Hydrol. Earth Syst. Sci. Discuss., 8, 7399–7460, 2011
www.hydrol-earth-syst-sci-discuss.net/8/7399/2011/
doi:10.5194/hessd-8-7399-2011


Hydrology and Earth System Sciences Discussions



# Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability

**Y. Wada**[1], **L. P. H. van Beek**[1], **and M. F. P. Bierkens**[1,2]

[1]Department of Physical Geography, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[2]Unit Soil and Groundwater Systems, Deltares, Princetonlaan 6, 3584 CB Utrecht, The Netherlands

Received: 20 July 2011 – Accepted: 26 July 2011 – Published: 1 August 2011

Correspondence to: Y. Wada (y.wada@geo.uu.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

During the past decades, human water use more than doubled, yet available freshwater resources are finite. As a result, water scarcity has been prevalent in various regions of the world. Here, we present the first global assessment of past development of water scarcity considering not only climate variability but also growing water demand, desalinated water use and non-renewable groundwater abstraction over the period 1960–2001 at a spatial resolution of 0.5°. Agricultural water demand is estimated based on past extents of irrigated areas and livestock densities. We approximate past economic development based on GDP, energy and household consumption and electricity production, which is subsequently used together with population numbers to estimate industrial and domestic water demand. Climate variability is expressed by simulated blue water availability defined by freshwater in rivers, lakes and reservoirs by means of the global hydrological model PCR-GLOBWB. The results show a drastic increase in the global population living under water-stressed conditions (i.e., moderate to high water stress) due to the growing water demand, primarily for irrigation, which more than doubled from 1708/818 to 3708/1832 $km^3 yr^{-1}$ (gross/net) over the period 1960–2000. We estimate that 800 million people or 27 % of the global population were under water-stressed conditions for 1960. This number increased to 2.6 billion or 43 % for 2000. Our results indicate that increased water demand is the decisive factor for the heightened water stress, enhancing the intensity of water stress up to 200 %, while climate variability is often the main determinant of onsets for extreme events, i.e. major droughts. However, our results also suggest that in several emerging and developing economies (e.g., India, Turkey, Romania and Cuba) some of the past observed droughts were anthropogenically driven due to increased water demand rather than being climate-induced. In those countries, it can be seen that human water consumption is a major factor contributing to the high intensity of major drought events.





HESSD

8, 7399–7460, 2011

## 1 Introduction

Freshwater (i.e., blue water) is a vital resource for various human activities and food production yet the available amount is finite. Large numbers of reservoirs (e.g., dams) are constructed to store water but the increase of impoundment by dams has been tapering off since the 1990s (Chao et al., 2008). At the same time, water needs, primarily for irrigation, have been increasing rapidly since the 1960s. Figure 1 shows past trends of water withdrawal along with the increase in population, GDP and irrigated areas over the globe and for each continent. The global water withdrawal increased at a rate of 17 % per decade between 1960 and 2000 (Vörösmarty et al., 2005) similar to that of North America, South America, Europe and Asia and eventually doubled to 4000 $km^3 yr^{-1}$ in 2000. As a result, water scarcity has become prevalent in many regions of the world (e.g., India, China and the Middle East). The United Nations report that water scarcity is beginning to constrain economic growth in those regions (World Water Assessment Programme, 2009).

To assess global freshwater scarcity (i.e., blue water stress) various studies applied global hydrological models (i.e., GHMs) commonly at a spatial resolution of 0.5° (i.e., 50 km by 50 km at the equator). An overview of those studies is shown in Table 1. In several GHMs (e.g., H07 and PCR-GLOBWB) reservoir operation schemes have been implemented to return more accurate results for seasonal river discharge by considering effects of altered flow conditions in which water is stored for a dry period to meet demand. Also, reduction of river discharge by upstream human water consumption through river networks is realized by exogenous runoff scheme (cf., Oki et al., 2001; Wada et al., 2011). In many studies, water scarcity is expressed by the Water Scarcity Index (WSI; see Sect. 2.1) in which simulated freshwater availability is confronted against estimated water demand. As shown in Table 1, the results of population under high water stress (i.e., WSI≥0.4) vary considerably. Grid-based estimate results in higher values, as a country-based estimate hides substantial within-country variation of water availability and demand (Arnell, 2004) while sub-annual assessments capture



HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

seasonal variations of water stress and thus return higher values than annual assessments (Hanasaki et al., 2008b; Wada et al., 2011). Despite these differences, most studies indicate high water stress in many (semi-)arid regions such as India, Pakistan, North East China, Central and West USA, North Africa, Iran, Saudi Arabia, South Spain and parts of Australia. In such regions, the demand often exceeds the available surface freshwater resources due to heavy irrigation (UNEP, 1996) which requires large volumes of water in a certain time of the year, when groundwater is additionally used to supplement the deficiency. Only Wada et al. (2011) explicitly incorporated groundwater abstraction in the assessment.

The previous assessments shown in Table 1 have identified regions suffering from current water scarcity and vulnerable to future water scarcity due to the effects of climate change and prone to frequent droughts, yet almost no global studies have assessed the past development of water scarcity. One exception is a recent study of Kummu et al. (2010) whose result indicated that 1960 is a clear turning point for the global population under water scarcity. They showed that the global population experiencing high water stress soared up from 0.3 to 2.3 billion, i.e. 9 % to 35 % of the global population, over the period 1960–2005 while the figure was less than 0.1 billion before the 1940s. However, they estimated water demand based on only population growth, such that neither past expansion of irrigated areas nor economic growth was considered. Moreover, their coarse spatial and temporal resolution neglected significant spatial and inter- and sub-annual variability of water demand and availability.

To quantify the development of past water stress considering the effects of not only population growth but also economic growth and expanding irrigated areas at a finer temporal and spatial scale, we develop a method to reconstruct past monthly water demand for agricultural, industrial and domestic sector from 1960 to 2001 at 0.5°, while blue water availability is simulated by using the global hydrological model PCR-GLOBWB at the same spatial and temporal resolution. Past water demand is estimated by using the latest available global data sets of socio-economic (e.g., population and GDP), technological (e.g., energy and household consumption and electricity





HESSD
8, 7399–7460, 2011

production) and agricultural (e.g., the number of livestock and irrigated areas) drivers. Throughout the paper we will consistently use the term water "demand" to indicate that we can only estimate potential use, i.e. the water that would be used by a given activity or sector if sufficient water were available. In many analyses (e.g., Döll and Siebert, 2002; Wisser et al., 2008; Wada et al., 2011) one distinguishes gross demand from net demand. The latter is sometimes equated with consumptive water use (e.g., Döll and Siebert, 2002). Net demand is consequently lower than gross demand as water withdrawn for industrial and domestic sectors is recycled and returned to river networks while part of water used for irrigated crops is met by green water (i.e., soil water). In addition, apart from most of the previous studies, the development of desalinated water use and groundwater abstraction are explicitly considered for the same period since these particular water resources provide additional water availability and subsequently reduce blue water demand.

Thus, the main objective of this study is to test the method to reconstruct past water demand and most importantly to quantify the transient effects in past development of blue water stress considering not only climatic variability but also growing water demand over the period 1960–2001. The results pinpoint regions where water scarcity is intensified by climate variability (e.g., decreased water availability) and/or growing water demand, which might give an important implication for coping with future potential water scarcity or droughts.

## 2 Methodology

### 2.1 Definition of blue water stress

We define blue water stress by comparing blue water availability with corresponding net total water demand for each grid cell, i, at 0.5°. WSI is defined as a mean to express how much of the available water is taken up by the demand (Falkenmark,





HESSD
8, 7399–7460, 2011

1989; Falkenmark et al., 1997):

$$\mathrm{WSI}_i = \frac{\left(D_{T_{\mathrm{Net}}i} - (\mathrm{DSW}_i + \mathrm{NRGW}_i)\right)}{\mathrm{SFWA}_i} \tag{1}$$

where $D_{T_{\mathrm{Net}}i}$ is the net total water demand as a sum of livestock, irrigation, industrial and domestic water demand, DSW and NRGW are the desalinated water use and the non-renewable groundwater abstraction, i.e. abstraction in excess of recharge, and SFWA is the surface freshwater availability [all in $10^6\,\mathrm{m}^3\,\mathrm{yr}^{-1}$]. This study uses the monthly average of net demand and availability. The volume of the total water demand is corrected after subtracting the amount of desalinised water use and non-renewable groundwater abstraction.

