

Global modeling of withdrawal, allocation and consumptive use

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Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources

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Abstract

To sustain growing food demand and increasing standard of living, global water withdrawal and consumptive water use have been increasing rapidly. To analyze the human perturbation on water resources consistently over a large scale, a number of macro-scale hydrological models (MHMs) have been developed over the recent decades. However, few models consider the feedback between water availability and water demand, and even fewer models explicitly incorporate water allocation from surface water and groundwater resources. Here, we integrate a global water demand model into a global water balance model, and simulate water withdrawal and consumptive water use over the period 1979–2010, considering water allocation from surface water and groundwater resources and explicitly taking into account feedbacks between supply and demand, using two re-analysis products: ERA-Interim and MERRA. We implement an irrigation water scheme, which works dynamically with daily surface and soil water balance, and include a newly available extensive reservoir data set. Simulated surface water and groundwater withdrawal show generally good agreement with available reported national and sub-national statistics. The results show a consistent increase in both surface water and groundwater use worldwide, but groundwater use has been increasing more rapidly than surface water use since the 1990s. Human impacts on terrestrial water storage (TWS) signals are evident, altering the seasonal and inter-annual variability. The alteration is particularly large over the heavily regulated basins such as the Colorado and the Columbia, and over the major irrigated basins such as the Mississippi, the Indus, and the Ganges. Including human water use generally improves the correlation of simulated TWS anomalies with those of the GRACE observations.

1 Introduction

In 1900, global population was less than 1.7 billion, but grew by more than 4 times during the 20th century, currently exceeding 7 billion. To sustain growing food demand

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globally the reduction of river discharge by human water consumption. Hanasaki et al. (2008a,b) and Pokhrel et al. (2012) developed respectively the H08 (1°) and MAT-SIRO (1°) which incorporate the anthropogenic effects (e.g. irrigation, reservoir regulation) into global surface water balance model. Wada et al. (2011a,b) used the PCR-GLOBWB model (0.5°) to calculate the surface water balance and sectoral water demand, and incorporated groundwater abstraction at the global scale. However, these models generally calculate water demand independent of water availability, i.e. there is no feedback between water availability and water demand, and equate water demand with either water withdrawal or consumptive water use (Döll and Siebert, 2002; Wisser et al., 2010; Wada et al., 2011b). In addition, water allocation or water use per source, e.g. surface water and groundwater, has rarely been explicitly incorporated in the simulation.

Here, we integrate the global water demand model developed by Wada et al. (2011a,b) into the global water balance model PCR-GLOBWB (Wada et al., 2010; Van Beek et al., 2011) to simulate water withdrawal use and consumptive water use considering water allocation from surface water and groundwater resources and explicitly taking into account feedbacks between supply and demand. We implement a new irrigation water scheme, which works dynamically with daily surface and soil water balance, and include a newly available extensive reservoir data set. In addition, we use the newly available climate datasets of the ERA-Interim re-analysis data and the MERRA re-analysis product over the period 1979–2010 that extends beyond most global analyses. Thus, the objective of this paper is to develop a global hydrological and integrated water use model, and to evaluate the performance of the integrated modeling approach.

Section 2 of this paper presents the modeling framework which includes the calculation of water balance, irrigation and other sectoral water demand, routing and surface water retention, and water allocation and return flow. Section 3 explains the simulation protocol. Section 4 presents the results and evaluates the performance by comparing

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as the height of the groundwater storage over the storage coefficient on top of the streambed elevation and the sub-grid distribution of elevation). Groundwater storage is fed by groundwater recharge and drained by a reservoir coefficient that includes information on lithology and topography (e.g. hydraulic conductivity of the subsoil). The ensuing capillary rise is calculated as the upward moisture flux that can be sustained when an upward gradient exists and the moisture content of the soil is below field capacity. Also, it cannot exceed the available storage in the underlying groundwater reservoir.

2.2 Snow accumulation and melt

Snow accumulation and melt are temperature driven and modeled according to the snow module of the HBV model (Bergström, 1995). To represent rain-snow transition over sub-grid elevation dependent gradients of temperature, 10 elevation zones was made on each grid cell based on the HYDRO1k Elevation Derivative Database, and scaled the 0.5° grid temperate fields with a lapse rate of 0.65°C per 100 m (Wada et al., 2012b, 2013). Over the 10 elevation zones, precipitation accumulates as snow if the temperature, T , is below the melt temperature (0°C), T_m . The snowmelt [m], SC_m , is then modeled using a degree day factor [$\text{m}^\circ\text{C}^{-1}\text{day}^{-1}$], f_d :

$$SC_m = f_d (T - T_m). \quad (1)$$

Above the melt temperature precipitation and meltwater are stored as liquid water in the available pore space in the snow cover. Meltwater in the snow cover can refreeze depending on the water holding capacity of the snow (10 % of snow water equivalent). Excess water from snowmelt and rainfall forms direct runoff or infiltrates into the first soil layer, which can further infiltrates into the second soil layer and percolates into the third groundwater reservoir.

