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Impact of water withdrawals from groundwater and surface water on continental water storage variations

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ABSTRACT

Humans have strongly impacted the global water cycle, not only water flows but also water storage. We have performed a first global-scale analysis of the impact of water withdrawals on water storage variations, using the global water resources and use model WaterGAP. This required estimation of fractions of total water withdrawals from groundwater, considering five water use sectors. According to our assessment, the source of 35% of the water withdrawn worldwide (4300 km^3/year during 1998–2002) is groundwater. Groundwater contributes 42%, 36% and 27% of water used for irrigation, households and manufacturing, respectively, while we assume that only surface water is used for livestock and for cooling of thermal power plants. Consumptive water use was 1400 km^3/year during 1998–2002. It is the sum of the net abstraction of 250 km^3/year of groundwater (taking into account evapotranspiration and return flows of withdrawn surface water and groundwater) and the net abstraction of 1150 km^3/year of surface water. Computed net abstractions indicate, for the first time at the global scale, where and when human water withdrawals decrease or increase groundwater or surface water storage. In regions with extensive surface water irrigation, such as Southern China, net abstractions from groundwater are negative, i.e. groundwater is recharged by irrigation. The opposite is true for areas dominated by groundwater irrigation, such as in the High Plains aquifer of the central USA, where net abstraction of surface water is negative because return flow of withdrawn groundwater recharges the surface water compartments. In intensively irrigated areas, the amplitude of seasonal total water storage variations is generally increased due to human water use; however, in some areas, it is decreased. For the High Plains aquifer and the whole Mississippi basin, modeled groundwater and total water storage variations were compared with estimates of groundwater storage variations based on groundwater table observations, and with estimates of total water storage variations from the GRACE satellites mission. Due to the difficulty in estimating area-averaged seasonal groundwater storage variations from point observations of groundwater levels, it is uncertain whether WaterGAP underestimates actual variations or not. We conclude that WaterGAP possibly overestimates water withdrawals in the High Plains aquifer where impact of human water use on water storage is readily discernible based on WaterGAP calculations and groundwater observations. No final conclusion can be drawn regarding the possibility of monitoring water withdrawals in the High Plains aquifer using GRACE. For the less intensively irrigated Mississippi basin, observed and modeled seasonal groundwater storage reveals a discernible impact of water withdrawals in the basin, but this is not the case for total water storage such that water withdrawals at the scale of the whole Mississippi basin cannot be monitored by GRACE.

1. Introduction

Improved quantification of not only continental freshwater flows but also freshwater storage in different compartments (snow and ice, canopy, soil, groundwater, and surface water including lakes and wetlands) enables a better understanding of the global

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water cycle and the overall Earth system. It allows a better assessment of freshwater resources and how they are impacted by global change. Temporal freshwater storage variations cause significant variations in Earth's gravity field and lead to load-induced deformations of the Earth's crust. Measured gravity variations and derived total continental water storage variations, most notably those of the GRACE (Gravity Recovery and Climate Experiment) mission (http://www.csr.utexas.edu/grace/), can be interpreted in detail only by relating them to independent estimates of compartmental water storage variations. Compartmental storage variations can be derived from hydrological models (Güntner et al., 2007), ground observations (e.g. of soil moisture and groundwater levels, e.g. Yeh et al., 2006; Swenson et al., 2008), or by subtracting model-based estimates of storage variations in all but one storage compartment from GRACE estimates of total water storage variations (Rodell et al., 2007, 2009; Strassberg et al., 2009). Alternatively, hydrological models can be calibrated (Werth and Güntner, 2010; Lo et al., 2010) and evaluated using GRACE data (Alkama et al., 2010), or GRACE-based water storage variations can be integrated into models via data assimilation (Zaitchik et al., 2008). The same is true for geodetic measurements such as GPS, which are impacted by deformations caused by large-scale continental water mass variations (Fritsche et al., 2011).

Continental water storage variations depend on characteristics of the storage compartments (e.g. soil texture and rooting depth in the case of soil water storage or existence of surface water bodies in the case of surface water storage) and are strongly driven by climate, in particular precipitation. For more than a century now, human water use has become another strong driver of water storage variations, in particular in densely populated areas and semi-arid and arid areas with significant irrigation. About 70% of global water withdrawals and about 90% of global consumptive water use (the part of the withdrawn water that evapotranspires during use) is for irrigation purposes (Döll, 2009). Dam construction and, more importantly, water withdrawals from groundwater and surface water have altered not only freshwater flow dynamics (Döll et al., 2009) but also water storage variations in surface water bodies and aquifers.

In global-scale assessments, natural freshwater flows and storages are modeled by global hydrological models or land surface models. These models generally combine climate data with physiographic data (including soil and vegetation) to compute time series of freshwater flows (in particular runoff and river discharge). Some of the models do not include all relevant storage compartments such as surface water bodies and groundwater. Very few models take into account the impact of human action, in particular of dams and water withdrawals. These include VIC (Haddeland et al., 2006), H08 (Hanasaki et al., 2008), LPJ (Gerten et al., 2004), WBM$_{plus}$ (Wisser et al., 2010) and WaterGAP (Alcamo et al., 2003; Döll et al., 2009). While these models were used to study the impact of dams and water withdrawals on freshwater flows, the impact on water storage has not yet been analyzed. Up to now, impacts of human water use on water storage could not be evaluated appropriately because no estimates of water withdrawals according to source, i.e. no estimates that differentiate between water withdrawals from groundwater and water withdrawals from surface water, existed at the global scale. Therefore, in all these models water withdrawals were assumed to be taken from surface water only, and not from groundwater. An exception is WBM$_{plus}$ where total irrigation requirements (other sectoral water uses are neglected and no distinction of requirements by source is made) are satisfied first by local reservoirs, then by groundwater and then by river water (Wisser et al., 2010). A further exception is the recent study on global groundwater depletion by Wada et al. (2010), where total groundwater withdrawals were roughly estimated based on country-scale data from only one information source (International Groundwater Resources Assessment Centre (IGRAC), www.igrac.net), the impact of irrigation return flow was neglected, and groundwater depletion was computed simply as the difference between groundwater withdrawals and groundwater recharge.

In order to properly estimate the impact of surface water and groundwater withdrawals on water storage variations in the different continental water storage compartments, we estimated, for each 0.5° grid cell, the fractions of total water withdrawals and consumptive water use that are taken from groundwater in the following sectors: irrigation, household (domestic sector) and manufacturing. We assumed that water for cooling of thermal power plants and water for livestock (a generally small amount) is taken only from surface water. Using estimates of total sectoral (groundwater and surface water) water use and taking into account the different compartments to which return flow occurs, we then estimated, with the new version 2.1h of WaterGAP (Water – Global Assessment and Prognosis), net water abstractions from groundwater (NA_g) and from surface water (NA_s). Net abstraction is equal to the difference between all abstractions due to human water withdrawals from either groundwater or surface water and all return flows into the respective compartment. These net abstractions were then subtracted from groundwater storage and surface water storages (rivers, lakes, and reservoirs), respectively, and the impact of water withdrawals from groundwater and surface water on continental water storage variations (total and compartmental) was determined. For this paper we concentrated on the impact of water use on seasonal variations in water storage, and did not evaluate trends in our global-scale analysis. Modeled groundwater storage (*GWS*) variations were compared with estimates derived from measured groundwater level variations in the High Plains aquifer (Strassberg et al., 2009) and the Mississippi river basin (Rodell et al., 2007), while computed total water storage (*TWS*) variations were compared with *TWS* variations derived from GRACE satellite data. The High Plains aquifer is an area with intensive groundwater-fed irrigation and an estimated area-weighted average groundwater level decline from predevelopment (about 1950) to 2007 of 4.27 m, with a relatively constant decline rate since the mid 1980s (McGuire, 2009). The much larger Mississippi basin, to which most of the High Plains aquifer belongs, also includes other areas of intensive irrigation but is on average less affected by water withdrawals than the High Plains aquifer.

2. Methods

2.1. Modeling water flows, storage variations and water use with the global water model WaterGAP

WaterGAP (Alcamo et al., 2003) consists of both the WaterGAP Global Hydrology Model (WGHM; Döll et al., 2003) and five water use models for the sectors irrigation (Döll and Siebert, 2002), livestock, households (Voß et al., 2009), manufacturing and cooling of thermal power plants (Voß and Flörke, 2010; Vassolo and Döll, 2005). With a spatial resolution of 0.5° × 0.5°, WaterGAP covers all land masses of the Earth except Antarctica.

Modeling of water use refers to computation of water withdrawals and consumptive water uses (the part of the withdrawn water that evapotranspires during use) in each grid cell. Consumptive irrigation water use is computed by the Global Irrigation Model (GIM) as a function of irrigated area (Siebert et al., 2005, 2006) and climate in each grid cell. Regarding crops, only rice and non-rice-crops are distinguished, and crop growth periods are not prescribed but modeled. Water withdrawals are calculated by dividing consumptive use by a country-specific irrigation water use efficiency (Döll and Siebert, 2002). The compilation of a time series of irrigated area per country from 1901 to 2010 (Freydank and Siebert, 2008, updated) allows consideration of the changing impact of irrigation. Livestock water use is calculated as a function of the animal numbers and water requirements of different livestock types. Grid cell values of domestic and manufacturing water use are based on national values that are downscaled to the grid cells using population density. Cooling water use takes into account the location of more than 60,000 power plants, their cooling type and their electricity production (Vassolo and Döll, 2005). Temporal development of household water use since 1960 is modeled as a function of technological and structural change (the latter as a function of gross domestic product), taking into account population change (Voß et al., 2009). The temporal development of manufacturing and thermal power water use since 1900 is modeled also as a function of structural and technological change, with national manufacturing output (for manufacturing water use) and national electricity output (for thermal power plant use) as the drivers of water use (Voß and Flörke, 2010). Time series of monthly values of irrigation water use are computed, while all other uses are assumed to be constant throughout the year and to only vary from year to year.