Water stress occurs whenever the amount of water demand reaches a certain threshold in that of water availability in a same sptio-temporal domain. Moderate and severe water stress occur between $0.2 \leq \mathrm{WSI} < 0.4$ or water availability of 1700 and $1000\,\mathrm{m}^3\,\mathrm{yr}^{-1}$ per capita and $\mathrm{WSI} \geq 0.4$ or that of $1000\,\mathrm{m}^3\,\mathrm{yr}^{-1}$ per capita respectively (Falkenmark et al., 2007; Kundzewicz et al., 2007).

## 2.2 Simulation of blue water stress

To distinguish the effect of growing water demand from that of climate variability on the development of past water stress, we performed two simulation runs. First we simulated transient blue water stress over the period 1960–2001. Next we simulated blue water stress again but with fixed water demand for 1960 (see Eq. 1). The same transient blue water availability simulated by PCR-GLOBWB was used for the both simulations. We then applied a linear regression (linear least squares) to analyze trends for both results with a level of significance of 95 %. The result of the second simulation enables us to quantify the impact of climate variability on a development of past water stress while the differences between that of the first and second simulation enable us to quantify the effects of growing water demand. We used yearly average and maximum blue water stress for the both simulations, respectively. Maximum blue water stress was defined by the month with the highest water stress each year.

### 2.3 Reconstruct past water demand over the period 1960–2001

Data on country-specific water withdrawal is obtainable from the FAO AQUASTAT data base and the WRI (http://www.wri.org/), but it generally has a limited temporal and spatial coverage. Moreover, country statistics on consumptive water use rarely exists. For these reasons, most of previous studies estimated sectoral water demand from various data. Irrigation water, being by far the largest demand among sectors, was estimated by using spatially distributed irrigated areas which are available from several sources commonly at 0.5° such as Global Map of Irrigated Areas (Döll and Siebert, 2002; Siebert et al., 2005), GIAM (Thenkabail et al., 2006, 2008), Ramankutty et al. (2008) and MIRCA2000 (Portmann et al., 2010). Temporal coverage of these data is, however, limited to the present condition, i.e. around the year 2000. To overcome the lack of available spatially-explicit data, we downscaled the country statistics of the number of livestock, the extent of irrigated areas and population numbers to 0.5° and used these to reconstruct past water demand over the period 1960–2001. Past economic development was approximated by using GDP, energy and household consumption and electricity production. To compute net demand, we estimated return flow for industrial and domestic sectors by using spatially explicit recycling ratios and accounted green water availability which was simulated by PCR-GLOBWB to partition water used for irrigated crops into blue and green water sources. To capture seasonal variations characterised by high demand and low availability at certain times of the year, water demand and water availability were computed per month.

Figure 2 shows a schematic diagram that describes how we computed sectoral water demand from various data sources. In the following sections the computation of sectoral water demand is subsequently described in more detail.





HESSD
8, 7399–7460, 2011



Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

### 2.3.1 Livestock water demand

Livestock water demand shares less than 1 % of the global gross water demand and the amount is small in most countries compared to the other sectors. However, livestock water demand is not negligible in some of African countries. For example, in Botswana where people suffer from periodic water scarcity, livestock water demand is larger than irrigation water demand and accounts 23 % of the total water demand (Els and Rowntree, 2003).

We computed livestock water demand by combining livestock densities (i.e., the number of livestock per grid cell) with their drinking water requirements (see Fig. 2). The gridded global livestock densities include separate maps for cattle, buffalo, sheep, goats, pigs and poultry in 2000 (Wint and Robinson, 2007). We multiplied the number of each livestock in a grid cell by its corresponding drinking water requirements to estimate livestock water demand. We assumed that gross demand for livestock equals net demand; no return flow to the soil or river system occurs. Due to the lack of past gridded livestock densities, we downscaled the country statistics of the numbers of each livestock type for 200 countries (FAOSTAT) to 0.5° from 1960 to 2001 by using the distribution of the gridded livestock densities of 2000 (see Fig. 2).

The drinking water requirements for livestock are generally higher in summer and lower in winter and are a function of air temperature, for example a sheep requires daily 8.7, 12.9 and 20.1 litres under 15°, 25° and 35° air temperature respectively (Steinfeld et al., 2006). We thus determined the drinking water requirements for each livestock type by using spatially and temporally explicit monthly air temperature (0.5°) from 1960 to 2001. The monthly livestock water demand consequently fluctuates over the year while the livestock density of a given year remains constant.

### 2.3.2 Irrigation water demand

Irrigation, being by far the largest demand, comprises 70 % of the global gross water demand (Döll et al., 2009). Various studies computed the global irrigation water





HESSD
8, 7399–7460, 2011

demand as shown in Table 2 but their estimates vary depending on the methods and the data used in their calculation. Döll and Siebert (2002), Flörke and Alcamo (2004), Hanasaki et al. (2006) and Sulser et al. (2010) used the CROPWAT method (Smith, 1992) to estimate the global irrigation water demand. They estimated optimal crop calendar from precipitation and temperature (cf., Döll and Siebert, 2002). Rost et al. (2008) and Hanasaki et al. (2010) also simulated a crop calendar by using LPJmL (Bondeau et al., 2007) and H08 (Hanasaki et al., 2008b) respectively while Siebert and Döll (2010) used a prescribed crop calendar compiled by Portmann et al. (2010).

We opted to use a prescribed crop calendar of Portmann et al. (2010) as done in Siebert and Döll (2010) since uncertainties in simulating a crop calendar are large (Döll and Siebert, 2002). We obtained monthly irrigated areas and crop calendars for 26 crops around 2000 which account a seasonal variability due to the various growing seasons of different crops and regional cropping practices under different climatic conditions, and distinguish up to nine sub-crops that represent multi-cropping systems in different seasons in different areas per grid cell (see Fig. 2). The corresponding crop development stages, crop factors and crop rooting depth were also obtained from Siebert and Döll (2010). We then combined gridded irrigated areas with crop factors and growing season lengths to yield monthly crop-specific potential evapotransiration under optimal conditions (i.e., no water scarcity during irrigation practices) as done in the previous studies. Using the same crop calendars and crop factors, actual evapotranspiration without irrigation was simulated by PCR-GLOBWB and used as an estimate of green water use over the irrigated areas. We subtracted this amount from the calculated crop-specific potential evapotranspiration for the irrigated areas to estimate monthly net irrigation water demand. Multiplication with country-specific efficiency factors (Rohwer et al., 2007) to account for losses (i.e., conveyance and application losses) finally resulted in monthly gross irrigation water demand. For an extensive description of the methods we refer to Van Beek et al. (2011) and Wada et al. (2011).





HESSD
8, 7399–7460, 2011

To obtain monthly time series for the past period we repeated this procedure for each year (see Fig. 2), while estimating the growth of irrigated areas by downscaling country-specific statistics for 230 countries (FAOSTAT) to 0.5° from 1960 to 2001 by using the distribution of the gridded irrigated areas for 2000 following the method of Wisser et al. (2010).

### 2.3.3 Industrial water demand and recycling ratio

Industrial water demand amounts to 20 % of the global gross water demand and is generally higher in developed countries where the ratio of industrial to total water demand often exceeds 50 %.

In general, industrial water demand increases with GDP (Oki and Kanae, 2006). Alcamo et al. (2007) used GDP per capita and electricity production to model future increase of industrial water demand. Later, Shen et al. (2008) revealed a strong linear relationship between relative growths in electricity consumption and industrial GDP and used electricity consumption to model future increase of industrial water demand. We generally followed their approaches but included four variables to better approximate past course of increase in industrial water demand. We thus developed a simple algorithm to compute water use intensities, WUI, for the period 1960–2001.

$$\mathrm{WUI}_{\mathrm{cnt}} = \mathrm{EDev}_{\mathrm{cnt}} \times \mathrm{TDev}_{\mathrm{cnt}} \quad (2)$$

$$\mathrm{EDev}_{\mathrm{cnt}} = \mathrm{Average}\left(\begin{array}{cc} \left(\dfrac{\mathrm{GDP}_{\mathrm{pc,past}}}{\mathrm{GDP}_{\mathrm{pc,present}}}\right)^{0.5}, & \left(\dfrac{\mathrm{EL}_{\mathrm{pc,past}}}{\mathrm{EL}_{\mathrm{pc,present}}}\right)^{0.5}, \\ \left(\dfrac{\mathrm{EN}_{\mathrm{pc,past}}}{\mathrm{EN}_{\mathrm{pc,present}}}\right)^{0.5}, & \left(\dfrac{\mathrm{HC}_{\mathrm{pc,past}}}{\mathrm{HC}_{\mathrm{pc,present}}}\right)^{0.5} \end{array}\right) \quad (3)$$

$$\mathrm{TDev}_{\mathrm{cnt}} = \frac{\left(\dfrac{\mathrm{EN}_{\mathrm{pc,past}}}{\mathrm{EL}_{\mathrm{pc,past}}}\right)}{\left(\dfrac{\mathrm{EN}_{\mathrm{pc,present}}}{\mathrm{EL}_{\mathrm{pc,present}}}\right)} \quad (4)$$



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
8, 7399–7460, 2011

where GDP is the gross domestic product, EL is the electricity production and EN and HC are energy and household consumption respectively. pc and cnt denote per capita and per country. present and past indicate year 2000 and years 1960–2001.