2.3 Irrigation water requirement

Previous studies used various method simulating irrigation water requirement (IWR) as shown in Table 1. In this study, IWR including evaporative and percolation losses per unit crop area was estimated by simulating the daily soil and surface water balance with crop-related data. Crop-specific calendars and growing season lengths were obtained from the MIRCA2000 data set (Portmann et al., 2010), which accounts for various growing seasons of different crops and regional cropping practices under different climatic conditions, and distinguishes up to nine sub-crops that represent multi-cropping systems in different seasons in different areas per grid cell. The corresponding crop coefficient per crop development stage and maximum crop rooting depth were additionally obtained from the Global Crop Water Model (Siebert and Döll, 2010). Although the MIRCA2000 data set considers 26 crop classes, we aggregated these to paddy and non-paddy crop classes since distinct flooding irrigation is applied over most of paddy fields. The crop-specific data were aggregated by weighing the area of each crop class.

Daily (potential) crop evapotranspiration [m d^{-1}], ET_c , was calculated combining a crop coefficient [dimensionless], k_c , that accounts for crop-specific transpiration and bare soil evaporation over the surface, with reference (potential) evapotranspiration [m d^{-1}], ET_0 , computed by the Penman–Monteith equation according to FAO guidelines (Doorenbos and Pruitt, 1977; Allen et al., 1998):

$$ET_c = k_c ET_0. \quad (2)$$

Irrigation water [m d^{-1}] was applied over the paddy, IWR_{paddy} , and non-paddy, IWR_{nonpaddy} , fields to ensure optimal crop growth. To represent flooding irrigation over the paddy fields, we maintained a 50 mm surface water depth, S_{max} (Wisser et al., 2008, 2010) until the late crop development stage (~ 20 days) before the harvest:

$$IWR_{\text{paddy}} = S_{\text{max}} - (S_{0,t-1} + P_{\text{net}}) \quad (3)$$

$$S_0 = S_{0,t-1} + P_{\text{net}} + IWR_{\text{paddy}} - \text{Inf}_{S_0 \rightarrow S_1} - EW_{S_0} \quad (4)$$

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economic development (Wada et al., 2011a). Technological development was then approximated by energy consumption per unit electricity production, which accounts for industrial restructuring or improved water use efficiency. Water recycling was calculated per country according to the method developed by Wada et al. (2011b), who interpolated recycling ratios on the basis of GDP and the level of economic development, i.e. high income (80 %), middle income (65 %), and low income economies (40%). The ratio was kept at 80 % if a country reached the high income economy, and the ratio of 40 % was assigned to countries with no GDP data.

Household water demand was estimated multiplying the number of persons in a grid cell with the country-specific per capita domestic water withdrawal. The daily course of household water demand was estimated using daily air temperature as a proxy (Wada et al., 2011a). The country per capita domestic water withdrawals in 2000 were taken from the FAO AQUASTAT data base (<http://www.fao.org/nr/water/aquastat/main/index.stm>) and Gleick et al. (2009), which were multiplied with water use intensities to account for economic and technological development. Available gridded global population maps per decade (Klein Goldewijk and van Drecht, 2006) were used to downscale the yearly country population data (FAOSTAT) to produce gridded population maps for each year. Return flow to the river system occurs from the areas where urban and rural population have access to water (UNEP; <http://www.unep.org/>) at the recycling ratios developed per country on the same day as the water is withdrawn.

2.5 Routing and surface water retention

The simulated local direct runoff, interflow, and baseflow were routed along the river network based on the Simulated Topological Networks (STN30; Vörösmarty et al., 2000a). The routing is based on the characteristic distances, R_{cd} :

$$R_{cd} = \frac{bz}{b + 2z}^{2/3} \times \frac{G^{0.5}}{n} \quad (9)$$

where b and z are the channel width and channel depth respectively [m], G is the gradient derived from the elevation and the drainage network, and n is the Manning's roughness coefficient.

Reservoirs are located on the river network based on the newly available and extensive Global Reservoir and Dams Dataset (GRaND) (Lehner et al., 2011) that contains 6862 reservoirs with a total storage capacity of 6197 km³. If more than one reservoir fell into the same grid cell, we aggregated the storage capacities and modeled a single reservoir. In case no reported value was available, reservoir surface area [m²], A , was calculated using the storage volume (V) – reservoir depth (h) relationship (Campos, 2010):

$$V(h) = \alpha h^3 \quad (10)$$

$$A(h) = \frac{dV(h)}{dh} = 3\alpha h^2 \quad (11)$$

where α is the reservoir specific shape factor [dimensionless], computed from the reported dam height and the reported storage capacity or S_{\max} .

Similar to Hanasaki et al. (2006), reservoir release was simulated to satisfy local and downstream water demands that could be reached within ~ 600 km (\sim a week with an average discharge velocity of 1 m s⁻¹) or a next downstream reservoir if present. In case of no water demand, the reservoir release [m³ day⁻¹], R_r , was simulated as a function of minimum, S_{\min} (set to $\sim 10\%$ of storage capacity), maximum, S_{\max} (set to $\sim 100\%$ of storage capacity), and actual reservoir storage [all in m³], S_r , and mean average inflow [m³ day⁻¹], I_{avg} :

$$R_r = \frac{S_r - S_{\min}}{S_{\max} - S_{\min}} \times I_{\text{avg}} \quad (12)$$

$$S_{r,t} = \max(S_{\max}, S_{r,t-1} + I + P_{\text{local}} - R_r - EW_r) \quad (13)$$

where I is the inflow to the reservoir, P_{local} is the local precipitation over the reservoir surface, and EW_r is the open water evaporation from the reservoir surface, assumed

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to occur at a rate of potential evapotranspiration [all in m^3]. The reservoir spill occurs when the reservoir storage exceeds the maximum reservoir storage.