WGHM computes time-series of fast-surface and subsurface runoff, groundwater recharge and river discharge as well as storage variations of water in canopy, snow, soil, groundwater, lakes, wetlands and rivers as a function of climate, soil, land cover, relief and observed river discharge. Location and size of lakes, reservoirs and wetlands are defined by the global lakes and wetland database (GLWD) (Lehner and Döll, 2004), with a recent addition of more than 6000 man-made reservoirs (Döll et al., 2009). Groundwater storage is affected by diffuse groundwater recharge via the soil, which is modeled as a function of total runoff, relief, soil texture, hydrogeology and the existence of permafrost or glaciers. For semi-arid areas, a comparison with independent estimates of diffuse groundwater recharge led to a modification of this groundwater recharge algorithm (Döll and Fiedler, 2008). Focused groundwater recharge from rivers, lakes and wetlands is not taken into account in WGHM. This type of recharge may be important, in particular in semi-arid and arid regions, but is difficult to quantify.

In former versions of WGHM, the impact of water use on the water cycle was taken into account by subtracting total consumptive water use from river, reservoir and lake storage (in this order of preference). The impact of groundwater withdrawals was not taken into account due to lack of data on withdrawals differentiated by source. If surface water storage in a grid cell, on any day, was less than consumptive use (or rather requirement), the unsatisfied use was taken out of storage of the neighboring cell with the largest river, reservoir and lake storage (but not the upstream cells). If, after the subtraction of the water stored in the neighboring cell, the full consumptive water use was still not satisfied, the remaining consumptive water requirement was carried forward in the model, and it was determined whether it could be taken out of surface storage the next day (in addition to the consumptive use of the next day). Any non-satisfied consumptive water use was carried forward in the model for one year, and then dropped. Allowing such delayed satisfaction of consumptive water use requirement implicitly mimicked water withdrawals from shallow (renewable) groundwater. Groundwater can be withdrawn even if surface water has run dry. Delayed satisfaction was also intended to account for the fact that WGHM cannot model reservoir operations accurately.

WGHM, in the standard approach, is calibrated against long-term average river discharge at 1235 stations world-wide, adjusting 1–3 model parameters individually in each of the 1235 upstream basins (Hunger and Döll, 2008). WGHM was evaluated mainly by comparing simulated river discharge to observed flow regime characteristics such as seasonality and statistical monthly low and high flows (Döll et al., 2003, 2009; Hunger and Döll, 2008).

2.2. Quantification of water withdrawals and consumptive uses from groundwater and surface water

The water use models of WaterGAP compute time series of consumptive water use in the irrigation sector, for temporally invariant irrigated areas, and consumptive (CU) and withdrawal water uses (WU) for each of the four sectors households, manufacturing, cooling of thermal power plants and livestock. CU and WU of livestock are assumed to be equal. In the water use models, no distinction is made regarding the source of water. To model water use according to source of water, a new submodel of WaterGAP called GWSWUSE was developed. GWSWUSE computes, based on the nine water use data sets from the water use models, the sector-specific consumptive and withdrawals water uses from groundwater and surface waters (rivers, lakes and reservoirs) separately. GWSWUSE also computes net abstractions from surface water (NA_s) and from groundwater (NA_g) (see Section 2.3).

As a first step within GWSWUSE, the time series of irrigation CU, which is computed by GIM for temporally constant irrigation areas but changing climate variables, is scaled by using an annual time series of irrigated area by country (Freydank and Siebert, 2008, updated). Then, irrigation WU is computed by dividing irrigation CU by irrigation water use efficiencies at the scale of individual irrigation projects (so-called project efficiencies). Irrigation water use efficiencies were estimated for each country by combining information from three sources (Kulkarni et al., 2006; Rohwer et al., 2007; Aus der Beek, personal communication, 2010). To obtain sectoral groundwater uses in the sectors irrigation, households and manufacturing, total sectoral WUs and CUs in each grid cell are then multiplied by sector- and cell-specific temporally constant groundwater use fractions f_g which are assumed to be the same for WU and CU. Surface water use was computed as the difference between total and groundwater use.

We assumed that water for cooling of thermal power plants and water for livestock are only abstracted from surface water. In order to obtain groundwater fractions for irrigation water use, we estimated the area equipped for irrigation with groundwater as a fraction of total irrigated area (f_{a_irr}). We derived these for 15,038 spatial statistical units (SSU), i.e. national and sub-national administrative units (Siebert et al., 2010). Statistics on area equipped for irrigation were collected from national census reports or online databases and complemented with country information available from the Food and Agriculture Organization (FAO) of the United Nations AQUASTAT library, data collected by other international organizations or statistical services (e.g. EUROSTAT) or data taken from the literature. Statistics on area equipped for irrigation by either surface water or groundwater were available for only about 12% of all SSUs. However, about 75% of the global area equipped for irrigation is located in these SSUs. In this study, we used the estimates of f_{a_irr} of Siebert et al. (2010), except in Russia where Siebert et al. (2010) only estimated a constant value for the whole country. Here, we used subnational data on total groundwater withdrawals as a fraction of total water withdrawals for 11 large river basins, assuming that f_{a_irr} is equal to this fraction.

Groundwater fractions of domestic and manufacturing water use were estimated for 5938 SSUs, mainly based on information from the International Groundwater Resources Assessment Centre (IGRAC, www.igrac.net), international reports and national sources. No information at all was available for 55 out of 196 countries or territorial units. For 10 countries, subnational data (mostly at the level of federal states/provinces, with a total of 5752 SSUs) could be evaluated. Subnational data on both domestic and manufacturing groundwater fractions were available for only 3 of the 10 countries: USA (for counties), Mexico (for counties) and Germany (for federal states). For the other countries with subnational data, only data on total groundwater withdrawals as a fraction of total withdrawals

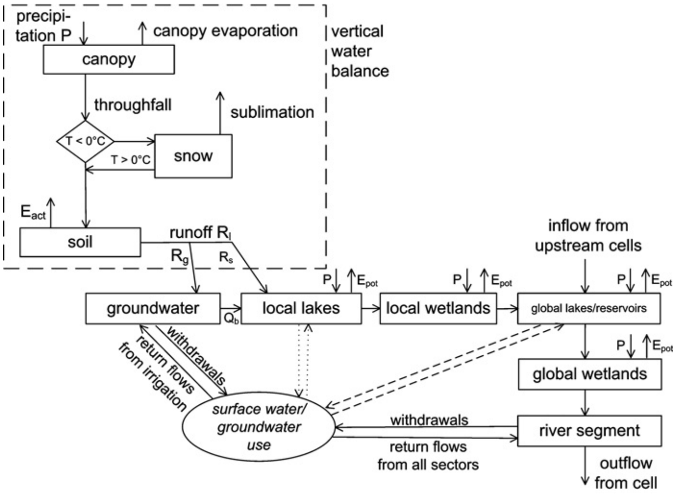

Fig. 1. Schematic of water storage compartments (boxes) and flows (arrows) within each 0.5° grid cell of WGHM, including the simulation of water use impacts on water storage in groundwater and surface water based on estimates of groundwater and surface water use. The water use estimates are computed by the water use models of WaterGAP (including GWSWUSE that quantifies water use by source for each grid cell). Local lakes and wetlands are those lakes and wetlands that only receive inflow originating from precipitation within the cell.

were available, or only data for either the domestic or the manufacturing sector. Regarding national-scale data, groundwater use fractions f_g for both domestic and manufacturing sectors could be derived directly from data on sectoral groundwater and total water withdrawals for only 20 countries. In most countries, inconsistencies of total sectoral water uses and sectoral groundwater uses that are mostly due to different data sources, or simple lack of data, made reliable estimation of specific domestic and manufacturing groundwater fractions impossible. In Appendix A, generation of the data sets of cell-specific groundwater use fractions of domestic and manufacturing water withdrawals is described in more detail.

Sectoral groundwater fractions for the SSUs were interpolated to the 0.5° grid cells by weighting with intersection area. At the grid cell level, f_{a_irr} is assumed to be equivalent to the fraction of irrigation water withdrawal and consumptive use that stems from groundwater.

2.3. Modeling the impact of groundwater and surface water use on groundwater and surface water storages

Fig. 1 shows the water flows and storages that are modeled in WGHM 2.1h within each 0.5° grid cell. Groundwater receives input from groundwater recharge and loses water to outflow to surface water (the river, or lakes, reservoirs and wetlands if they exist in the cell), the outflow being a linear function of groundwater storage (for observational evidence of the resulting exponential relation between groundwater outflow and storage, see Fig. 12b of Eltahir and Yeh, 1999). Unlike in former versions of WGHM, in the new model version 2.1h, groundwater storage is decreased (or increased) by the so-called net abstraction of groundwater NA_g, i.e. the difference between water withdrawals from groundwater and return flows to groundwater. Return flows to groundwater are assumed to only occur in irrigated areas, due to irrigation water that was either taken from groundwater or surface water (Fig. 1). A fraction f_{rgi} of the return flows from irrigation recharges groundwater, while the rest directly flows to surface water bodies. NA_g is computed as

$$NA_g = [WU_{gi} + WU_{gd} + WU_{gm}] - [f_{rgi}\,(WU_{gi} - CU_{gi} + WU_{si} - CU_{si})] \tag{1}$$

with WU: withdrawal use, in km^3/month, CU: consumptive use, in km^3/month, NA: net abstraction, in km^3/month, f_{rgi}: fraction of return flow (WU–CU) from irrigation to groundwater, and subscripts g: groundwater, s: surface water, i: irrigation, d: domestic, m: manufacturing. The term that is subtracted at the right-hand side of Eq. (1) can be regarded as artificial groundwater recharge.