EDev approximates an economic development based on four variables, each of which has a strong correlation to the growth of industrial water demand (see Fig. 2). However, EDev does not account for technological development, i.e. industrial restructuring or improved water use efficiency. In general, an increase in industrial water withdrawal considerably slows down after reaching a certain technological advancement. We then used energy consumption per unit electricity production to approximate technological development, TDev. TDev converges as energy consumption intensity reaches a saturation amount. Finally, the computed WUI was multiplied with the industrial water demand for 2000 (Shiklomanov, 1997; World Resources Institute, 1998; Vörösmarty et al., 2005) to estimate the gross demand from 1960 to 2001 (see Fig. 2).

Significant amounts of water withdrawn for industrial purposes return to the river system after use due to water recycling technology particularly in developed countries where 80 % of water used in the industrial sectors is currently recycled in Japan (Oki and Kanae, 2006; Ministry of Land, Infrastructure, and Transport in Japan, 2007). As a result, only part of water withdrawn for industry is actually consumed or lost i.e. yielding a net demand. Since the data on country recycling ratios rarely exists, we used the method of Wada et al. (2011) who interpolated country recycling ratios on the basis of the historical development of the recycling ratios and GDP per capita of Japan and resulted three averaged values of 80 %, 65 % and 40 % for developed (i.e., high income), emerging (i.e., middle income) and developing (i.e., low income) economies respectively. We applied their method from 1960 to 2001 in which the recycling ratios were specified after countries were classified into three different stages of economic development. If a country reached the developed economy as a result of GDP growth, the ratio was kept as 80 % throughout the period.

Gross industrial water demand was then combined with the interpolated recycling ratios to arrive as net demand. If there was no GDP data (e.g., Western Sahara), we applied the minimum 40 % as it is reasonable to assume that water recycling is present along with industrial facilities. The monthly net industrial water demand was kept as constant over the year similar to the study of Hanasaki et al. (2006) and Wada et al. (2011).

### 2.3.4 Domestic water demand

The domestic sector accounts for 10 % of the global gross water demand. Domestic water demand has increased rapidly due to population growth, particularly in emerging and developing countries such as China, India, Pakistan, Bangladesh and Mexico.

We estimated gross domestic water demand by multiplying the number of persons in a grid cell with the country-specific per capita domestic water withdrawal from 1960 to 2001 (see Fig. 2). The past country-specific per capita domestic water withdrawals were estimated by multiplying the country-specific per capita domestic water withdrawal in 2000, which were taken from the FAO AQUASTAT data base and Gleick et al. (2009), with $WUI_{cnt}$ (see Sect. 2.3.3) to account the past economic and technological development. As gridded maps of the global population are only available for each decade (Klein Goldewijk and van Drecht, 2006), we combined these with yearly country population data (FAOSTAT) to estimate gridded population maps for each year. For instance, we downscaled the country population statistics from 1966 to 1975 to 0.5° according to the distribution of the gridded global population map of 1970.

Similar to the industrial sector, large parts of water withdrawn for the domestic sector return to the river network. The amount depends on technological development and the number of households which are connected to water supply and sewer facilities. To estimate this return flow (which subsequently enables us to quantify net demand), we used the interpolated recycling ratios (see Sect. 2.3.3) and data on access to water for urban and rural population obtained from the UNEP. Here, gridded time series of the global urban and rural population were computed with the same method as the global



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
8, 7399–7460, 2011
Modelling global water stress of the recent past
Y. Wada et al.

population (see Fig. 2). Net domestic water demand was then calculated as follows:

$$D_{\mathrm{Dom}_{\mathrm{Net}}i} = D_{\mathrm{Dom}_{\mathrm{Gross}}i} \times (1.0 - (\mathrm{AW}_i \times \mathrm{RR}_{\mathrm{cnt}})) \quad (5)$$

$$\mathrm{AW}_i = \left(\left(\mathrm{FP}_{\mathrm{Urban},i} \times \mathrm{AW}_{\mathrm{Urban,cnt}}\right) + \left(\mathrm{FP}_{\mathrm{Rural},i} \times \mathrm{AW}_{\mathrm{Rural,cnt}}\right)\right) \quad (6)$$

where $D_{\mathrm{Dom}}$ is the domestic water demand [$10^6$ m$^3$]. AW is the fractional distribution of population which have access to water, RR is the recycling ratio and FP is the gridded fraction over total population [all in dimensionless]. Net, Gross, Urban and Rural denote net and gross demand, and urban and rural population, respectively.

To consider seasonal variability of domestic water demand which is generally higher in summer and lower in winter, we used air temperature (New et al., 2000) as a proxy to compute monthly fluctuations of net domestic water demand. We refer to Wada et al. (2011) for a detailed description of this method.

## 2.4 Simulate blue water availability

We simulated available freshwater in rivers, lakes and reservoirs by using the global hydrological model PCR-GLOBWB (PCRaster GLOBal Water Balance; Van Beek and Bierkens, 2009; Van Beek et al., 2011). PCR-GLOBWB is a conceptual, process-based water balance model of the terrestrial part of the hydrological cycle except Antarctica. PCR-GLOBWB is in line with existing GHMs such as WBM (Vörösmarty et al., 2000), WaterGAP (Alcamo et al., 2000), WGHM (Döll et al., 2003) and WASMOD-M (Widén-Nilsson et al., 2007). It simulates for each grid cell (0.5° × 0.5° globally) and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evaporation and snow melt). The model also calculates canopy interception and snow storage. Sub-grid variability is taken into account by considering separately tall and short vegetation, open water (i.e., lakes, reservoirs, floodplains and wetlands), different soil types (FAO Digital Soil Map of the





HESSD
8, 7399–7460, 2011

World), and the area fraction of saturated soil calculated by Improved ARNO scheme (Hagemann and Gates, 2003) as well as the frequency distribution of groundwater depth based on the surface elevations of the 1 × 1 km Hydro1k data set. Fluxes between the lower soil reservoir and the groundwater reservoir are mostly downward, except for areas with shallow groundwater tables, where fluxes from the groundwater reservoir to the soil reservoirs are possible (i.e., capillary rise) during periods of low soil moisture content. The total specific runoff of a cell consists of saturation excess surface or direct runoff, melt water that does not infiltrate, runoff from the second soil reservoir (interflow) and groundwater runoff (baseflow) from the lowest reservoir.

PCR-GLOBWB was forced with daily fields of precipitation, reference evapotranspiration and temperature over the period 1958 to 2001. Precipitation and air temperature were prescribed by the CRU TS 2.1 monthly dataset (New et al., 2000) which was subsequently downscaled to the daily fields by using the ERA40 re-analysis data (Uppala et al., 2005). Although the CRU TS 2.1 underestimates precipitation due to snow undercatch (Fiedler and Döll, 2007) over the Arctic regions, this weakness is of little consequence for this study as water stress rarely exists. Prescribed reference evapotranspiration was calculated based on the Penman-Monteith equation (Allen et al., 1998) by using time series data of CRU TS 2.1 with additional inputs of radiation and wind speed from the CRU CLIM 1.0 climatology data (New et al., 2002).

Simulated specific runoff from the two soil layers (i.e., direct runoff and interflow) and the underlying groundwater layer (i.e., base flow) was routed along the drainage network based on DDM30 (Döll and Lehner, 2002) by using the kinematic wave approximation of the Saint-Venant equation (Chow et al., 1988). The effect of open water evaporation, storage changes by lakes and attenuation by floodplains and wetlands were taken into account. A newly developed reservoir operation scheme was also implemented, which is dynamically linked with the routing module (Van Beek et al., 2011). This reservoir scheme works with the target storage over a defined period (e.g., a month) ensuring its proper functioning given the forecasts of inflow and downstream demand along the drainage network. The target storage determines outflow





HESSD
8, 7399–7460, 2011

from reservoirs and is updated when actual inflow and demand differ from the previously forecasted figures based on past average values. Four reservoir operations being water supply, flood control, hydropower generation and navigation are distinguished (cf., Haddeland et al., 2006) while reservoir data is obtained from the GLWD dataset (Lehner and Döll, 2004). The effect of upstream water consumption was incorporated by an exogenous runoff scheme which simulates the reduction of river discharge by subtracting net total water demand through the drainage networks (Wada et al., 2011).