2.6 Water allocation and return flow

Water demand for irrigation, livestock, industry, and household can be met from three water resources; (1) surface water, (2) groundwater, and/or (3) desalination. Country desalination water withdrawal use was taken from the FAO AQUASTAT database and the WRI EarthTrends (<http://www.wri.org/project/earthtrends/>) (global total $\approx 15 \text{ km}^3 \text{ yr}^{-1}$), and was downscaled onto a global coastal ribbon of around 40 km based on gridded population intensities (Wada et al., 2011b). Daily desalinated water withdrawal use was kept at constant over the year.

Allocation of surface water and groundwater to satisfy the remaining water demand (after subtracting desalinated water withdrawal use) depends on available surface water, and local and upstream reservoirs, and readily extractable groundwater reserves. Since the absolute amount of available groundwater resources is not known at the global scale, we used the simulated baseflow [$\text{m}^3 \text{ day}^{-1}$], Q_{base} , against the long-term average river discharge [$\text{m}^3 \text{ day}^{-1}$], Q_{avg} , as a proxy to infer the readily available amount of groundwater reserves [$\text{m}^3 \text{ day}^{-1}$], WA_{gw} .

$$WA_{\text{gw}} = \frac{Q_{\text{base}}}{Q_{\text{avg}}} \times WD_{\text{tot}} \quad (14)$$

WA_{gw} was then extracted from groundwater storage [$\text{m}^3 \text{ day}^{-1}$], S_3 , to meet part of the water demand [$\text{m}^3 \text{ day}^{-1}$], WD_{tot} . The remaining water demand was then withdrawn from the simulated surface water. However, in case reservoirs are present at local and upstream grid cells, we first allocated surface water predominantly to meet the water demand, and the remaining water demand was met from available groundwater storage or S_3 .

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3 Model simulation

To simulate global water use, i.e. water withdrawal and consumptive water use, we obtained daily climate drivers (e.g. precipitation and mean air temperature) over the period 1979–2010. We retrieved the data from the ERA-Interim reanalysis, where the precipitation was corrected with GPCP precipitation (GPCP: Global Precipitation Climatology Project; <http://www.gewex.org/gpcp.html>) (Dee et al., 2011). To account for climate uncertainty, we also retrieved the data from the MERRA reanalysis product (available at <http://gmao.gsfc.nasa.gov/merra>). Over the same period, we calculated reference evapotranspiration based on the Penman-Monteith equation according to FAO guidelines for a hypothetical grass surface with a specified height of 0.12 m, an albedo of 0.23, and a surface resistance of 70 s m^{-1} (Allen et al., 1998) with relevant climate fields (e.g. cloud cover, vapor pressure, wind speed) retrieved from the ERA-Interim and MERRA datasets. For compatibility with our overall analysis, we bias-corrected these datasets, i.e. precipitation, reference evapotranspiration, and temperature, by scaling the long-term monthly means of these fields to those of the CRU TS 2.1 data set (Mitchell and Jones, 2005) over the overlapping period (1979–2001), wherever at least two CRU stations are present. Otherwise the original ERA-Interim and MERRA data were returned by default.

4 Results

To evaluate our modeling approach, we first compared our simulated water use to available reported national and sub-national statistics. Since simulated river discharge, total water withdrawal and total consumptive water use have been extensively validated in earlier work (Van Beek et al., 2011; Wada et al., 2011a, 2012a), we, here, focus on validating simulated water withdrawal per source, i.e. surface water withdrawal and groundwater withdrawal, to assess our water allocation scheme. Reported statistics on consumptive water use per water source rarely exists even at a national or sub-national

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level. After the validation, we provide a regional overview of water withdrawal and consumptive water use trends over the period 1979–2010. We then compare our simulated terrestrial water storage (TWS) anomalies with those of the GRACE observations over the period 2003–2010 to assess the impacts of human water use and associated reservoir operations on TWS over the selected catchments.

4.1 Accuracy of simulated irrigation water requirement (IWR)

Figure 1 compares per country our simulated IWR with reported statistics obtained from the FAO AQUASTAT database. IWR was simulated with the CRU TS 2.1, ERA-Interim and MERRA climate respectively. Table 2 shows the correlation between the simulated IWR and reported statistics per country. The results show generally good agreement with R^2 (the coefficient of determination) above 0.95 (p value < 0.001). Our estimates are also comparable to those of previous studies as shown in Table 1. With the CRU TS 2.1 climate, our model tends to overestimate IWR including that in India, the USA, China, Pakistan, and Iran. With the ERA-Interim and MERRA climate, we slightly overestimate IWR, but the magnitude is less compared to that of the CRU TS 2.1 climate. With the ERA-Interim climate, IWR is generally overestimated over South and East Asia, e.g. India, Pakistan, China, Japan, and is underestimated over Europe, Africa, and South America, e.g. Spain, France, Germany, Egypt, South Africa, Brazil, Argentina. With the MERRA climate, the overestimation is less obvious due to the wetter climate compared to the CRU TS 2.1 and ERA-Interim climate, and our simulated IWR is rather underestimated over many regions, e.g. Europe, Africa, Asia except East Asia, North America. When we use the average of the two or the three simulated IWRs, the correlation generally improves and the deviation between the simulated and reported values decreases. We thus used the average of the two simulated results with the ERA-Interim and MERRA climate for the following analysis.