Temporal development of groundwater storage is computed as follows:

$$GWS(t) = GWS(t-1) + GWR(t) - k_g GWS(t-1) - NA_g(t) \tag{2}$$

with GWS: groundwater storage, in km^3, GWR: groundwater recharge, in km^3/day, k_g: outflow coefficient from groundwater to surface water, set globally to 0.01/day, t: time step (1 day).

The different surface water bodies receive water from precipitation, from the soil by fast surface or subsurface runoff or from the groundwater compartment by baseflow, or from other surface water bodies. They lose water by evaporation and outflow to the next surface water body (Fig. 1). Surface water storage is affected by NA_s, the difference between withdrawals from surface water and the return flows to surface water. This is different from the previous WGHM versions, where total consumptive use was taken out of surface water storage.

Water withdrawals for all sectors and sources result in return flow (WU–CU) to surface water. In the case of all sectors except irrigation, the total return flow is assumed to directly flow into surface water even if the water source is groundwater. In the case of irrigation, a part of the return flow of the irrigation water withdrawn from either surface water or groundwater flows directly back to surface water, while the other part (f_{rgi}) recharges groundwater (Fig. 1). For water uses where the source of water and the sink for the return flow are the surface water bodies, only consumptive use needs to be included in the computation of NA_s. This is the case for water use for cooling of thermal power plants and for livestock as well as for surface water use in the domestic and manufacturing sectors. Thus, net abstraction from surface water NA_s, i.e. from rivers, lakes and reservoirs, is defined as

$$\begin{aligned} NA_s = {} & [CU_l + CU_t + CU_{sd} + CU_{sm} + WU_{si}] - [(1 - f_{rgi})(WU_{gi} - CU_{gi} \\ & + WU_{si} - CU_{si}) + (WU_{gd} - CU_{gd} + WU_{gm} - CU_{gm})] \end{aligned} \tag{3}$$

with subscripts l: livestock, t: thermal power plants. The temporal development of the rivers, lakes and reservoirs as impacted by NA_s is modeled using a water balance similar to Eq. (2). The sum of NA_s and NA_g is equal to consumptive water use.

NA_s is taken preferentially from river storage (full line in Fig. 1). Only if no river water is available, water will be taken from (1) global reservoirs (if actual reservoir storage exceeds 10% of total storage capacity, (2) global lakes (if storage is greater than zero), or (3) local lakes (Fig. 1). So-called local lakes and wetlands are recharged only from runoff generated within the grid cells, while so-called global lakes, reservoirs and wetlands also get water from the upstream cell (Fig. 1). If, on any day, not enough surface water is available in a grid cell to allow subtraction of NA_s from that particular grid cell, NA_s is taken from the neighboring grid cell as described in Section 2.1. Delayed satisfaction of water requirements was not allowed in the model runs presented in this paper.

Return flow of irrigation will partly recharge groundwater, and partly run off directly to surface water bodies. Return flows to surface water will be high in the case of artificial drainage when pipes or drainage canals cause water to bypass the groundwater store. We estimated the groundwater fraction of return flow f_{rgi} as a function of the fraction of irrigated area that is artificially drained f_{d_irr} as

$$f_{rgi} = 0.8 - 0.6 f_{d\_irr} \tag{4}$$

f_{d_irr} was derived from global-scale information on drainage in rainfed and irrigated agriculture as compiled by Feick et al. (2005). Due to a lack of data on drainage in irrigated areas in many countries, we had to combine data on drained irrigated area with data on drained area (without distinction of rainfed and irrigated agriculture). Values of f_{rgi} between 0.2 and 0.4 occur in regions where irrigated areas are strongly drained: the Nile in Egypt, the southern part of the Indus, Japan, Philippines, Indonesia and parts of Australia. The northern part of the Indus as well as Northeastern China show values between 0.4 and 0.6. In most of the USA, f_{rgi} is between 0.6 and 0.7, in India, the value is about 0.75. In the rest of the world, irrigated areas are not drained much and f_{rgi} is close to 0.8.

2.4. Model runs with WaterGAP 2.1h

For the period 1901–2002, WGHM and GIM were driven by monthly climate data from the Climate Research Unit (CRU) with a spatial resolution of 0.5° (covering the global land surface). The CRU TS 2.1 data set includes gridded data for the climate variables temperature, cloudiness and number of rain days from 1901 to 2002. This data set is based on station observations and uses anomaly analysis for spatial interpolation (Mitchell and Jones, 2005). To run the model for the GRACE period 2002–2009, monthly data on temperature, cloudiness and number of rain days for 2003–2009 from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational forecast system were used. For precipitation, the Global Precipitation Climatology Centre (GPCC) full data product v3 provided gridded monthly values for 1951–2004 (Rudolf and Schneider, 2005), also with a spatial resolution of 0.5°, except that for GIM the GPCC full data product v4 was used until 2002. For the years 2005–2009, the so-called GPCC monitoring product with a spatial resolution of 1° was used, which is based on a smaller number of station observations. In WGHM, monthly precipitation is distributed equally over the number of rain days within one month. The monthly precipitation data are not corrected for measurement errors, but precipitation, in particular snow is generally underestimated by measurements mainly due to wind induced undercatch. As this has a strong influence on simulated snow water storage, precipitation was corrected in WGHM using mean monthly catch ratios and taking actual monthly temperatures into account (Döll and Fiedler, 2008). Water use in the three sectors households, manufacturing, and cooling of thermal power plants was computed for 1901–2005, and assumed to be equal to the values for 2005 from 2006 to 2009. For livestock, the year with the last statistics available was 2002, and livestock use in 2003–2009 was assumed to be the same as in 2002. For the runs with WaterGAP 2.1h, the calibration parameter values of version 2.1g were used.

2.5. GWS variations developed from measured groundwater levels

For the High Plains aquifer, which covers about 450,000 km^2, Strassberg et al. (2009) developed a time series of *GWS* variations for the aquifer as a whole from measured groundwater levels in 1989 wells. Four seasonal values were developed per year (January–March, April–June, July–September, October–December), covering the years 2003–2006, based on an average of 983 wells per season. To convert water level variations to *GWS* variations, the former were multiplied by a constant specific yield of 0.15, which represent the area-weighted specific yield (McGuire, 2009). For the entire Mississippi basin (approx. 3,248,000 km^2), Rodell et al. (2007) developed a monthly time series of *GWS* from water level observations in 58 wells in unconfined aquifers. These wells were distributed almost evenly over the basin. To convert water level variations to *GWS* variations, the former were multiplied by specific yield values determined individually for each well, ranging from 0.02 to 0.32, with a mean of 0.14. For our comparison, we used an updated data set covering the period January 2002–June 2006.

2.6. Total water storage variations from GRACE satellite observations

We compared monthly *TWS* variations simulated with WaterGAP to values derived from GRACE satellite observations. To better understand the uncertainty in GRACE data, solutions computed by three different GRACE processing groups were used. To compute ITG-GRACE2010 monthly solutions (http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010), a set of spherical harmonic coefficients for degrees $n = 1\ldots120$ was estimated for each month from August 2002 to August 2009 without applying any regularization. More detailed information on this GRACE solution can be found in Mayer-Gürr et al. (2010). To determine continental water storage variation from the total GRACE signal, the following background models were taken into account: ocean, Earth and pole tides, atmospheric and oceanic mass variations as well as glacial isostatic adjustment (as described in Eicker et al., in press). Degree $n = 1$ (geo-center variations) was set to zero as GRACE does not deliver realistic estimates of these coefficients. This is justifiable as a comparison using GPS geo-center estimates has revealed that there is no significant contribution of degree 1 in the two investigation areas. In addition, GFZ release 4 monthly solutions (Flechtner et al., 2010) and CSR monthly solutions (Bettadpur, 2007) were considered.

All three GRACE solutions were smoothed using the non-isotropic filter DDK3 (Kusche et al., 2009). To allow a consistent comparison to WGHM results, the filtered results were interpolated to the WGHM 0.5° grid such that basin averages of *TWS* could be computed as averages over the respective WGHM grid cells. In order to compare *TWS* modeled with WGHM to GRACE-derived

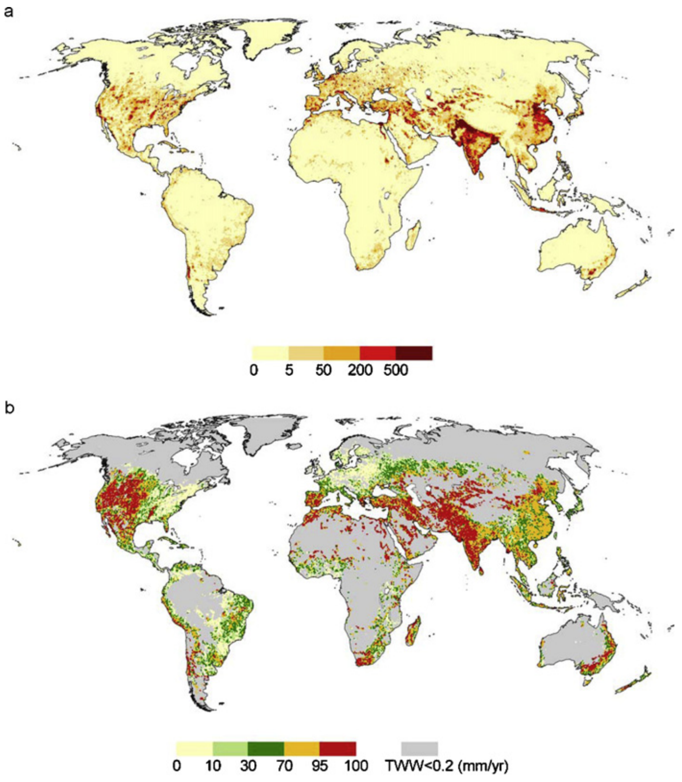

Fig. 2. (a) Total water withdrawals, in mm/year, and (b) irrigation water withdrawals in percent of total water withdrawals, for 1998–2002. The irrigation percentage is only shown if total water withdrawals are at least 0.2 mm/year.