### 2.5 Desalinated water use

Desalination is realised mostly by using distillation and membrane technology. Desalinated water use is generally limited to coastal areas but provides additional water availability. Around the globe, more than 10 000 desalination plants in 120 countries are in operation (World Water Assessment Programme, 2003). Large amounts of desalinated water are being consumed in the Middle East and North Africa (the MENA region), where over 70 % of the global desalination capacity is installed (World Water Assessment Programme, 2003) and people receive only 1 % of the global runoff (Vörösmarty et al., 2005). Although energy and economic costs to process sea water to produce purified water is still much higher than conventional water supply measures such as irrigation supply and groundwater pumping (The 2030 Water Resources Group, 2009), the amount of desalinated water use has been rising since the 1990s and reached 4.41 $km^3 yr^{-1}$ in 2000 (see Table 3).

We temporally downscaled the country statistics of desalinated water use (FAO AQUASTAT data base), which are reported at 5-year intervals to yearly statistics based on the country population growth for the period 1960–2001 (see Fig. 2). We then spatially downscaled the country values onto a global coastal ribbon of around 40 km based on the gridded population intensities (see Sect. 2.3.4) considering the fact that desalinated water is consumed by the coastal areas. Monthly desalinated water use is kept at constant over the year.





HESSD
8, 7399–7460, 2011

### 2.6 Estimate non-renewable groundwater abstraction

The amount of groundwater that is abstracted in excess of groundwater recharge will, albeit temporally and non-renewably, decrease the demand for blue water, which subsequently mitigate blue water stress. For the period 1960 to 2001, we estimated the amount of non-renewable groundwater abstraction by subtracting simulated groundwater recharge from gridded groundwater abstraction, similar to the method of Wada et al. (2010, 2011) but followed an improved approach when downscaling country-based data on groundwater abstraction to grid-based estimates, while additionally accounting for artificial recharge that occurs from irrigation. These methods are described in the following sections in more detail.

#### 2.6.1 Natural and artificial groundwater recharge

Unlike Wada et al. (2010), we simulated both natural and artificial groundwater recharge by using PCR-GLOBWB. The natural groundwater recharge equals to net flux from the lowest soil layer to the groundwater layer, i.e. deep percolation minus capillary rise (Wada et al., 2010). Note that without abstraction the long-term average of the natural groundwater recharge equals that of base flow from the groundwater layer in PCR-GLOBWB. To account for return flow from irrigation gift, $R_{\mathrm{Irr}}$, to the groundwater layer, we simulated artificial recharge by the following approximation:

$$R_{\mathrm{Irr,i}} = \mathrm{Min.}\left(L_{\mathrm{Irr,i}}, k\left(\theta_{\mathrm{E\_FC,i}}\right) \times T_{\mathrm{Irr,i}} \times A_{\mathrm{Irr,i}}\right) \quad (7)$$

where $L_{\mathrm{Irr}}$ is the amount of irrigation losses as estimated from the country-specific efficiency factors [m$^3$ day$^{-1}$], $k(\theta_{\mathrm{E\_FC}})$ is the unsaturated hydraulic conductivity at field capacity [m day$^{-1}$], $T_{\mathrm{Irr}}$ is the number of days irrigated [day] and $A_{\mathrm{Irr}}$ is the corresponding irrigated areas [m$^2$].

This formulation is based on the fact that in irrigation practice water is supplied to wet the soil to field capacity during the application and the amount of irrigation water in excess of the field capacity can percolate to the groundwater system. The additional





HESSD
8, 7399–7460, 2011

recharge rate thus equals the unsaturated hydraulic conductivity of the top soil layer at field capacity, assuming gravity drainage. However, the total percolation losses were further constrained by the reported country-specific loss factors (Rohwer et al., 2007). From this, we estimated globally the return flow during irrigation application from 1960 to 2001.

### 2.6.2 Groundwater abstraction

Groundwater abstraction is *somewhat* uncertain due to scarce observation data and has been rarely incorporated in global hydrological modelling. Table 4 shows data and model based estimates of the global groundwater abstraction. The data based estimates are mainly based on country statistics and have a fairly good agreement, falling into a range of 600 to 800 $km^3 yr^{-1}$. On the other hand, the model based estimates vary significantly among the studies. Wisser et al. (2010) estimate total groundwater abstraction to be 1708 $km^3 yr^{-1}$ which is twice as large as the data based estimates. Döll (2009) estimates that to be 1100 $km^3 yr^{-1}$ based on a fraction of groundwater to total water withdrawals per country multiplied with grid cell estimates of total water withdrawals computed by WaterGAP (Alcamo et al., 2003). Vörösmarty et al. (2005), Rost et al. (2008), Wisser et al. (2010) and Hanasaki et al. (2010) implicitly quantified the amount of non-renewable groundwater abstraction based on the amount of water demand exceeding locally accessible supplies of blue water. As a result, their estimates are sensitive to estimated water demand (1206–3557 $km^3 yr^{-1}$) and simulated blue water availability (36 921–41 820 $km^3 yr^{-1}$) and the uncertainties are large. Therefore, we used reported country groundwater abstraction data from the IGRAC GGIS data base (see Fig. 2). Since the exact locations where groundwater is abstracted are not known, we then downscaled the country value to a grid by taking deficits of surface freshwater availability over corresponding net total water demand. This approach differs from that of Wada et al. (2010) who downscaled country abstraction by using only net total water demand as a proxy.



HESSD
8, 7399–7460, 2011

First, for each month, m, from the year 2000 and for each grid cell, we calculated deficits, $\text{Defs}_{\text{m,i}}$, between the surface water availability, $\text{SFWA}_{\text{m,i}}$, as simulated by PCR-GLOBWB and the computed net total water demand, $D_{\text{T}_{\text{Net}}\text{m,i}}$. Because we are interested in groundwater as an alternative source, we limited our analysis to regions where the aquifers are present (major groundwater regions of the world according to the IGRAC GGIS). We subsequently estimated annual deficits, $\text{Defs}_{\text{a,i}}$, for 2000 as:

$$\text{Defs}_{\text{a,i}} = \sum_{m=1}^{12} \text{Defs}_{\text{m,i}} = \sum_{m=1}^{12} \left( D_{\text{T}_{\text{Net}}\text{m,i}} - \text{SFWA}_{\text{m,i}} \right) \tag{8}$$

We thus assumed that grid cells with deficits are the main locations where groundwater is abstracted as an alternative resource to satisfy the demand.

Second, the annual deficits, $\text{Defs}_{\text{a,i}}$, were filled by the amount of available country groundwater abstraction until total water demand was satisfied by groundwater abstraction per grid cell. Total annual deficits per country, $\text{Defs}_{\text{a}}$, were given by:

$$\text{Defs}_{\text{a}} = \sum_{i=1}^{n} \text{Defs}_{\text{a,i}} \tag{9}$$

$n$ is the number of grid cells with deficits per country.

If the total annual deficits are larger than the available annual groundwater abstraction in a country, $\text{Defs}_{\text{a}} > \text{Ground}_{\text{Wa}}$, (e.g., Egypt, Sudan, Mali, Niger, Sudan, Turkmenistan and Uzbekistan), we distributed the country abstraction according to the intensities rather than the volume of the deficits. In most cases the available abstraction is larger than the total deficits in a country and the remaining country-based abstraction $(\text{Ground}_{\text{Wa}} - \text{Defs}_{\text{a}})$ was further allocated relative to the intensity of the net total water demand over its country total (again limited to cells in major groundwater regions):

$$\text{Ground}_{\text{Wa,i}} = \text{Defs}_{\text{a}} + (\text{Ground}_{\text{Wa}} - \text{Defs}_{\text{a}}) \times \frac{D_{\text{T}_{\text{Net}}\text{a,i}}}{\sum_{i=1}^{n} D_{\text{T}_{\text{Net}}\text{a,i}}} \tag{10}$$



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

We assessed the past trend of groundwater abstraction at first-order by assuming that country-based groundwater abstraction increases linearly with water demand. So for a given year, k, an estimate of country-based groundwater abstraction was obtained by multiplying the groundwater abstraction of 2000 by the ratio of country-based water demand of year, k, over that of 2000 water demand:

$$\mathrm{Ground}_{\mathrm{Wa,cnt},k} = \mathrm{Ground}_{\mathrm{Wa,cnt},2000} \times \frac{D_{\mathrm{T_{Net}a,cnt},k}}{D_{\mathrm{T_{Net}a,cnt},2000}} \tag{11}$$

Next, by repeating for each year the methodology previously described, we thus computed gridded groundwater abstraction over the period 1960–2001.