4.2 Accuracy of simulated surface water and groundwater withdrawal

Figure 2 and Table 3 shows the comparison of our simulated water use per water source, i.e. surface water and groundwater withdrawal, to reported country and state values for the year 2005 over the globe and for Europe, the USA, and Mexico. The comparison shows good agreement for both surface water and groundwater withdrawal over the Globe ($R^2 \geq 0.96$, p value < 0.001). However, our model tends to overestimate surface water withdrawal over South, Central, and East Asia ($\approx +30\%$), and tends to underestimate it over Southeast Asia and Africa ($\approx -20\%$). Simulated groundwater withdrawal shows good agreement with reported value over most of the regions of the world except Africa where the deviation is rather large ($\approx \pm 30\%$). Over Europe, the comparison shows reasonable agreement for surface water withdrawal and groundwater use with R^2 above 0.93 (p value < 0.001). However, our simulated surface water withdrawal is generally overestimated with α (the slope of regression line) being 0.85. Conversely, our simulated groundwater withdrawal is underestimated ($\alpha = 1.08$). The overestimation of surface water withdrawal and the underestimation of groundwater withdrawal is large for the UK, and Central and Eastern Europe ($> \pm 20\%$) respectively. Over the conterminous USA and Mexico, the correlation is lower ($R^2 < 0.9$, p value < 0.001) compared to that over the Global average and Europe, although regional variations of surface water and groundwater withdrawal are captured reasonably well. Our model generally overestimates both surface water and groundwater withdrawal for Central and Eastern USA, whereas the deviation between the simulated and reported water use is smaller over Western USA. For Mexico, the comparison shows a contrasted trend compared to that of Europe in which surface water withdrawal is underestimated, but groundwater withdrawal is overestimated over North and South Mexico.

In Fig. 3 we compare simulated and reported trends of groundwater withdrawal per country over the period 1980–2005 when the statistics are available. The comparison for 19 countries indicates that our scheme is able to capture the decadal trends of

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groundwater withdrawal ($R^2 > 0.95$, p value < 0.001). However, the deviation is large for several countries including Spain, Poland, Austria, where the partitioning between surface water and groundwater withdrawal represented by our scheme needs further consideration or adjustment.

4.3 Regional trends of surface water and groundwater withdrawal and consumption

In Figs. 4 and 5 we provide a regional overview of desalination water, surface water and groundwater withdrawal and consumption over the period 1979–2010. Global water withdrawal and consumptive water use respectively increased from $\sim 2000 \text{ km}^3 \text{ yr}^{-1}$ and $\sim 1000 \text{ km}^3 \text{ yr}^{-1}$ in 1979 to $\sim 3300 \text{ km}^3 \text{ yr}^{-1}$ and $\sim 1500 \text{ km}^3 \text{ yr}^{-1}$ in 2010. This increase is primarily driven by increase in the agricultural sector, (mostly irrigation), accounting for as much as $\sim 80\%$ of the total. Most of industrial and domestic water that is withdrawn from surface water and groundwater returns to river systems (40–80%). Surface water and groundwater withdrawal increased respectively from ~ 1350 and $\sim 650 \text{ km}^3 \text{ yr}^{-1}$ in 1979 to ~ 2100 and $\sim 1200 \text{ km}^3 \text{ yr}^{-1}$ in 2010. During the period 1979–1990, groundwater withdrawal increased by $\sim 1\%$ per year, while surface water use rose by $\sim 2\%$ per year. However, during the recent period 1990–2010, the rate of groundwater withdrawal increased to $\sim 3\%$ per year, while that of surface water use decreased to $\sim 1\%$. This is likely due to the fact that surface water has been extensively exploited in response to the consistent increase of global water demand, while the construction of new (large) reservoirs has been decreasing since the 1990s (Chao et al., 2008). The results suggest that the net increase in the demand has been mostly supplemented by groundwater withdrawal. These trends can also be seen from the global change in consumptive water use during the period 1979–2010. Siebert et al. (2010), Kummu et al. (2010), and Wada et al. (2012a) also report an increasing dependency of consumptive water use on groundwater resources in recent decades.

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groundwater storage and reservoir operation releasing more water during the low flow period. This subsequently improves R^2 (between the simulated and observed TWS) from 0.75 to 0.80 (p value < 0.001) for the Columbia, but not for the Colorado where R^2 does not change substantially (~ 0.65 , p value < 0.001). Over the Mississippi and the Nile basin, human water use, primarily for irrigation, decreases the peak TWS. This is less obvious for the Nile basin where negative groundwater storage change is compensated by return flow from surface water irrigation. Döll et al. (2012) also describe similar trends of TWS changes over these basins. R^2 slightly improves from 0.73 to 0.76 (p value < 0.001) for the Mississippi basin and from 0.74 to 0.76 (p value < 0.001) for the Nile basin when incorporating human water use. The impact of human water use is obvious over the Indus basin where irrigation water use exceeds more than 90 % of the total. Observed seasonal TWS change exhibits very different trends over the years, which are captured reasonably well by our model. Over the Ganges basin, contrary to the other basins, human water use increases the seasonal amplitude of TWS change. This is due to the fact that the low flow periods coincide with the growing season of irrigated crops (Spring) which require large amounts of water. Irrigation water use thus decreases both surface water and groundwater storage during the low flow season. This improves R^2 from 0.85 to 0.90 (p value < 0.001) for the Ganges basin. Over the Syr Darya and the Euphrates basin, similar to most of the basins, human water use decreases the seasonal amplitude of TWS change, but does not substantially improve the correlation between the simulated and observed TWS.