Table 1
Global water use during the period 1998–2002. Total water withdrawals and consumptive water use were computed by the five sectoral water use models of WGHM (Section 2.1). The new groundwater fractions were derived as described in Section 2.2, Appendix A and Siebert et al. (2010).

Water use sector	Withdrawals *WU* [km^3/year]	Groundwater fraction of *WU* [%]	Consumptive use *CU* [km^3/year]	Groundwater fraction of *CU* [%]
Irrigation	3185	42	1231	43
Thermal power	534	0	13	0
Domestic	330	36	53	37
Manufacturing	264	27	110	24
Livestock	27	0	27	0
All sectors	4340	35	1436	40

TWS, WGHM model output was smoothed using the same procedure.

3. Results and discussion

3.1. Global-scale results

According to WaterGAP, global water withdrawals have increased from 1615 km^3/year in 1951 to 4090 km^3/year in 1998 and 4436 km^3/year in 2002. Water withdrawals for irrigation may vary appreciably from year to year due to climate variability. Therefore, to provide a global characterization of water withdrawals, we focus on average values for the period 1998–2002. Most data that informed the computation of water withdrawals are from this period. Knowledge of temporal development of water withdrawals before and especially after this period is limited. Average water withdrawals for 1998–2002 sum to a global average of 4340 km^3/year (Fig. 2a, Table 1). In many semi-arid and arid regions, irrigation is the dominant water use sector, with irrigation water withdrawals often accounting for more than 95% of total withdrawals (Fig. 2b). This contrasts with the situation in most of Europe (except southern Europe) and eastern North America, where less than 10% of total water withdrawals are for irrigation. Globally, irrigation accounts for 73% of total water withdrawals but for 86% of total consumptive use (Table 1). During crop growing periods, seasonally variable irrigation water withdrawals account for an even higher percentage of total water withdrawals. Consumptive use is 33% of water withdrawals and is concentrated in semi-arid and arid regions with extensive irrigation even more strongly than water withdrawals (not shown).

The fraction of sectoral and total water withdrawals that stems from groundwater varies strongly across the globe (Fig. 3). Please note, however, that we underestimate spatial variability as data were not available at the grid cell scale. The highest fractions for domestic water use occur in countries such as Mongolia, Iran, Saudi Arabia, Austria and Morocco, and large parts of the USA and Mexico (Fig. 3a). Groundwater fractions of manufacturing water withdrawals are similar to those of domestic water use, either because this really is the case or because no specific data were available for groundwater use in the domestic and manufacturing sectors (Fig. 3b). Please note that in the WaterGAP manufacturing water use model, country values are downscaled to the grid scale by density of urban population, which leads to many cells without any manufacturing water use. This is different from domestic water use, where downscaling is done by total urban and rural population. The resolution of the groundwater fractions in irrigation is much higher than in the domestic and manufacturing water use sectors (Fig. 3c). Groundwater fractions of water withdrawals for irrigation exceed 80% in Central USA and Mexico, western India and parts of Pakistan, West Asia including Iran, large parts of Northern Africa and North America (in particular the High Plains aquifer and the lower part of the Mississippi) and in Argentina. Groundwater

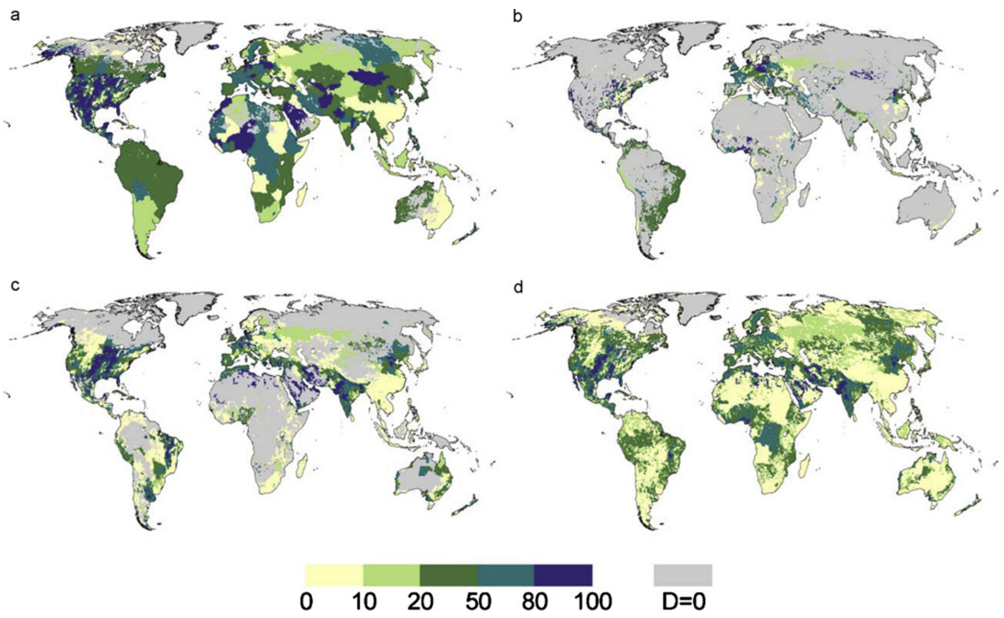

Fig. 3. Importance of groundwater withdrawals in the different water use sectors as estimated in this study. (a) Groundwater withdrawals for domestic purposes in percent of total surface and groundwater withdrawals for domestic purposes, (b) groundwater withdrawals for manufacturing in percent of total surface and groundwater withdrawals for manufacturing, (c) groundwater withdrawals for irrigation in percent of total surface and groundwater withdrawals for irrigation (equivalent to area equipped for irrigation by groundwater in percent of irrigated area), and (d) total groundwater withdrawals in percent of total withdrawals. Mean values for 1998–2002, spatial resolution 0.5°. $D=0$ means that the denominator is zero.

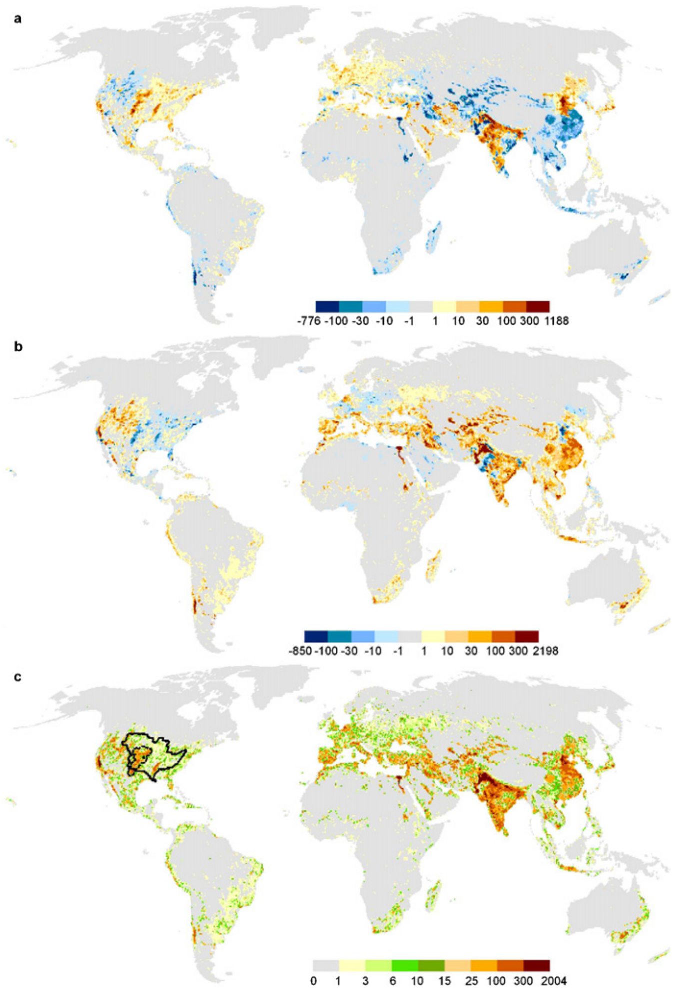

Fig. 4. (a) Net abstraction of groundwater NA_g and (b) of surface water NA_s, and (c) consumptive water use CU (sum of NA_g and NA_s), in mm/year, for 1998–2002. If net abstraction is negative, water is added to storage. In the lower panel, the outlines of the High Plains aquifer and the Mississippi river basin are shown.

fractions of less than 10% occur, for example, along the Nile in Egypt, in South Africa, in the lower Euphrates–Tigris basin, in Southeast Asia and in Japan. Groundwater fractions of total water withdrawals (Fig. 3d) are rather similar to the groundwater fractions in irrigation, because irrigation is the largest water use sector.

According to our assessment, 42% and 43% of global irrigation water withdrawals and consumptive use, respectively, are from groundwater. This fraction is the highest of all water use sectors (Table 1). As the dominant water use sector irrigation accounts for a larger fraction of consumptive use than of water withdrawals, the groundwater fraction of consumptive water use (global average of 40%) is higher than the groundwater fraction of water withdrawals (global average of 35%, Table 1).