# 3 Results

## 3.1 Accuracy of reconstructed water demand

We subsequently tested the reliability of our computed water demand. The computed gross sectoral and total water demand per country were compared to reported values taken from the FAO AQUASTAT data base. Furthermore, the computed gross and net total water demand were compared with estimated values for 80 countries taken from Shiklomanov (2000a,b).

### 3.1.1 Sectoral water demand

Table 5 shows the computed livestock water demand from 1960 to 2000. Total livestock water demand increased more than 50 % from 10.61 to 16.26 $\mathrm{km^3\,yr^{-1}}$ over the period. Cattle accounts for 70 % of all the livestock water demand. Buffaloes and sheep comprise only 10 % while goats, pigs and poultry share less than 5 % of the livestock water demand. Our estimates are slightly lower but agree well with those of Steinfeld et al. (2006) for 2000. For irrigation, our computed gross/net irrigation water demand



HESSD
8, 7399–7460, 2011

globally increased more than two-fold from 1268/645 to 2628/1376 km$^3$ yr$^{-1}$ over the period 1960–2000. Our estimates are comparable to the other estimates and the reported values of the FAO AQUASTAT data base (see Table 6). It should however be noted that the FAO AQUASTAT data base contains many missing values before 1990 inclusive. For 2000, our estimates are also in line with those of the previous studies (see Table 2). We compared per country the computed gross agricultural water demand with the reported value taken from the FAO AQUASTAT data base (see Fig. 3.a). Good agreements were obtained from 1970 to 2000 including major agricultural water users such as India, China, USA, Pakistan and Mexico while deviations were large for Iraq, Finland, Austria, Central African Republic and Trinidad and Tobago. The reported values are not available before 1970. Overall, $R^2$ (coefficient-of-determination) and $\alpha$ (slope of regression line) range from 0.96 to 0.99 and from 0.90 to 1.12, respectively (see Table 7).

Our computed global gross/net industrial water demand more than doubled from 356/116 to 752/257 km$^3$ yr$^{-1}$ over the period 1960–2000 (Table 6). Comparisons of computed gross industrial water demand per country with the reported values show good correlations (Fig. 3b). $R^2$ is over 0.97 except 1995 (Table 7). Deviations were large for Argentina, Ethiopia, Greece, Indonesia, Lebanon, Nicaragua, Panama, Puerto Rico and Turkmenistan. Nevertheless, we generally have good agreements for most of countries including major industrial water users such as USA, China, Germany, Canada and India.

Computed gross/net domestic water demand nearly quadrupled from 85/57 to 328/198 km$^3$ yr$^{-1}$ over the period 1960–2000 and is comparable to the other studies (Table 6). Comparison with the reported value per country also shows a good agreement from 1970 to 2000 in which $R^2$ is over 0.95 (Fig. 3c; Table 7). Although the correlations were high for most of the countries, deviations were large for several countries such as Iraq, Lithuania, Puerto Rico, Mali, Djibouti and Bhutan.





HESSD
8, 7399–7460, 2011

### 3.1.2 Total water demand

The computed gross/net total water demand more than doubled and reached 3708/1831 $km^3\,yr^{-1}$ for 2000 primarily due to the large increase in irrigation water demand (Table 6). Irrigation is responsible for 80 % of the net total water demand (see Fig. 4) and is the cause of most of the heightened intensities of the demand in regions such as India, Pakistan, China, West and Central USA, Mexico, South Europe, the Middle East and Central Asia (see Fig. 5).

Comparison of computed gross total water demand with reported total water withdrawal per country shows a good agreement with $R^2$ ranging from 0.96 to 0.99 (see Fig. 6; Table 7). The large deviations observed in the sectoral comparisons cancelled out after summing all the sectoral demands. The deviations remain large only for Greece and Iraq (+50 %) and Mali and Turkmenistan (−40 %). Additional comparisons of computed gross and net total water demand with estimated water withdrawal and water consumption of Shiklomanov (2000a,b) also show good agreements for most of the countries with $R^2$ ranging from 0.91 to 0.97 (see Fig. 7; Table 7). Our values are generally lower because of our lower irrigation water demand.

## 3.2 Accuracy of blue water availability

Climate variability expressed by inter- and sub-annual variability of blue water has a strong influence on our water stress assessment. Extensive validations of the estimates of PCR-GLOBWB were performed by Van Beek et al. (2011) by comparing the simulated river discharge to observations (Global Runoff Data Centre, 2008). Comparisons with over 3600 GRDC stations showed that the coefficient-of-determination ($R^2$) was high (≈0.9) for most of the stations but the coefficient-of-determination decreased when the mean minimum and maximum monthly discharge were considered instead of the mean discharge. Inter-annual variability was mostly well reproduced in major rivers except the Niger ($R^2 = 0.54$), Orange ($R^2 = 0.54$), Murray ($R^2 = 0.60$), Indus ($R^2 = 0.62$), Zambezi ($R^2 = 0.75$) and Nile ($R^2 = 0.87$) where the simulated river





HESSD
8, 7399–7460, 2011

discharge was often overestimated. We refer to Van Beek et al. (2011) for a detailed description of these validations.

### 3.3 Estimated non-renewable groundwater abstraction

For 2000, our simulated groundwater recharge amounted to 15 645 $km^3 yr^{-1}$ in which natural and artificial recharge contributed 15 225 $km^3 yr^{-1}$ and 420 $km^3 yr^{-1}$ respectively. Table 8 shows computed total and non-renewable groundwater abstraction from 1960 to 2000. Non-renewable groundwater abstraction nearly tripled over the period. Non-renewable groundwater abstraction rapidly increased in regions such as India, East China, USA, Pakistan, South Europe, South Mexico, North Iran and Central Saudi Arabia primarily due to expansion of irrigated areas (see Fig. 8). The sum of non-renewable groundwater abstraction of these regions amounts to 90 % of the global total. Although our results are in line with those of Wada et al. (2010), the amounts are somewhat lower due to the inclusion of additional artificial recharge from irrigation, while the extents are smaller by considering the surface water deficits over the water demand, which is clearly depicted along the Indus (Fig. 8).

### 3.4 Development of past water stress

Table 9 shows the global population under different degrees of water stress from 1960 to 2000. Our results generally show larger number of the global population under water stress than those of Kummu et al. (2010) due to our finer temporal and spatial resolution and inclusion of expansion of irrigated areas. Long-term trends show a drastic increase in the global population living under water-stressed conditions (i.e., moderate to high water stress). For 1960, 800 million people or 27 % of the global population are under water-stressed conditions. This figure increased to 1.1 billion or 30 %, 1.5 billion or 34 % and 1.9 billion or 36 % for 1970, 1980 and 1990, respectively. The global population living under water-stressed conditions eventually grows to 2.6 billion or 43 % for 2000. While the number of people experiencing moderate water stress grew from 300 to 800 million over the period 1960–2000, that of high water stress soared from 500 million to 1.8 billion, one-third of the global population. Although the global population increased by around 700 million per decade, the rapid increase of the global population under high water stress indicates a worsened condition and severer competition for the global surface freshwater resources.

### 3.5 Heightened water stress in relation to growing water demand and climate variability: global analysis

High water stress occurs mainly over heavily irrigated, densely populated and water scarce regions such as India, Pakistan, North East China, USA, Mexico, Argentina, Spain, the MENA region, Central Asia and parts of Australia. Many of those regions already experienced high water stress before 1960, but the intensities significantly increased towards 2000 (see Fig. 9). East to South Europe emerged to have high water stress for 2000.

The result of the linear regression to distinguish the contribution of climate variability and growing water demand to heightened water stress is shown in Fig. 10 (see Sect. 2.2). Figure 10 shows that increased water demand has a dominant effect on heightened water stress for India, China, Mexico, South Europe and Central Asia while decreased water availability has a lesser but still significant impact over India, North East China, South Europe and the Sahel (Fig. 10a,b). India experienced a decreasing rainfall trend between 1960 and 2001 over the winter and pre-monsoon season (Joshi and Rajeevan, 2006; Guhathakurta and Rajeevan, 2006) in which the highest water stress generally occurs. North East China experienced higher frequency of extreme dry conditions during the late 1900s (Shen et al., 2007; Zhuguo et al., 2004). South Europe experienced dry conditions over the 1980s and 1990s and the Sahel suffered from long-term drought conditions during the 1970s and late 1980s (Sheffield and Wood, 2007).