5 Discussion and conclusions

In this study, we integrated a global water demand model into a global hydrological model, and simulated water use, i.e. water withdrawal and consumptive water use, considering water allocation from surface water and groundwater resources. We implemented a new irrigation water scheme, which works with daily surface and soil water balance, and included a newly available extensive reservoir data set. To simulate global

water use, we used the newly available climate datasets of the ERA-Interim re-analysis data and the MERRA re-analysis product over the period 1979–2010. The simulation period extended beyond most previous global analyses and the results provided new insights of the trends in global surface water and groundwater use over the recent decades.

To evaluate simulated water withdrawal, we compared our results with available reported statistics. Comparison of simulated IWR to reported statistics showed good agreement for most of the countries of the world. Although our model tends to overestimate IWR over some regions, e.g. Asia, the deviation is not substantial. Compared to the ERA-Interim climate, the MERRA produces lower IWR due to the wetter climate over many regions, e.g. Europe, Africa, North America. The results showed substantial variability over country IWR depending on a climate input used. As a result, we opted to use the average of the two simulated results for the following analysis.

We also compared simulated water withdrawal per source to reported statistics. We first compared simulated surface water and groundwater withdrawal to reported statistics per country, and obtained good agreement with R^2 above 0.93 (p value < 0.001). However, simulated surface water withdrawal was overestimated over Asia, and Central and Eastern Europe. Contrarily, groundwater withdrawal was underestimated over the same regions. To evaluate the spatial variability within a country, we then compared our estimates to reported subnational statistics. Results for the USA and Mexico show that regional variations of surface water and groundwater withdrawal are captured reasonably well, although the correlation was lower compared to that for the country comparison. Comparison of simulated trends of groundwater withdrawal to reported trends also show generally good agreement, but reported statistics were available for only ~20 countries. Our simulated global groundwater withdrawal of ~1000 km³ yr⁻¹ for 2000 lies in the middle when comparing to previous global estimates varying between ~600 and ~1700 km³ yr⁻¹ (Döll, 2009; Siebert et al., 2010; Wisser et al., 2010). Validation of simulated consumptive water use (per source) remains difficult due to a lack of reliable information in many regions of the world. Recent study by Anderson et

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Although we used two climate datasets to account the climate uncertainty, our model uncertainty can be large as model outputs can vary substantially among different global hydrological models (GHMs) with different model structure (Gosling et al., 2010, 2011; Haddeland et al., 2011). Nevertheless, our simulated water use and TWS anomalies show good agreement with reported statistics and observed TWS data, respectively.

This study builds upon previous modeling efforts and contributes to improve a current modeling framework that quantifies the impact of anthropogenic impacts on global hydrology. Our new modeling framework enables one to assess human-induced change in global water systems and to track those changes over time. It can be also used to assess future increase in water use per source due to population growth and economic development that will pose a serious threat to regions currently under substantial water scarcity, and to identify regions of looming water scarcity under future climate or under envisaged socio-economic developments.

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Table 1. Previous global studies to simulate irrigation water requirement (IWR).

	Climate input	Reference apotranspiration	Irrigated area	Crop	Crop calendar	Additional components	IWR (km ³ yr ⁻¹)	Year	Spatial resolution
Döll and Siebert (2002)	CRU TS 1.0 (New et al., 2000)	Priestley and Taylor	Döll and Siebert (2000)	Paddy Non-paddy	Optimal growth	Irrigation efficiency Cropping intensity	2452	Avg. 1961–1990	0.5°
Hanasaki et al. (2006)	ISLSCP (Meeson et al., 1995)	FAO Penman–Monteith	Döll and Siebert (2000)	Paddy Non-paddy	Optimal growth	Irrigation efficiency	2254	Avg. 1967–1988	0.5°
Rost et al. (2008)	CRU TS 2.1 (Mitchell and Jones, 2005)	Gerten et al. (2007): Priestley and Taylor	Siebert et al. (2007) Evans (1997)	11 crops pasture	Simulate vegetation/crop growth by LPJmL (Bondeau et al., 2007)	IPOT and ILIM Green water use Irrigation efficiency	2555 ^{POT} 1161 ^{ILIM}	Avg. 1971–2000	0.5°
Wisser et al. (2008)	CRU TS 2.1 ^{CRU} NCEP/NCAR ^{NCEP} (Kalnay et al., 1996)	FAO Penman–Monteith	Siebert et al. (2005, 2007) ^{FAO} Thenkaball et al. (2006) ^{WMI}	Monfreda et al. (2008)	Optimal growth	Irrigation efficiency Flooding applied to paddy irrigation	3000–3400 ^{CRU,FAO} 3700–4100 ^{CRU,JWMI} 2000–2400 ^{NCEP,FAO} 2500–3000 ^{NCEP,JWMI}	Avg. 1963–2002	0.5°
Siebert and Döll (2010)	CRU TS 2.1	FAO Penman–Monteith ^{FM} Priestley and Taylor ^{PT}	Portmann et al. (2010)	26 crops Portmann et al. (2010)	Portmann et al. (2010)	Green water use	2099 ^{FM} 2404 ^{PT}	Avg. 1998–2002	0.083333°
Hanasaki et al. (2010)	NCC-NCEP/NCAR reanalysis CRU corr. (Ngo-Duc et al., 2005)	Bulk formula (Robock et al., 1995)	Siebert et al. (2005)	Monfreda et al. (2008)	Simulate a cropping calendar by H07 (Hanasaki et al., 2008b)	Irrigation efficiency Virtual water flow	2380	Avg. 1985–1999	0.5°
Sulser et al. (2010)	CRU TS 2.1	Priestley and Taylor	Siebert et al. (2007)	20 crops (You et al., 2006)	FAO CROPWAT with some adjustments	Future scenarios (TechnoGarden, SRES B2 HadCM3 climate)	3128 ²⁰⁰⁰ 4060 ²⁰²⁵ 4396 ²⁰⁵⁰	2000 2025 2050	281 Food Producing Units
Wada et al. (2011b)	CRU TS 2.1	FAO Penman–Monteith	Portmann et al. (2010)	26 crops Portmann et al. (2010)	Portmann et al. (2010) Siebert and Döll (2010)	Green water use Irrigation efficiency	2057	Avg. 1958–2001	0.5°
Pokhrel et al. (2011)	JRA-25 Reanalysis (Kim et al., 2009; Onogi et al., 2007)	FAO Penman–Monteith	Siebert et al. (2007) Freydanck and Siebert (2008)	18 crops (Leff et al., 2004)	SWIM model (Krysanova et al., 1998)	Energy balance Soil moisture deficit Preplanting irrigation	2158(±134) ^a 2462(±130) ^b	Avg. 1983–2007 ^a 2000 ^b	1.0°