Net abstractions from groundwater NA_g and net abstractions from surface waters NA_s can be positive or negative (Fig. 4). Positive values indicate groundwater or surface water storage losses, whereas negative values indicate storage gains. Groundwater storage can only increase (i.e. NA_g is negative) if there is irrigation in the cell for which water is withdrawn from surface water, as the return flow partly leaches to the groundwater after application (Fig. 1 and Eq. (1)). Surface water storage can only increase (i.e. NA_s is negative) if there are groundwater withdrawals for the domestic, manufacturing or irrigation sectors, because then return flow to surface water is generated (Fig. 1 and Eq. (3)). In this case, however, baseflow from groundwater to surface water is reduced due to decreased groundwater storage. In many areas with high positive NA_g, NA_s is negative, and vice versa. Where significant water withdrawals from both surface water and groundwater occur, NA_g and NA_s are both positive, and groundwater and surface water storage decrease. Examples of regions with high positive NA_s (decreased surface water storage) and negative NA_g (increased groundwater storage) are the Nile in Egypt, the Euphrates–Tigris basin, the lower Indus basin in Pakistan and Southeastern China, where irrigation water use from surface water is dominant (Fig. 4). Examples of areas with high positive NA_g (decreased groundwater storage) and negative NA_s (increased surface water storage) are the High Plains of the central USA, the westernmost part of India (among others the states of Gujarat and Rajasthan) and the North China Plain in northeastern China, where return flows of irrigation water pumped from groundwater may increase surface water flows and storages. Both NA_g and NA_s show high positive values in most of the Ganges basin, Southern India, the Central Valley (California, USA) and in most of Spain.

Globally, NA_g is calculated to be 257 km^3/year while NA_s is 1179 km^3/year, which sum to total CU of 1436 km^3/year (Table 1). NA_g is less than half of total CU from groundwater (571 km^3/year), i.e. the part of the withdrawn groundwater that does not evapotranspire during use, because a large fraction of surface water withdrawals for irrigation recharges the groundwater and thus decreases NA_g (Eq. (1)). In areas without artificial drainage, 80% of return flows in the irrigation sector are assumed to recharge groundwater (Eqs. (1) and (4)).

Continental water storage is affected by water withdrawals at seasonal and longer time scales. The seasonal amplitude of TWS, taking into account human water use (average 1998–2002), is calculated as the difference between the highest and lowest mean monthly value (Fig. 5a). According to WaterGAP, seasonal storage amplitudes of more than 1000 mm occur in the downstream stretches of large rivers such as the Amazon and Lena, and some other grid cells, e.g. in western Canada with very high precipitation. Amplitudes between 250 and 1000 mm occur in regions with high precipitation (e.g. Bangladesh, Amazon basin), and/or with high snow storage in winter (Alps, parts of Siberia and Canada), but also in large rivers like the Yangtze. Seasonal amplitudes of less than 50 mm are found in semi-arid and arid regions. Human water use mostly increases seasonal amplitudes of TWS (Fig. 5b). However, significant increases of more than 10% only occur, according to WaterGAP, in a few semi-arid regions with intensive irrigation, in the High Plains aquifer (USA), the Indus (Pakistan) and upper Ganges (India) basins, in Iran, on the Arabian Peninsula and in Northern China (e.g. Haihe and Tarim River basins).

The reasons for a seasonal amplitude increase are manifold. If irrigation water is withdrawn from surface water during a period with high TWS, an additional return flow to the groundwater due to irrigation by surface water increases TWS (because water is stored longer in groundwater than in rivers), e.g. in the lower Indus or Nile basins (Fig. 5b). If irrigation water is mainly derived from groundwater, seasonal withdrawals during dry periods lead to lower storage minima and thus to increased TWS amplitudes, e.g. in the lower Mississippi basin. Finally, if groundwater depletion occurs, and groundwater storage is constantly decreasing, the difference between the highest and lowest mean monthly values increases, too, just because of impressing a trend on a seasonal variation. This is the case, for example, in the North China Plains and the High Plains aquifer.

In Asia, in particular, there are also some areas where the seasonal amplitude of TWS decreased due to human water use (Fig. 5b). This occurs in particular along large rivers such as the Amu Darya and the Yellow River where surface water use is dominant, and water withdrawals occur during periods of low TWS. Then groundwater storage is increased due to groundwater recharge

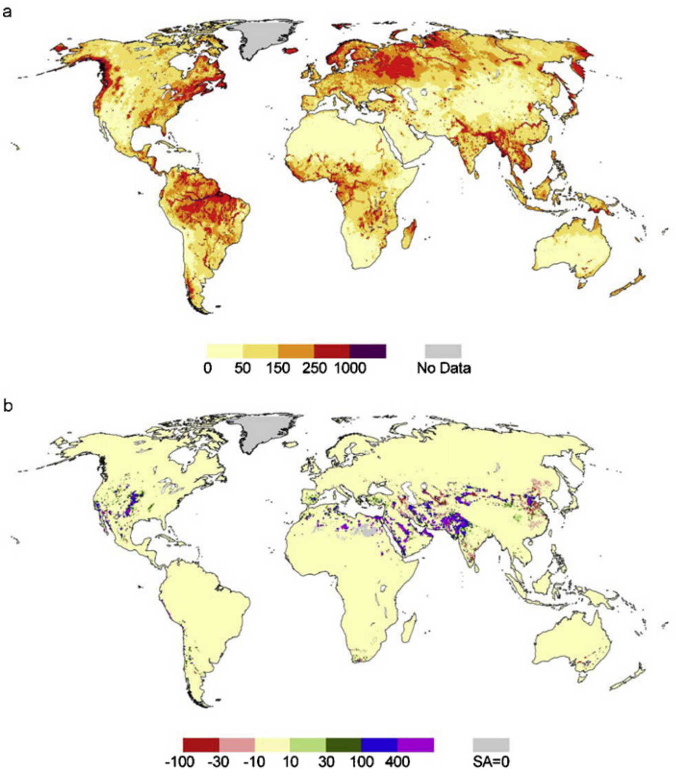

Fig. 5. Impact of human water use on seasonal amplitude (*SA*) of *TWS*. *SA* computed as the grid-cell specific value of maximum mean monthly *TWS* minus minimum mean monthly *TWS*, averaged over 1998–2002, taking into account water withdrawals, in mm (a), and change of *SA* with water withdrawals relative to *SA* without water withdrawals, in percent of *SA* without water withdrawals (b). Positive values indicate that water withdrawals increase *SA*s of *TWS*.

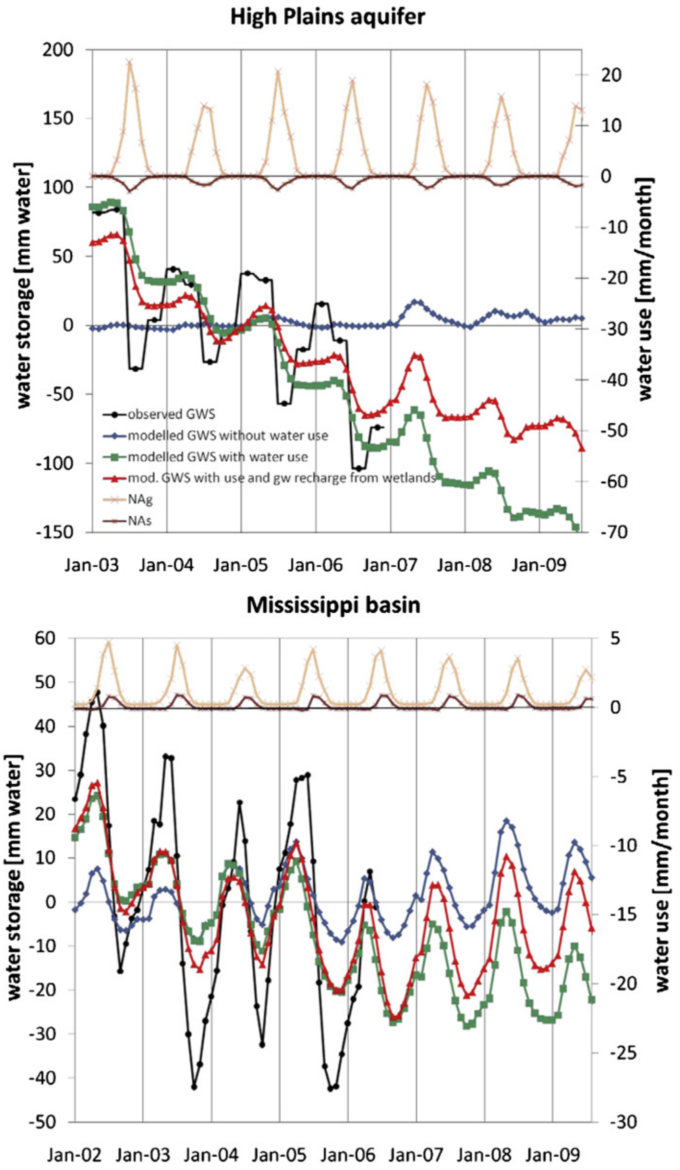

Fig. 6. Modeled monthly groundwater storage (*GWS*) variations as compared with groundwater storage variations derived from well observations, for High Plains aquifer between January 2003 and August 2009 (top), and for the Mississippi basin between January 2002 and August 2009 (bottom). Modeled groundwater storage variations include WaterGAP 2.1h results with and without taking into account human water use, and results with human water use and additional groundwater recharge below local wetlands. All time series were normalized to the average values for the respective periods of *GWS* observation. In addition, basin-average net water abstractions from groundwater (NA_g) and from surface water (NA_s) are shown.

by irrigation return flow, and thus the seasonal amplitude is decreased.

3.2. Evaluation for two selected basins

In this section, we compare modeled groundwater storage (*GWS*) variations to *GWS* variations derived from groundwater well observations and modeled total water storage (*TWS*) variations to *TWS* variations derived from GRACE observations, both for the High Plains aquifer, with very intensive irrigation, and for the entire Mississippi basin (Fig. 4c).