Increased water demand also intensified maximum water stress by 0.2 to 0.4 for North East China, Central India, Central Asia and East and South Europe while





HESSD
8, 7399–7460, 2011

decreased water availability intensified maximum water stress particularly for Central India and the Sahel (Fig. 10c,d). Overall, the results suggest that increased water demand is the decisive factor for heightened water stress throughout the globe, except for the Sahel where decreased water availability has a larger impact. This can be explained by the fact that in the Sahel water demand is substantially lower compared to the other water-stressed regions.

### 3.6 Development of water stress in relation to growing water demand and climate variability: country analysis

As a limited validation exercise, we here show monthly time series of past water stress and compare these with reported periods of major water shortage, i.e. major drought events according to Wilhite and Glantz (1985) in a country or state. To obtain a country WSI, we averaged the simulated WSI for all pertinent cells, which may neglect water scarcity that occurs in a particular part of the domain. Thus, the averaged intensity of the simulated WSI may diminish due to offsets within the domain. We selected several emerging and developing countries where water demand increased rapidly over the period 1960–2001: Mexico, Kerala (India), Shanxi (China), Turkey, Romania, Bulgaria and Cuba. In the following sections, we describe for each country results of two simulation runs (see Sect. 2.2) to assess detrimental effects of climate variability and increased water demand on major water shortage (see Fig. 11).

#### 3.6.1 Mexico

Mexico characterized by (semi-)arid lands has a long experience with drought (Liverman, 2000). The climate varies significantly across Mexico where most of the rainfall occurs in a rainy season between June and September. Mexico suffers persistent droughts partly associated with EL Niño Southern Oscillation (ENSO). Major droughts occurred during the periods 1969–1979, 1982–1984, 1987–1988 and 1994–2003 (Liverman, 2000; Stahle et al., 2009) which agree reasonably well with our simulated WSI



HESSD
8, 7399–7460, 2011
Modelling global water stress of the recent past
Y. Wada et al.

(Fig. 11). Our result indicates that the water demand more than doubled in Mexico over the period 1960–2001 due to a large increase in irrigation water demand. Increased water demand clearly worsened water scarcity particularly after the mid-1990s. Stahle et al. (2009) suggest human influence related with land use and climate change on the persistent drought condition during 1994–2003 while our result suggests the increased water demand intensified the drought condition up to 35 % (year 2000). In Mexico, however, climate variability is a main determinant for dry and wet conditions (e.g., the wet years of 1985, 1992 and 1997).

### 3.6.2 Kerala (India)

Kerala, a state in South West India, is characterized by tropical monsoon climate. The state receives excessive rainfall in a monsoon season (May-September) which contributes more than 80 % of the annual rainfall but also suffers from periodic drought conditions (Nathan, 2000). Kerala experienced major droughts during the periods 1982-1983, mid 1980s-early 1990s and late 1990s-early 2000s (Nathan, 2000; Simon and Mohankumar, 2004; Tyagi et al., 2006) which were also captured by our simulated WSI (Fig. 11). In Kerala, droughts occurred primarily due to rainfall deficits and late onsets of the monsoon. However, our results suggest that water scarcity was intensified by 200 % (1992, 1996 and 2000) due to increased water demand which nearly tripled over the period 1960–2001. Our simulated WSI clearly shows a rising trend with the increasing water demand in Kerala. Water demand has been a dominant factor for the intensities of water scarcity since the mid-1980s while climate variability determined the onsets.

### 3.6.3 Shanxi (China)

Shanxi, a province in North East China, is characterized by continental monsoon climate. Average annual precipitation varies between 400 and 600 mm within the province. Climate records suggest that 1966 was the driest year in North East China



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

during the 1900s (Shen et al., 2007). Many parts of North East China also suffered major drought conditions during the period 1972, 1978, 1987–1988, 1991–1992, 1997 and 2000–2001 due to rainfall deficits (Zhuguo et al., 2004; Shen et al., 2007). Our simulated WSI agrees well with those years (Fig. 11). However, our results show the highest water stress for 2001 when water demand is taken into account. The estimated water demand doubled in Shanxi during the period 1960–2001, which intensified water stress by 40 % (2001). Shanxi has a large water demand with a population exceeding 30 million (2000). Heightened water demand thus has a large impact on water scarcity while climate signals are the main determinant for onsets of droughts and drought intensities in Shanxi.

#### 3.6.4 Turkey

Turkey characterized by temperate Mediterranean climate has a dry summer followed by a wet winter. The country is exposed to recurrent drought conditions partly due to unevenly distributed precipitation within the territory, where the central parts annually receive around 500 mm while coastal parts annually enjoy more than 1000 mm. After a major wet period 1962–1970 persistent dry conditions started after the mid-1970s and major droughts resulted in 1973, 1977, 1984, 1989–1991, 1992–1994 and 1999–2001 (Türkes, 1996; Komuscu, 2001; Yildiz, 2009). Although 1973 was the driest year (Türkes, 1996), our results show severer water stress after the mid-1980s, if growing water demand is taken into account (Fig. 11). Increased irrigation water demand contributed most of the heightened water demand, while the population more than doubled to 70 million in 2001. The increased water demand consistently enhanced the intensities of water scarcity by more than 50 % after the mid-1980s. Water consumption has become a decisive factor determining the intensity of water scarcity in Turkey while climate variability dominated the onsets and intensities of water scarce conditions before the 1980s.





HESSD
8, 7399–7460, 2011

### 3.6.5 Romania

Romania in South East Europe has a temperate to continental climate, with varying annual precipitation from 400 to more than 1000 mm. Nearly half of the country's surface freshwater is supplied through the Danube River. In 1970 Romania suffered from extensive floods due to excessive rainfall in combination with snowmelt while the country experienced major droughts during the periods 1986-1988, 1990, 1992, 1994–1995 and 2000 due to rainfall deficits (Sandu and Mateescu, 2009; Mihailescu et al., 2010). Our simulated WSI agrees well with those years (Fig. 11e) but our results also indicate that the reported droughts were mostly due to increased water demand. Our estimated water demand quintupled between 1960 and 2001, which is close to the estimates of Zavoianu (1993). Agricultural water demand amounts to half of the total water demand and exhibits a large inter-annual variability, i.e. larger green water availability as a result of above average rainfall reduced irrigation water demand notably in 1991, 1997 and 1999. Overall it can be seen that in Romania the major droughts after the 1980s were anthropogenically driven due to heightened water demand rather than being climate-induced.

### 3.6.6 Bulgaria

Bulgaria, a southern neighbour of Romania, suffers from frequent droughts. Climate records indicate that precipitation was in a decreasing trend after the early 1980s until the early 2000s, where annual precipitation was 80 % of the normal during the period (Alexandrov and Genev, 2003; Knight et al., 2004; Koleva and Alexandrov, 2008). As a result, prolonged droughts occurred during the period 1982–1994 in which droughts of 1985–1986 and 1989–1990 were particularly severe (Knight et al., 2004). Our simulated WSI clearly shows heightened water stress during the same period (Fig. 11f), but also suggests that during the 1980s water scarcity was intensified by 50 % as a result of heightened water demand which doubled compared to that for 1960. Estimated water demand diminished after the 1990s due to decreased overall usage which





HESSD
8, 7399–7460, 2011

subsequently reduced the intensity of water scarcity.

### 3.6.7 Cuba

Cuba, located in the North Caribbean Sea, has moderate (sub-)tropical climate. The wet season starts in May and continues until October followed by a dry season. Cuba receives abundant rainfall which annually exceeds 1300 mm but also faces water shortage in the dry season (Naranjo-Diaz and Pérez, 2007). Freshwater withdrawal, being one of the highest in the Caribbean, substantially increased from 8 to 13 $km^3\,yr^{-1}$ over the period 1975-1990, mainly due to irrigation, because Cuba increased irrigated areas for water-consuming crops such as rice and sugarcane (United States Department of Agriculture, 2008). The increase in the freshwater withdrawal diminished after the 1990s along with the country's economic decline. Our estimated gross demand is in line with United States Department of Agriculture (2008) and the FAO AQUASTAT data base while Fig. 11g shows the estimated net demand along with the simulated WSI. Our results indicate that increased water demand considerably worsened Cuba's water stress after the 1970s. The heightened water demand enhanced the intensity of water stress by 100 % up to 200 % after the 1980s. These results thus show the dominant role of agricultural water consumption in aggravating Cuba's water scarcity, while climate variability has only a minor impact.