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Table 2. Correlation of simulated IWR to reported statistics per country for the year 2000 ($N = 212$). IWR was simulated with the CRU TS 2.1 (C), ERA-Interim (E), and MERRA climate (M), respectively. Average indicates the mean of the two or three results. Reported statistics were obtained from the FAO AQUASTAT data base (Globe: $2434 \text{ km}^3 \text{ yr}^{-1}$). R^2 and α denote the coefficient of determination and the slope of regression line respectively. R^2 was derived from the comparisons between normal values. The value with the CRU TS 2.1 climate is provided for a reference and is not included in our overall analysis.

	IWR ($\text{km}^3 \text{ yr}^{-1}$)	R^2	α
CRU TS 2.1 (C)	2885	0.96	0.88
ERA-Interim (E)	2618	0.96	0.92
MERRA (M)	2348	0.95	0.95
Average (C, E, M)	2617	0.98	0.94
Average (E, M)	2348	0.98	0.96

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Table 3. Correlation between simulated and reported water withdrawal per source (SWW: surface water withdrawal, GWW: groundwater withdrawal) for the year 2005 over the Globe per country ($N = 100$), Europe per country ($N = 34$), the USA per state ($N = 50$), and Mexico per state ($N = 32$) in log-log plots. R^2 and α denote the coefficient of determination and the slope of regression line respectively. R^2 was derived from the comparisons between normal values.

		R^2	α
Globe	SWW	0.96	0.86
	GWW	0.98	0.96
Europe	SWW	0.95	0.85
	GWW	0.93	1.08
USA	SWW	0.85	0.82
	GWW	0.86	0.84
Mexico	SWW	0.82	1.08
	GWW	0.80	0.80

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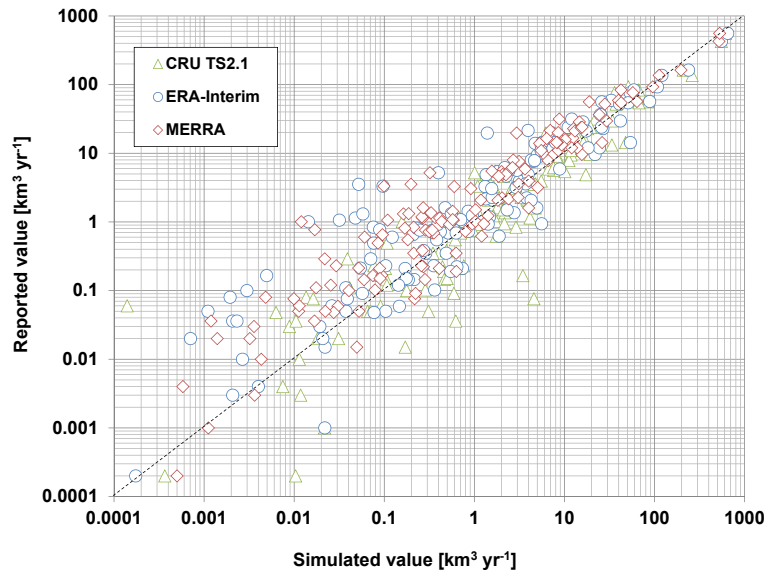


Fig. 1. Comparison of simulated IWR to reported statistics [$\text{km}^3 \text{yr}^{-1}$] per country for the year 2000 ($N = 212$). IWR was simulated with the CRU TS 2.1, ERA-Interim and MERRA climate respectively. Reported statistics was obtained from the FAO AQUASTAT database (<http://www.fao.org/nr/water/aquastat/main/index.stm>). The dashed line represents the 1:1 slope. Simulated IWR with the CRU TS 2.1 is provided for a reference and is not included in our overall analysis.