Alkama et al. (2010) compared *TWS* as modeled by the ISBA land surface model with GRACE *TWS* for the western and eastern part of the Mississippi basin (separated at longitude 95 °W). The largest fraction of the western part is covered by the High Plains aquifer (Fig. 4c). Alkama et al. (2010) found that ISBA, which shows a seasonal *TWS* amplitude of only 20 mm (smoothed) in the western part, strongly underestimates the GRACE amplitude, while the fit for the eastern part was good. As a possible reason, they indicated that ISBA does not take into account the impact of water withdrawals and dams on *TWS*.

3.2.1. GWS variations in the High Plains aquifer and the Mississippi basin

Three variants of *GWS* as simulated by WGHM as well as observed *GWS* (Strassberg et al., 2009) are shown in Fig. 6. Observed *GWS* averaged over the whole High Plains aquifer varies seasonally, with the lowest values in July–September and the highest values in January–March (Fig. 6 top). Observed decreases from the January–March period to the April–June period are only small. Regarding the quality of the *GWS* variations that were developed from well observations, Strassberg et al. (2009) noted that “comparison of annual *GWS* changes with the storage changes published by the USGS provides confidence in our analysis of *GWS* changes on interannual time scales. However, seasonal *GWS* anomalies may be overestimated in our analysis, especially summer drawdown. This overestimation could result from bias in sampling locations because many of the wells monitored during the summer season are close to irrigated areas where drawdown is expected.” If temporal variations of water table variations close to wells, with fast reactions to temporal dynamics of groundwater withdrawals, are interpolated to the area between the wells, seasonal amplitude of the spatially averaged *GWS* may be overestimated.

The seasonality of *GWS* as measured by well observations fits to the modeled seasonality of net water abstractions from groundwater, NA_g, which has a maximum in July, with slightly lower values in June and September (Fig. 6 top). About two thirds of the approximately 55 mm of annual NA_g are abstracted during July–September (looking at the four years 2003–2006). NA_s is negative throughout the year due to return flow of withdrawn groundwater to surface water, summing up to about −8 mm/year. A comparison of the consumptive use of about 48 mm/year computed for the High Plains aquifer to estimates of groundwater withdrawals of Maupin and Barber (2005) (53 mm in the year 2000) and McGuire (2009) (50 mm in 2005) suggests that we may overestimate NA_g in the High Plains aquifer. The interannual variability of water use appears to fit well to observe *GWS*. NA_g was relatively low in 2004 due to high precipitation, and different from other years, groundwater storage in the following winter reached the value of the previous winter and did not decline.

Regarding the trend of observed *GWS*, a downward trend can be seen for the four observation years. While *GWS* in July–September decreased from −31 mm in 2003 to −104 mm in 2006, *GWS* in January–March decreased from 82 mm in 2003 to 15 mm in 2006. This is equivalent to an observed decrease of *GWS* of about 23 mm/year. *GWS* computed by WGHM under the assumption that no water withdrawals took place (blue line in Fig. 6 (for interpretation of the references to color in this text, the reader is referred to the web version of the article)) only varies slightly, and not with a seasonal regularity, and there is no decreasing trend during the observation period. This is completely different from observed *GWS*. When WGHM simulates the impact of groundwater and surface water use on *GWS*, the resulting *GWS* time series shows a decreasing trend and stronger seasonality (green line in Fig. 6). However, with −42 mm/year, the modeled trend is almost equal to twice the observed trend, and the observed storage recovery during the fall and winter is not simulated by the model.

Considering the water balance of the groundwater store (Eq. (2)), overestimation of *GWS* loss may be due not only to overestimation of NA_g (which is likely the case here) but also to underestimation of groundwater recharge. In the semi-arid High Plains aquifer, modeled average diffuse groundwater recharge for 2003–2006 is 17 mm/year. According to WGHM, 6% of the High Plains aquifer is covered by surface water bodies, almost all of them local wetlands (wetlands only fed by water generated within the 0.5° grid cell, not by an upstream grid cell). No groundwater recharge is assumed to occur beneath wetlands in WGHM. We tested the effect of additional groundwater recharge under local wetlands by assuming that every day 1% of total water storage in local wetlands recharges the groundwater. With this additional groundwater recharge, the trend decreases to −29 mm/year, closer to the observed trend of −23 mm/year (red line in Fig. 6). However, the observed recovery of *GWS* in fall and winter can be simulated only slightly better with the additional groundwater recharge from local wetlands. The small impact may be due to the fact that in WGHM local wetlands do not always store less water in summer than in fall and winter such that focused groundwater recharge is similar throughout the year.

Regarding the Mississippi basin, area-specific NA_g is 14 mm/year, only about one fourth of the value in the High Plains aquifer, but shows a similar seasonality (Fig. 6 bottom). NA_s is positive from June to September, but is small (1 mm/year). Observed average *GWS* is lowest around October and highest around May. This is very well simulated by WGHM (Fig. 6 bottom). Overall, *GWS* shows a decreasing trend in the first two years, with a minimum seasonal maximum in June 2004. Afterwards, *GWS* recovers slightly in the first half of 2005 (due to the relatively wet year 2004 as reflected by the low NA_g) before decreasing strongly until October 2005 and then not recovering well in the fall and winter of 2006. The overall decreasing trend of observed *GWS* is not mimicked by the WGHM run without water use, but is mimicked by both simulations with water use (Fig. 6 bottom). The simulation with water use and additional focused groundwater recharge from local wetlands (covering about 8% of the Mississippi basin according to WGHM) appears to better represent both the observed interannual variation and seasonality than the simulation with water use but without groundwater recharge from wetlands. Seasonal variations are stronger, while the negative trend is smaller. However, observed seasonality of *GWS* is still 2–3 times larger than the modeled *GWS* (with additional focused recharge).

Thus, for both the High Plains aquifer and the Mississippi basin, WGHM is not capable of reproducing the large seasonal variations even though seasonality is increased appreciably by considering human water use as compared to not taking into account groundwater and surface water withdrawals in the model. In the case of the Mississippi basin, one might argue, that the amplitude of the observed *GWS* would become similar to the modeled amplitude if specific yield of the observation wells were overestimated by a factor of 2–3. Such an overestimation appears to be possible though not very likely. Besides, each observation well represents an average area of 56,400 km^2 (circular area with radius of 134 km) such that very large interpolation errors are expected. In the case of the High Plains aquifer, the many wells considered are unevenly distributed, and they are likely to be located, in many cases, close to pumping wells, which may lead to an overestimation of the seasonal amplitude of *GWS* derived from water table variations (Strassberg et al., 2009).

3.2.2. TWS variations in the High Plains aquifer and the Mississippi basin

Time series of *TWS* as observed by GRACE were compared with modeled *TWS* for the period August 2002–August 2009, for which GRACE data were available (Fig. 7). GRACE data for the High Plains aquifer show a very high month-to-month variability because the High Plains aquifer is relatively small and the relatively weak filter may not remove all noise (Fig. 7 top). Further, the narrow, north–south orientation of the aquifer is not conducive to observations by the polar orbiting GRACE satellites. Comparison of the ITG, GFZ and CSR GRACE solutions indicates that monthly values are highly uncertain as the three solutions differ strongly, often by more than 50 mm water storage (Fig. 7 top). GRACE data shown by Strassberg et al. (2009) for 2003–2006 who used an isotropic filter with a filter radius of 500 km are smoother but show the same overall behavior. Strassberg et al. (2009) estimated that GRACE *TWS* values for the High Plains aquifer have an error of 21 mm from March 2003 onward, and of 35 mm before. During 2003–2006 when observed *GWS* had a downward trend, GRACE *TWS* shows no trend according to Strassberg et al. (2009). Longuevergne et al. (2010), investigating estimation bias and leakage error of GRACE for the High Plains aquifer, determined an overall error of 25 mm. Using data from two GRACE processing centers, they determined a decreasing trend of *TWS* during 2003–2006.

TWS in the High Plains aquifer as modeled by taking into account water withdrawals and groundwater recharge from local wetlands fits quite well to GRACE *TWS* until mid/end of 2006 when both GRACE *TWS* and modeled *TWS* reach a minimum (Fig. 7 top). Afterwards, *TWS* increases in both cases until January 2007 but the ensuing further increase until mid 2007 seen by GRACE is not mimicked by WGHM. The years 2007 and 2008 appear to be wet years as reflected both by WGHM (Figs. 6 and 7) and GRACE *TWS*. While all three GRACE solutions show no trend after mid 2007, modeled *TWS* shows a declining trend. This could indicate that our model overestimates water withdrawals, in particular after 2006, but independent support for this is lacking. Unfortunately, *GWS* storage changes based on groundwater level measurements have not yet been computed for the period after 2006.

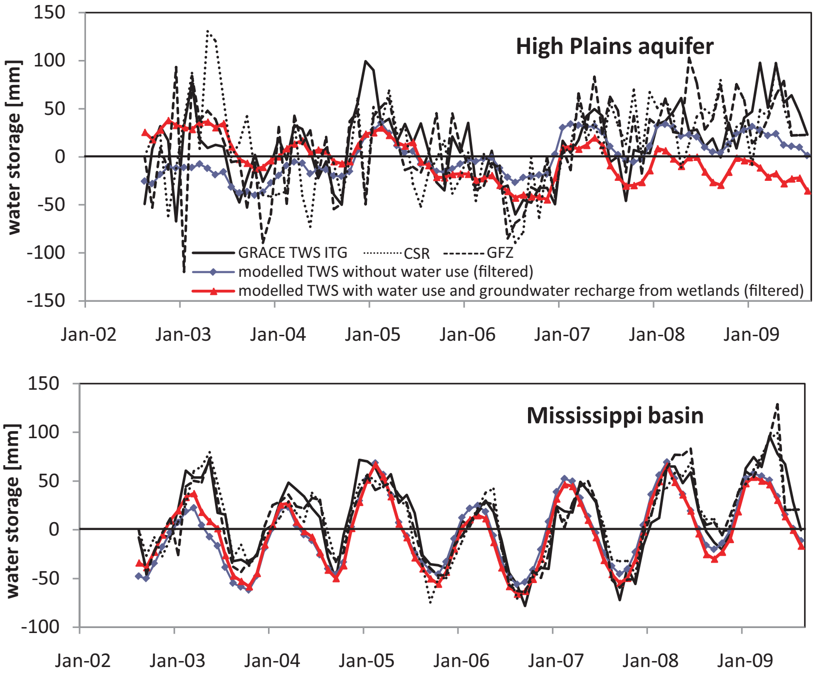

Fig. 7. Modeled monthly total water storage (*TWS*) variations as compared to GRACE satellite observations (ITG, GFZ and CSR solutions) from August 2002 to August 2009, for High Plains aquifer (top), and for the whole Mississippi basin (bottom). Modeled groundwater storage variations include WaterGAP 2.1h results with and without taking into account human water use. All data were smoothed using the non-isotropic DDK3 filter, and normalized to the average values for August 2002–August 2009.

