater abstraction and groundwater depletion through the last decades we assumed the increase of groundwater abstraction to keep pace with the increase in water demand. Using statistics on population, irrigated area and livestock (obtained

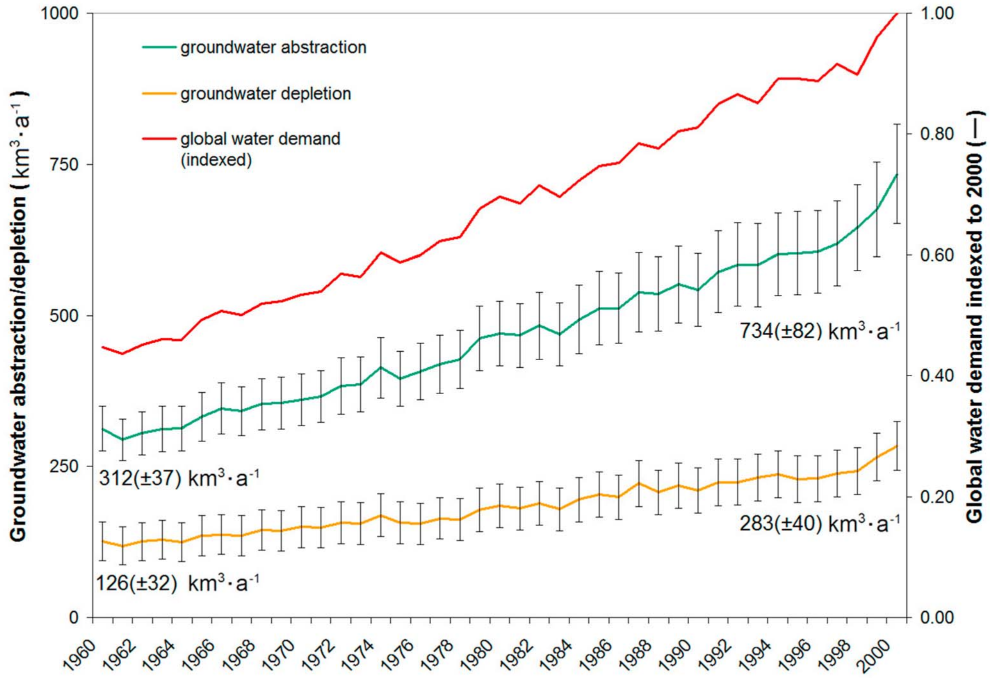

Figure 3. 1960–2000 trends in total global water demand (right axis; indexed for the year 2000), global groundwater abstraction (left axis; $km^3\ a^{-1}$) and global groundwater depletion (left axis; $km^3\ a^{-1}$).

from FAOSTAT, http://faostat.fao.org/) we first constructed yearly net total water demand on a 0.5° × 0.5° cell-by-cell basis from 1960 to 2000 (similar to the work by *Döll et al.* [2009]). Next, for each 0.5° × 0.5° cell and each year, the ratio of yearly total water demand to the year 2000 total yearly water demand was calculated and multiplied with the year 2000 groundwater abstraction. Repeating the uncertainty analysis as described in the auxiliary material for groundwater abstraction and groundwater depletion then yields maps of estimated groundwater depletion for each year. Because of the strong assumption that groundwater abstraction is in sync with water demand, we only provide global totals in Figure 3. We thus estimate that since the 1960s groundwater abstraction has more than doubled (from 312 ± 37 to 734 ± 82 $km^3\ a^{-1}$), resulting in an increase in groundwater depletion from 126 ± 32 to 283 ± 40 $km^3\ a^{-1}$.

[10] Most of the groundwater released from storage due to groundwater depletion will end up in the ocean, partly by runoff and, as most of the groundwater use is for irrigation purposes, predominantly through evaporation and then precipitation. Based on the ratio of groundwater recharge ($15 \cdot 10^3\ km^3 \cdot a^{-1}$) to total precipitation on earth ($574 \cdot 10^3\ km^3 \cdot a^{-1}$) [*German Advisory Council on Climate Change*, 1999] and assuming all other stores (atmospheric moisture and surface waters) to remain constant, we can thus estimate which fraction of the depleted groundwater returns to the groundwater store by additional recharge (15/574 = 0.03) and which part ends up in the ocean (559/574 = 0.97) and contributes to sea level rise. We estimate the contribution of groundwater depletion to sea level rise to be 0.8 (±0.1) mm a^{-1}, which is 25 (±3) % of the current rate of sea level rise of 3.1 mm a^{-1} reported in the last IPPC report [*Bindoff et al.*, 2007] and of the same order of magnitude as the contribution from glaciers and ice caps (without Greenland and Antarctica). Our estimate (0.6–1.0 mm a^{-1} in terms of range) sits in the upper region of the range of 0.2–1.0 mm a^{-1} reported by *Gornitz et al.* [1997] and is larger than the 0.55 mm a^{-1} given by *Postel* [1999] (see *Huntington* [2008] for a recent overview). The possible contribution of groundwater over-exploitation to sea level rise is mentioned in the IPCC Third Assessment Report [*Church et al.*, 2001, p. 657]. However, it is also mentioned that uncertainty is large and that the positive contribution of groundwater depletion may be offset by impoundment in reservoirs and associated recharge of surrounding aquifers. For this reason, anthropogenic contributions to sea level rise are not quantified in Fourth Assessment Report, although they are mentioned as the possible cause for the discrepancy between observed sea-level rise and the sum of the known sources [*Church et al.*, 2001]. However, global groundwater depletion has been increasing since the 1960 and is likely to increase further in the near future, while the increase of impoundment by dams has been tapering off since the 1990s [*Chao et al.*, 2008]. Consequently, the contribution of groundwater depletion to sea-level rise may become increasingly important in the coming decades.

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