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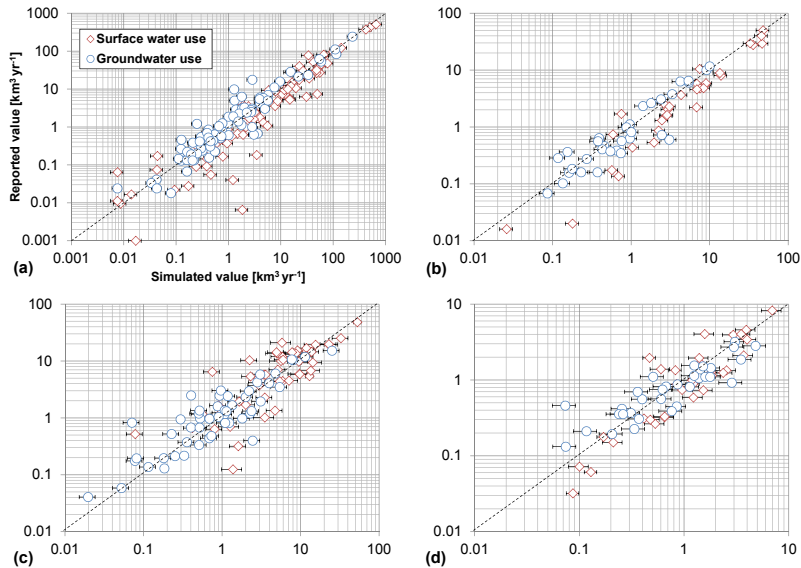


Fig. 2. Comparison of simulated water use per water source (surface water and groundwater withdrawal) to reported value [$\text{km}^3 \text{yr}^{-1}$] for the year 2005 over **(a)** the Globe per country ($N = 100$), **(b)** Europe per country ($N = 34$), **(c)** the USA per state ($N = 50$), and **(d)** Mexico per state ($N = 32$) in log-log plots. Simulated water use at 0.5° was spatially aggregated to country and state. Simulated value indicates the mean of the simulation with the ERA-Interim and MERRA climate. Error bars show standard deviation (σ) among the simulation with the ERA-Interim and MERRA climate. The dashed lines represent the 1 : 1 line. The reported water use per source was obtained from the FAO AQUASTAT database for the Globe, from the Eurostat database (<http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/database>) for Europe, from the US Geological Survey (Water Use in the United States; <http://water.usgs.gov/watuse/>) for the USA, and from the CONAGUA (Statistics on Water in Mexico; http://www.conagua.gob.mx/english07/publications/Statistics_Mexico2008.pdf) for Mexico.

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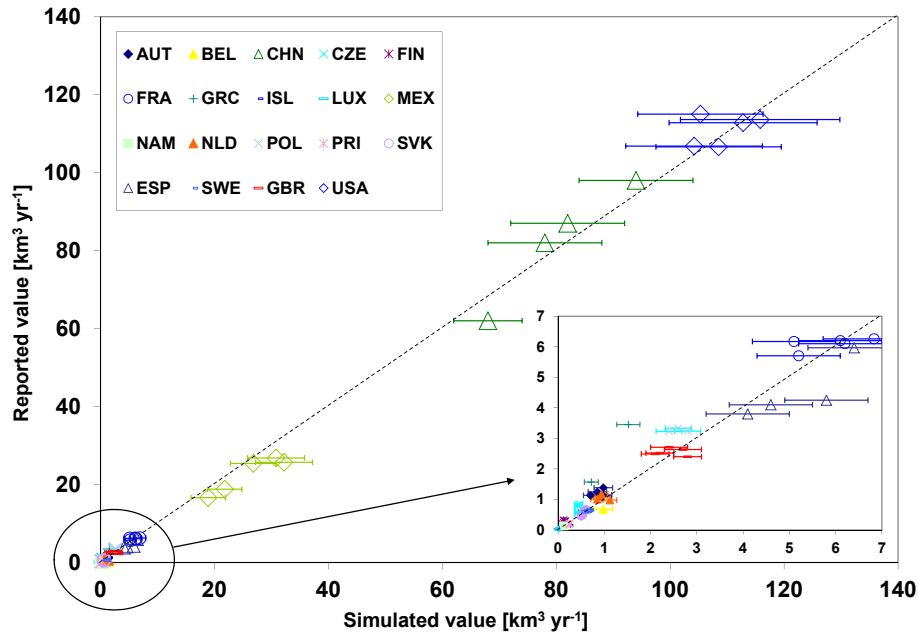


Fig. 3. Comparison of simulated and reported trends of groundwater withdrawal use per country over the period 1980–2005 ($N = 19$). Countries are identified with their ISO country codes. Reported groundwater withdrawal use was obtained from the FAO AQUASTAT database. Simulated value indicates the mean of the simulation with the ERA-Interim and MERRA climate. Error bars show standard deviation (σ) among the simulation with the ERA-Interim and MERRA climate. The dashed line represents the 1 : 1 slope.