Any negative trend of *TWS* in the High Plains aquifer due to water withdrawals is strongly decreased by filtering, because water withdrawals outside of the aquifer are very small. For the period August 2002–August 2009, the linear trend of −32 mm/year for the unfiltered WGHM *TWS* decreases by a factor of five to only −6 mm/year for the filtered data. The simulation without taking into account any water use leads to the best overall correspondence because GRACE solutions do not show this decreasing trend (Fig. 7 top).

Due to the high uncertainty of the monthly GRACE solutions, it is not clear whether seasonal variability of *TWS* is computed well by WGHM. Compared to monthly soil water anomalies derived from a large number of in situ measurements of soil moisture integrated over the uppermost 2–4 m as provided in Strassberg et al. (2009), seasonal soil moisture variation is strongly underestimated by WGHM (not shown). The difference between modeled minimum and maximum soil moisture (averaged over the High Plains aquifer) is 35 mm during 2003–2006, compared to an observed difference of 100 mm. Besides, the timing of peaks does not fit, and there is higher month-to-month variability of soil moisture in WGHM. One reason for the lower storage variations may be the rooting depth used in WGHM in the High Plains aquifer, which is mostly 1 m (for agricultural land use). The Noah land surface model used in Strassberg et al. (2009) simulated soil moisture in the top 2 m of the soil column. It is unlikely that uncertain precipitation data is the reason for the different estimates of soil moisture variations, as precipitation over the High Plains aquifer that is used in WGHM is similar to the precipitation data shown in Strassberg et al. (2009). The variation of modeled surface water storage (mostly in local wetlands) is about 10 mm during 2003–2006, while snow storage from November to March adds less than 10 mm.

In the much larger Mississippi basin, the difference between the ITG, GFZ and CSR GRACE solutions are rather small (Fig. 7 bottom), and filtering does not affect much both GRACE data and modeled *TWS* very much. In the Mississippi basin, with less intensive water use than in the High Plains aquifer, *TWS* simulated both with and without water use fits well to GRACE *TWS* (Fig. 7 bottom). It is not possible to determine whether simulated water storage with or without water use fits GRACE data better. Net abstractions, with about 3–5 mm/month at the seasonal maximum (Fig. 6 bottom) lead to a slightly increased seasonal amplitude of simulated *TWS* (Fig. 7 bottom) but the impact of water use is less than the discrepancies between GRACE data and model results. Large parts of the Mississippi basin have relatively low human water use (Fig. 4) and are essentially unaffected by changes in seasonal *TWS* amplitudes due to human water use (Fig. 5b), which explains, why averaged over the whole basin, only a small effect of water use was computed.

While WGHM strongly underestimates seasonal *GWS* amplitudes as derived from groundwater table observations, it models seasonal amplitudes of *TWS* as derived from GRACE very well. According to WGHM, seasonal surface water variations are 20–30 mm, comparable to *GWS* variations. Soil water variations account for 40–50 mm. While groundwater and surface water storage peak in March–April, soil water peaks in January–February. Snow storage contributes about 30–40 mm, with a peak in February. In contrast to the behavior of the seasonal amplitudes, the timing of peak *GWS* fits well between modeled and observed data, but there appears to be a shift between modeled and GRACE *TWS*, with later observed peak storage. This may indicate that snowmelt occurs too early in the WGHM simulation.

3.3. *Uncertainties*

When estimating the impact of groundwater and surface water withdrawals on continental water storage variations, major uncertainties stem from quantification of water withdrawals, in particular irrigation water withdrawals. Data on irrigation water use in census publications are mostly modeled or estimated values, as water withdrawals for irrigation are almost never measured. Even in the USA, with a high level of water-related information as compared to other countries, only 16% of wells used for irrigation in 2003 were equipped with meters (Veneman et al., 2004). Thus, to estimate irrigation water withdrawals, we first computed consumptive use as a function of uncertain information on irrigated areas and climatic variables. In particular, in our global approach, temporal changes of irrigated area are only taken into account by changing irrigated area in each grid cell within a country by the same percentage from year to year. Water withdrawals are then determined by dividing computed consumptive use by estimates of irrigation water use efficiency. We assumed that water use efficiencies of groundwater use are the same as those of surface water use. However, we expect higher irrigation efficiencies in the case of groundwater use, as conveyance losses should be less. This would decrease our withdrawal estimates.

Data on water withdrawals by source, i.e. of water withdrawals from groundwater or from surface water, are even scarcer than data on total water withdrawals. In our assessment, we could include subnational data from only three countries that provided sector-specific information on groundwater and surface water withdrawals for domestic and manufacturing use. For seven countries, we had subnational information only on non-sector-specific total groundwater withdrawals, or the domestic and manufacturing sectors were not differentiated. For many countries, IGRAC provides estimates for groundwater withdrawals for the sectors agriculture (includes irrigation and livestock), industry (includes manufacturing and cooling of thermal power plants) and households. However, no data are provided for total sectoral water withdrawals (sum of surface and groundwater withdrawals) by IGRAC. Data on total sectoral water withdrawals from other sources such as FAO AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm), which are required to compute sectoral groundwater fractions, often show values that are clearly inconsistent with withdrawals from IGRAC and may be even larger than total withdrawals from AQUASTAT.

We tested a number of approaches for downscaling groundwater fractions of SSUs to the 0.5° grid cells. Potential predictors tested were (1) aquifer type according to WHYMAP (www.whymap.org), (2) a water scarcity indicator, the mean monthly value of river discharge minus consumptive water use in the month of the year where this difference is at its minimum, (3) percent reservoir or lake area, (4) slope and (5) elevation. The success was mixed. Reasons for groundwater vs. surface water use differ among regions and sectors such that we could not identify a globally applicable approach. Therefore, we think that downscaling with such predictors currently would not lead to meaningful results.

Net water abstractions NA_g and NA_s additionally depend on the storage compartment that receives the return flows of irrigation. Here, we could only make rough assumptions based on the existence of artificial drainage because no data were available. Furthermore, the impact of water withdrawals on water storage variations depends on the other modeled and thus uncertain flows from and to groundwater and surface water, including groundwater recharge. Please note that in WGHM return flows to groundwater are assumed to occur instantaneously, while in reality, the transport of irrigation return flows to groundwater may take a long time, and water storage in the unsaturated zone is increased instead by the return flows (not represented in WGHM).

We estimated the 35% of total global water withdrawals are from groundwater, which is equivalent to about 1500 km^3/year during the period 1998–2000. This is twice the amount that was estimated by Wada et al. (2010). However, Wada et al. (2010) used more limited information than we did to determine groundwater withdrawals. They relied exclusively on estimates of total, i.e. not-sector-specific groundwater withdrawals by country as collected by IGRAC. No groundwater withdrawals were taken into account for North Korea, Afghanistan, Sri Lanka, Colombia and for several central African countries due to lack of data in the IGRAC database (Wada et al., 2010), but this alone cannot explain the large underestimation as compared to our estimate.

4. Conclusions

We developed a first time series of sector-specific groundwater and surface water withdrawals and consumptive uses at the global scale (spatial resolution 0.5°), assuming temporally invariant fractions of total withdrawals. Based on this, we computed, for each grid cell, net abstractions from groundwater and from surface water. These net abstractions indicate, for the first time at the global scale, where and when human water withdrawals decrease or increase groundwater or surface water storage. With 35% of total water withdrawals, groundwater withdrawals worldwide were estimated to reach approx. 1500 km^3/year during the period 1998–2002, which is twice the amount of Wada et al. (2010) who used more limited statistical information than we did in this study. Net abstraction from groundwater is computed to be only 250 km^3/year, because not only part of the withdrawn groundwater but also part of the withdrawn surface water recharges groundwater due to irrigation return flow. To assess groundwater depletion, net abstractions of groundwater (and not groundwater withdrawals) have to be compared to groundwater recharge. While global surface water withdrawals (2800 km^3/year) are almost twice as high as groundwater withdrawals, net abstraction of surface water (1200 km^3/year) is almost five times as high as net abstraction of groundwater.

The impact of water withdrawals on continental storage variations is significant in semi-arid and arid regions with intensive irrigation. There, seasonal amplitudes of total water storage (*TWS*) mainly increase due to irrigation, in particular if the dominant water source is groundwater. A long-term decline of groundwater storage is modeled in some regions. Seasonal amplitudes of *TWS* were shown to decrease in a few areas where surface water use is dominant and water withdrawals during periods of low water storage result in increased groundwater storage due to return flows of irrigation water.