## 4 Discussion and conclusions

To assess the development of water stress over the recent past, we developed a method to reconstruct past water demand and confronted it against the blue water availability simulated by the state-of-the-art global hydrological model PCR-GLOBWB. The comparisons of the reconstructed water demand with the reported and available estimates showed good agreements throughout the period, which increases our confidence in the resulting water stress assessment. Similar to Kummu et al. (2010), our





HESSD
8, 7399–7460, 2011

results show a drastic increase of the global population under high water stress due to increased water demand during the period 1960–2001. Increased irrigation water demand associated with the rapid global population rise globally contributed much of the heightened water stress. Time series of simulated country-average WSI were consistent with reported periods of major drought events. These results show that increased water demand has a significant impact on the magnitude of water scarcity while climate variability is often a main determinant of the onsets and intensities of water scarcity. However, our results also indicate that some of the past observed droughts were anthropogenically driven due to increased water demand rather than being climate-induced.

Various uncertainties associate with the methodologies and data employed in this study. We combined the available global gridded data sets with the country statistics to compute sectoral water demand. Irrigation water demand being by far the largest demand is a major source of uncertainty. Wisser et al. (2008) observed 30 % increase of the global irrigation water demand with the irrigated areas of Thenkabail et al. (2006) over with that of Siebert et al. (2005, 2007) while they found that the climate data of NCEP/NCAR result 30 % lower compared to that of CRU (see Table 2). The results also vary by 20 % when the FAO Penman-Monteith method or the Priestley-Taylor method is used to compute reference evapotranspiration (Siebert and Döll, 2010). The use of efficiency factors and the inclusion of green water availability by irrigated crops provide further sources of uncertainties (Wada et al., 2011). The results also vary with/without considering contributions of non-renewable and non-local blue water (IPOT/ILIM; cf., Rost et al., 2008). Furthermore, our past extents of irrigated areas are based on the country statistics but were distributed to 0.5° by using the present gridded irrigated areas. This method is unable to reproduce changes in the distribution within countries, which causes significant uncertainties primarily before the 1970s when many countries initiated intensive irrigation developments. However, it adequately reflects the large-scale dynamics of the expanding irrigated areas over the past decades (Wisser et al., 2010). The comparisons of the computed irrigation water demand showed good





HESSD
8, 7399–7460, 2011

agreements with the reported values for most of the countries while the large deviations were observed for several countries where irrigated areas are likely overestimated. In Iraq, for example, large parts of the irrigated areas remained uncultivated for some of the past periods.

Past economic development was approximated by using GDP, electricity production, energy and household consumption, which yields another source of uncertainty. For instance, we observed large deviations in computed gross industrial and domestic water demand in comparisons with reported water withdrawal for some of Middle American countries, where the computed WUI (see Sect. 2.3.4) may need to be further adjusted, although the validating data is scarce. The interpolated recycling ratios which account for return flow from the industrial and domestic sectors also cause uncertainties, but their potential errors are small compared to errors in irrigation water demand due to their smaller demands. Our recycling ratios were set lower than Shiklomanov (2000b) who proposes the global averages of 90 % and 85 % for industrial and domestic sector. These recycling ratios might be too optimistic particularly for developing countries with a low technological capability, where water recycling efficiency is expected to be lower compared to that for developed countries. Wada et al. (2011) indicated that the recycling ratio increased from 40 % to 80 % over the period 1960–2001 in Japan. Overall, the computed demands and reported values agree well for most of the countries.

Estimated groundwater abstraction is subject to large uncertainties. For instance, a considerable part of groundwater abstraction in major irrigated regions, such as North West India and North East Pakistan, may remain unreported. We used groundwater abstraction of 190 $km^3$ for 2000 for India while Foster and Loucks (2006) suggest 240 $km^3$. Given the fact that non-reported groundwater abstraction may be prevalent, implicit methods to estimate groundwater abstraction (e.g., Vörösmarty et al., 2005; Rost et al., 2008; Wisser et al., 2010; Hanasaki et al., 2010) have a clear advantage in countries where no abstraction rates have been reported. However, potential errors in these methods might be large given the considerable variation among these estimates (see Table 4). We therefore opted to use the country statistics regardless of the missing



HESSD
8, 7399–7460, 2011

values in several countries (e.g., Afghanistan and the Former Yugoslavia).

We used gross water demand as an estimate of water withdrawal and net water demand as that of consumptive water use as usually done in most of previous studies. This potentially leads an overestimation because actual withdrawal and consumption may be lower as a result of physical, technological or socio-economic limitations that exist in various countries. However, comparison of computed gross water demand with reported water withdrawal and computed net water demand with estimated consumptive water use showed overall good agreement. This consequently increases our confidence on the results but further improvements of water demand estimates undoubtedly increase an accuracy of water stress assessments.

In conclusion, this study quantified the past trajectories of water demand and climate variability that were liable to lead to heightened water scarcity. We also explored new data sources, approaches to assess water scarcity and highlights sources of uncertainty that may assist to increase the reliability of future studies on water scarcity. Our results show the strong anthropogenic intensification by human water consumption on water scarcity in several countries which underwent a consistent water demand growth over the period 1960–2001. In those countries climate variability has a relatively minor impact on the water scarcity. Thus, further increase in water demand will undoubtedly make future potential droughts severer. It is clear that managing water demand is a key factor to ease drought intensities.

*Acknowledgements.* This study was financially supported by Research Focus Earth and Sustainability of Utrecht University (Project FM0906: *Global Assessment of Water Resources*). This research benefited greatly from the availability of invaluable data sets as acknowledged in the references.





HESSD

8, 7399–7460, 2011



Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

## References

Alcamo, J., Henrichs, T., and Rösch, T.: World Water in 2025-Global modeling and scenario analysis for the World Commission on Water for the 21st Century, Kassel World Water Series 2, Center for Environmental Systems Research, University of Kassel, Germany, 2000. 7411, 7440

Alcamo, J., Döll, P., Henrichs, T., Kaspar, K., Lehner, B., Rösch, T., and Siebert, S.: Development and testing of the WaterGAP 2 global model of water use and availability, Hydrol. Sci. J., 48, 317–338, 2003. 7415

Alcamo, J., Flörke, M., and Märker, M.: Future long-term changes in global water resources driven by socio-economic and climatic changes, Hydrol. Sci. J., 52, 247–275, 2007. 7408, 7440

Alexandrov, V. and Genev, M.: Climate Variability and Change Impact on Water Resources in Bulgaria, European Water, 1, 25–30, 2003. 7425

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration – Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy, 1998. 7412

Arnell, N. W.: Climate change and global water resources, Global Environ. Change, 9, 31–49, 1999. 7440

Arnell, N. W.: Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environ. Change, 14, 31–52, 2004. 7401, 7440

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century, Global Change Biol., 13, 679–706, doi:10.1111/j.1365-2486.2006.01305.x, 2007. 7407, 7441

Chao, B. F., Wu, Y. H., and Li, Y. S.: Impact of artificial reservoir water impoundment on global sea level, Science, 320, 212–214, doi:10.1126/science.1154580, 2008. 7401

Chow, V. T., Maidment, D. R., and Mays, L. W.: Applied Hydrology, McGraw-Hill, New York, USA, 1988. 7412

Döll, P.: Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment, Environ. Res. Lett., 4, 035006, doi:10.1088/1748-9326/4/3/035006, 2009. 7415, 7443

Döll, P. and Lehner, B.: Validating of a new global 30-minute drainage direction map, J. Hydrol., 258, 214–231, 2002. 7412