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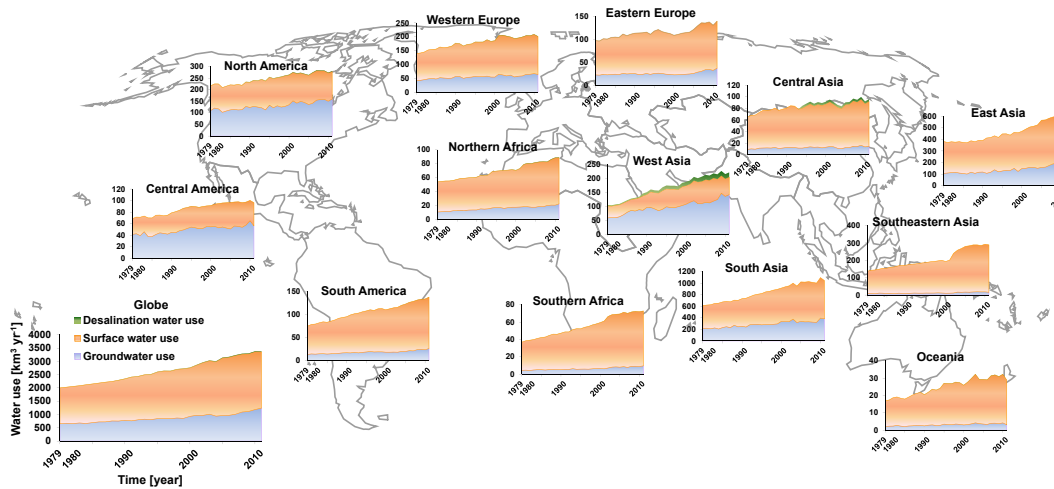


Fig. 4. Regional trends of water withdrawal use per source (desalination water, surface water, and groundwater) over the period 1979–2010. The results were obtained from the mean of the simulation with the ERA-Interim and MERRA climate. The global figure is shown at the left corner.

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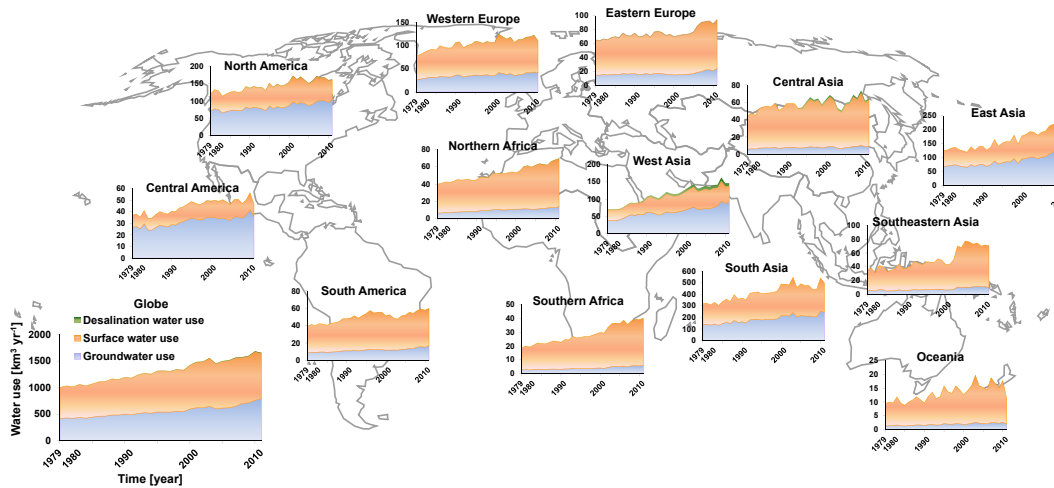


Fig. 5. Regional trends of consumptive water use per source (desalination water, surface water, and groundwater) over the period 1979–2010. The results were obtained from the mean of the simulation with the ERA-Interim and MERRA climate. The global figure is shown at the left corner.

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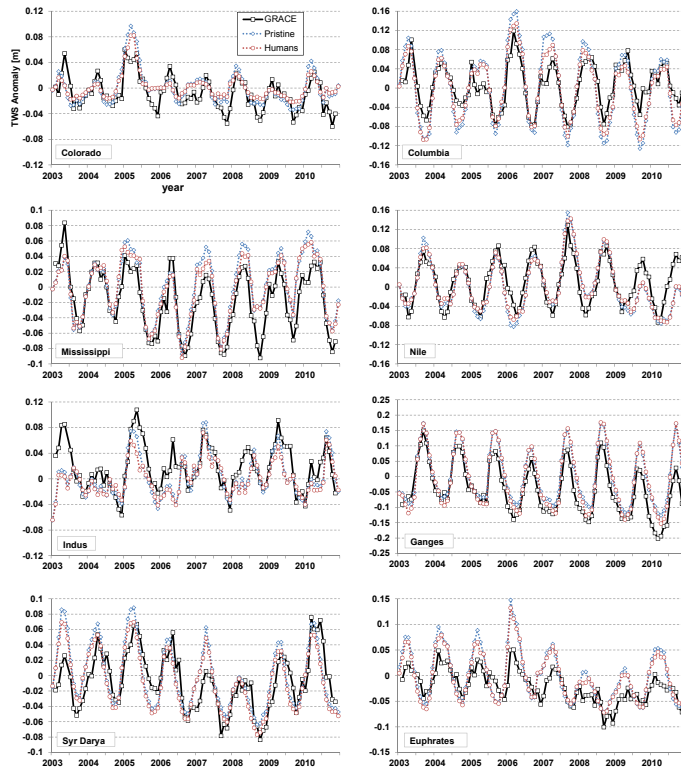


Fig. 6. Comparison of simulated monthly terrestrial water storage (TWS) anomalies with those of the GRACE observations [m month^{-1}] for selected major basins over the period 2003–2010. The results were obtained from the mean of the simulation with the ERA-Interim and MERRA climate. Black solid line, blue dashed line, and red dashed line indicate the GRACE observation, pristine condition (natural climate variability only), and human-induced change (water use and reservoir operations), respectively. Monthly GRACE terrestrial water storage anomaly data were obtained from the DEOS Mass Transport release 1/1b (DMT-1) model (Liu et al., 2010).

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