WaterGAP possibly overestimates withdrawals and net abstraction of groundwater for irrigation in the High Plains aquifer. For the time period 2003–2006, modeled groundwater storage (*GWS*) shows a trend of −42 mm/year (model variant without recharge beneath wetlands) or −29 mm/year (model variant with focused recharge beneath wetlands), while −23 mm/year are derived from groundwater well observations. The timing of modeled net abstractions of groundwater fits well to observed *GWS* variations. It is not possible to judge the quality of modeled seasonal amplitudes of *GWS* variations because *GWS* estimates based on well observations may overestimate spatially averaged *GWS* variations, e.g. due to observation wells being close to pumping wells. Modeled *TWS* fits to GRACE *TWS* from 2002 to 2007, but the model underestimates *TWS* in 2008–2009. Based on GRACE *TWS* only, we would not be able to conclude that significant water withdrawals that affect water storage occurred in the High Plains aquifer. This was only possible on the basis of observed groundwater levels. Whether the GRACE data for the High Plains aquifer indicate a recent decrease in groundwater withdrawals remains to be seen.

For the entire Mississippi basin, WaterGAP *TWS* variations are similar to GRACE *TWS* variations and show approximately the same seasonal amplitudes. As in the High Plains aquifer, WaterGAP appears to underestimate *GWS* variations, at least compared to *GWS* variations that were derived from groundwater levels measured in only 58 monitoring wells. While water withdrawals strongly affect *GWS* and *TWS* in the High Plains aquifer, only *GWS* is affected appreciably in the less intensively irrigated Mississippi basin. Therefore, water withdrawals at the scale of the entire Mississippi basin could not be monitored by GRACE.

Currently, it does not seem possible to quantify the historic development of the fractions of groundwater and surface water withdrawals. Assessment of the impact of groundwater and surface water withdrawals on continental water storage variations will be continued. We will analyze long-term developments including groundwater depletion globally, and we aim to determine under what conditions GRACE can be used for monitoring water withdrawals. To significantly reduce the uncertainties of such a global assessment, improved data on groundwater and surface water use would be needed. This requires national agencies to collect water use data by sector and source in a consistent manner, with subnational resolution. In addition, improved accuracy of GRACE data would be very helpful. Furthermore, analyses of the impact of water withdrawals from groundwater and surface water on river discharge are planned for the future.

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Appendix A. Estimation of groundwater fractions of domestic and manufacturing water withdrawals

To generate the global data set of groundwater fractions of domestic and manufacturing water withdrawals, data on the national level and the subnational level were combined for a total of 196 countries or territorial units used in the WaterGAP model. We first describe the procedure for countries with subnational data.

A.1. Estimation for countries with subnational data on groundwater withdrawals

For 10 countries, subnational data were available on groundwater and total water withdrawals: Australia (8 states and capital territory, for the year 2004, from Australian Bureau of Statistics), Canada (13 provinces, domestic for 1996 and manufacturing between 1999 and 2002, various sources), China (including Hong Kong and Taiwan, in total 33 provinces or Special Administrative Regions, for 2005, National Bureau of Statistics of China), Germany (16 federal states, domestic for 2004 and manufacturing for 2007, Statistisches Bundesamt), India (30 states or Union Territories, for 2004, Ministry of Water Resources of India/Central Ground Water Board), Mexico (2463 units on the level of “municípios”, averages 2005–2007, Comisión Nacional del Agua), New Zealand (14 regions, for 2000, Statistics New Zealand), Russian Federation (11 river basins, for 2005, ROSSTAT), Ukraine (25 oblasts, averages 2000–2006), USA (3139 units on the level of counties, for 2000, United States Geological Survey).

For 3 of the 10 countries (USA, Mexico, and Germany), information on sector-specific withdrawals by source were available, while for the other countries, only data on total groundwater withdrawals and total withdrawals were available for the subnational units. For the other 7 countries with subnational data, the procedure was as follows. For Australia, data on non-sector-specific groundwater and total water withdrawals were available. For Canada, groundwater withdrawal fractions for domestic use were available from the Municipal Use Database (MUD) for 1996, based on data of communities above 1000 inhabitants. The fractions for manufacturing were calculated based on percentages of withdrawal with respect to total groundwater withdrawal, available for different industries for each province between 1999 and 2005, from sources mentioned in a national report of 2004, combined with total groundwater withdrawal from another source and manufacturing withdrawal from WaterGAP. For China, provincial non-sector-specific groundwater and total water withdrawal were used. As no withdrawal data were available for the units Hong Kong and Taiwan Province of China, their fractions were estimated from the neighboring provinces Guangdong (Hong Kong) and Fujian (Taiwan), leading to eventually 33 considered units. For India, groundwater withdrawals for domestic and industry were not distinguished, such that only data on total groundwater withdrawals could be taken into account. We assumed that the groundwater fractions for domestic and manufacturing uses were the same, and used total (surface and groundwater) withdrawals in the domestic and manufacturing sectors as computed by WaterGAP. For New Zealand, for domestic uses, groundwater and total water were available. For manufacturing, national-level data on IGRAC sectoral percentage share of groundwater use and total groundwater withdrawal, and WaterGAP sectoral water withdrawal were used. For the Russian Federation, non-sector-specific groundwater withdrawals and total water withdrawals for 11 hydrographic basins were available. For two of these basins that are included in WaterGAP but not in the publication, the average groundwater withdrawal fraction was applied. For the Ukraine, for 25 oblasts, average 2000–2006 values on non-sector-specific groundwater withdrawal and total water withdrawal of a tabular statistical source were used to calculate the groundwater withdrawal fraction. As no irrigation water withdrawal from groundwater exists according to Siebert et al. (2010), the sectoral total water withdrawals from the same source was used to calculate a common groundwater withdrawal fraction valid for both domestic use and manufacturing.

The subnational withdrawal values were then upscaled or downscaled through area-averaged polygon shares to WaterGAP 0.5° grid cells belonging to the considered country. Final groundwater fractions were then calculated for each grid cell. When due to differences in geometry no intersection occurred, grid cells with missing values obtained the values of the nearest Euclidean distance neighbor cell.

A.2. Estimation for countries with national data only

For 20 out of the 186 national units, directly usable data of domestic and manufacturing/industrial groundwater and total water withdrawals were available either from international reports, national reports, or from estimates by experts (personal communication). In some of these cases the f_g-values were set to zero because of zero sectoral water withdrawal or zero total groundwater withdrawal.

For 66 countries, groundwater use fractions for domestic use f_{g_dom} were calculated from IGRAC data as follows. IGRAC domestic fraction of total groundwater withdrawals fgw_{dom} was applied to IGRAC total groundwater withdrawal WU_{g_tot} to get absolute domestic groundwater withdrawal. This sum was then divided by the domestic water withdrawal as computed by WaterGAP, such that

$$f_{g\_dom} = \frac{fgw_{dom} WU_{g\_tot}}{WU_{dom}} \tag{A1}$$

with *fgw*: fraction of (sectoral) groundwater withdrawal use with respect to total groundwater use from IGRAC, *WU*: water withdrawals, and subscripts *g*: groundwater, *dom*: domestic use.

The calculation of groundwater use fractions for manufacturing f_{g_man} could not follow the same procedure for these countries, as the IGRAC industrial fraction of groundwater withdrawal fgw_{ind} includes use for cooling of thermal power plants. First, the groundwater fraction for industrial use f_{g_ind} was calculated from the fraction of total groundwater withdrawals for industry as follows:

$$f_{g\_ind} = \frac{fgw_{ind} WU_{g\_tot}}{(WU_t + WU_{man})} \qquad (A2)$$

with subscripts *ind*: industry, *tot*: total water withdrawal over all sectors (irrigation, domestic, manufacturing, livestock, thermal power plants, manufacturing), *t*: thermal power plants, *man*: manufacturing. Then, the groundwater use fraction of manufacturing f_{g_man} was calculated using the assumption that only surface water is used for cooling of thermal power plants:

$$WU_{g\_man} = f_{g\_ind}(WU_t + WU_{man}) \qquad (A3)$$

Substituting $f_{g\_man} = WU_{g\_man}/WU_{man}$ in Eq. (A3) results in

$$f_{g\_man} = f_{g\_ind}(WU_t + WU_{man})/WU_{man} \qquad (A4)$$

This procedure was successfully applied to 53 countries. In 13 countries, the inconsistencies in data sources of sectoral groundwater and sectoral total water withdrawals would have led to groundwater fractions larger than 1, and the groundwater fraction for manufacturing f_{g_man} was set to that of domestic use f_{g_dom}.

When no sectoral fractions of total groundwater withdrawal were available from IGRAC, then a common groundwater use fraction f_g for both domestic and manufacturing uses was calculated if a non-sector-specific total groundwater use fraction f_{g_tot} or total groundwater withdrawals were available. Using water withdrawals from groundwater from irrigation (WU_{g_i}) as computed by multiplying total WaterGAP irrigation water withdrawals by groundwater fractions for irrigation according to Siebert et al. (2010), f_{g_man} was computed as

$$f_{g\_man} = f_{g\_dom} = (f_{g\_tot} WU_{tot} + WU_{g\_i})/(WU_m + WU_d) \qquad (A5)$$

This procedure was successfully applied to another 19 countries.

In further 26 countries, the above estimation procedures failed, e.g. when calculated groundwater withdrawal for irrigation was larger than reported total groundwater withdrawal. Then, the groundwater use fractions f_g for both domestic and manufacturing uses were set to f_{g_tot}. In the special sub-case of Barbados, f_{g_man} was set to zero because f_{g_ind} was zero.

For the final 55 countries without any information on groundwater withdrawals, both groundwater use fractions were drawn from neighboring countries with reliable information. Most estimates were made in Africa (16 units), America (13), and Asia (8), but only two in Europe (Faeroe Islands and Luxembourg). For 14 small islands, census data of US Virgin Islands (10 units) or American Samoa (4) were regionally applied. We assumed that there are no groundwater withdrawals in Greenland (due to permafrost) and the Falkland Islands. The national groundwater fractions were attributed without any downscaling to WaterGAP grid cells belonging to the considered country.

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