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

Döll, P. and Siebert, S.: A digital global map of irrigated areas, ICID J., 49, 55–66, 2000. 7441
Döll, P. and Siebert, S.: Global modeling of irrigation water requirements, Water Resour. Res., 38, 8.1–8.10, doi:10.1029/2001WR000355, 2002. 7403, 7405, 7407, 7441
Döll, P., Kaspar, F., and Lehner, B.: A global hydrological model for deriving water availability indicators: model tuning and validation, J. Hydrol., 270, 105–134, 2003. 7411, 7440
Döll, P., Fiedler, K., and Zhang, J.: Global-scale analysis of river flow alterations due to water withdrawals and reservoirs, Hydrol. Earth Syst. Sci., 13, 2413–2432, doi:10.5194/hess-13-2413-2009, 2009. 7406
Els, A. J. E. and Rowntree, K. M.: Water resources in the sanannah regions of Botswana, Tech. rep., EU INCO/UNEP/SCOPE Southern African Savannas Project, 2003. 7406
Evans, L. T.: Adapting and improving crops: The endless task, Philos. Trans. R. Soc. Lond., B. Biol. Sci., 352, 901–906, doi:10.1098/rstb.1997.0069, 1997. 7441
Falkenmark, M.: The massive water scarcity now threatening Africa-why isn't it being addressed?, Ambio, 18, 112–118, 1989. 7403
Falkenmark, M., Kijne, J. W., Taron, B., Murdoch, G., Sivakumar, M. V. K., and Craswell, E.: Meeting Water Requirements of an Expanding World Population [and Discussion], Phil. Trans. R. Soc. Lond., B., 352, 929–936, 1997. 7404
Falkenmark, M., Berntell, A., Jägerskog, A., Lundqvist, J., Matz, M., and Tropp, H.: On the Verge of a New Water Scarcity: A Call for Good Governance and Human Ingenuity, Tech. rep., Stockholm International Water Institute Policy Brief, Stockholm International Water Institute, 2007. 7404
Fekete, B. M., Vörösmarty, C. J., and Grabs, W.: High-resolution fields of global runoff combining observed river discharge and simulated water balances, Global Biogeochem. Cy., 16, 1042, doi:10.1029/1999GB001254, 2002. 7443
Fiedler, K. and Döll, P.: Global modelling of continental water storage changes sensitivity to different climate data sets, Adv. Geosci., 11, 63–68, doi:10.5194/adgeo-11-63-2007, 2007. 7412
Flörke, M. and Alcamo, J.: European Outlook on Water Use: Final Report, Tech. rep., Center for Environmental Systems Research, University of Kassel, Germany, 2004. 7407
Foster, S. and Loucks, D. P. (eds.): Non-Renewable Groundwater Resources: A guidebook on socially-sustainable management for water-policy makers, IHP-VI, Series on Groundwater No. 10, UNESCO, Paris, France, 2006. 7428
Gerten, D., Schaphoff, S., and Lucht, W.: Potential future changes in water limitation of the

terrestrial biosphere, Clim. Change, 80, 277–299, doi:10.1007/s10584-006-9104-8, 2007. 7441

Gleick, P. H., Cooley, H., Cohen, M. J., Morikawa, M., Morrison, J., and Palaniappan, M., eds.: The Worlds Water 2008–2009, The Biennial Report on Freshwater Resources, Island Press, Washington, DC, USA, 2009. 7410

Global Runoff Data Centre: Long-term mean monthly discharges and annual characteristics of GRDC stations, http://www.bafg.de, 2008. 7419

Guhathakurta, P. and Rajeevan, M.: Trends in the rainfall pattern over India, NCC Res. Report, 2, 1–23, 2006. 7421

Haddeland, I., Skaugen, T., and Lettenmaier, D. P.: Anthropogenic impacts on continental surface water fluxes, Geophys. Res. Lett., 33, L08 406, doi:10.1029/2006GL026047, 2006. 7413

Hagemann, S. and Gates, L. D.: Improving a sub-grid runoff parameterization scheme for climate models by the use of high resolution data derived from satellite observations, Clim. Dyn., 21, 349–359, 2003. 7412

Hanasaki, N., Kanae, S., and Oki, T.: A reservoir operation scheme for global river routing models, J. Hydrol., 327, 22–41, 2006. 7407, 7410, 7440, 7441

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources Part 1: Model description and input meteorological forcing, Hydrol. Earth Syst. Sci., 12, 1007–1025, doi:10.5194/hess-12-1007-2008, 2008. 7440, 7443

Hanasaki, N., Kanae, S. Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources - Part 2: Applications and assessments, Hydrol. Earth Syst. Sci., 12, 1027–1037, 2008b, http://www.hydrol-earth-syst-sci.net/12/1027/2008/. 7402, 7407, 7440, 7441, 7443

Hanasaki, N., Inuzuka, T., Kanae, S., and Oki, T.: An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model, J. Hydrol., 384, 232–244, 2010. 7407, 7415, 7428, 7441, 7443

Islam, S., Oki, T., Kanae, S., Hanasaki, N., Agata, Y., and Yoshimura, K.: A grid-based assessment of global water scarcity including virtual water trading, Water Resour. Manag., 21, 19–33, doi:10.1007/s11269-006-9038, 2007. 7440

Joshi, U. R. and Rajeevan, M.: Trends in Precipitation Extremes over India, NCC, Res. Report, 3, 1–25, 2006. 7421

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, Bull. Am. Meteorol. Soc., 77, 437–471, 1996. 7441

Klein Goldewijk, K. and van Drecht, G.: Integrated modelling of global environmental change: An overview of IMAGE 2.4, chap. HYDE 3: Current and historical population and land cover, 93–112, MNP (Netherlands Environmental Assessment Agency), Bilthoven, The Netherlands, 2006. 7410

Knight, C. G., Raev, I., and Staneva, M. P. (Eds.): Drought in Bulgaria: A Contemporary Analog for Climate Change, Ashgate Publishing, UK, 2004. 7425

Koleva, E. and Alexandrov, V.: Drought in the Bulgarian low regions during the 20th Century, Theor. Appl. Climatol., 92, 113–120, 2008. 7425

Komuscu, A.: An Analysis of Recent Drought Conditions in Turkey in Relation to Circulation Patterns, Drought Network News (1994-2001), Tech. rep., Drought - National Drought Mitigation Center, 2001. 7424

Kummu, M., Ward, P. J., de Moel, H., and Varis, O.: Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia, Environ. Res. Lett., 5, 034 006, 2010. 7402, 7420, 7426, 7440, 7448

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z., and Shiklomanov, I. A.: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, chap. Freshwater resources and their management, 173–210, Cambridge University Press, Cambridge, UK, 2007. 7404

Lehner, B. and Döll, P.: Development and validation of a global database of lakes, reservoirs and wetlands, J. Hydrol., 296, 1–22, 2004. 7413

Liverman, D. M.: Drought: A Global Assessment, chap. 31: Adaptation to drought in Mexico, 35–45, Routledge, New York, USA, 2000. 7422

Llamas, R., Back, W., and Margat, J.: Groundwater use: Equilibrium between social benefits and potential environmental costs, Appl. Hydrol., 1, 3–14, 1992. 7443

Meeson, B. W., Corprew, F. E., McManus, J. M. P., Myers, D. M., Closs, J. W., Sun, K. J., Sunday, D. J., and Sellers, P. J.: ISLSCP Initiative I - Global Datasets for Landatmosphere Models, 1987-1988, Tech. rep., NASA, 1995. 7441





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

Mihailescu, M., Mares, I., Mares, C., Hbener, H., and Cubasch, U.: Climate Variability of Drought Indices in Romania in the 20th and 21st Centuries, in: BALWOIS 2010: Water Observation and Information System for Balkan Countries, 25–29 May, Ohrid, Republic of Macedonia, 2010. 7425

Ministry of Land, Infrastructure, and Transport in Japan: Water Resources in Japan, Ministry of Land, Infrastructure, and Transport in Japan, Tokyo, Japan, 2007(in Japanese). 7409

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Clim., 25, 693–712, doi:10.1002/joc.1181, 2005. 7441

Monfreda, C., Ramankutty, N., and Foley, J. A.: Farming the planet, part 2: the geographic distribution of crop areas and yields in the year 2000, Global Biogeochem. Cy., 22, GB1022, doi:10.1029/2007GB002947, 2008. 7441

Naranjo-Diaz, L. and Pérez, P. C.: Cuba Country Case Study: Impacts and Responses to the 1997–1998 EL Niño Event, Tech. rep., University Corporation of Atmospheric Research, 2007. 7426

Nathan, K. K.: Characteristics of Drought in Kerala, India, Drought Network News (1994-2001), Tech. rep., Drought - National Drought Mitigation Center, 2000. 7423

New, M., Hulme, M., and Jones, P. D.: Representing twentieth century space-time climate variability. Part 2: development of 1901–1996 monthly grids of terrestrial surface climate, J. Clim., 13, 2217–2238, 2000. 7411, 7412, 7441

New, M., Lister, D., Hulme, M., and Makin, I.: A high-resolution data set of surface climate over global land areas, Clim. Res., 21, 1–25, 2002. 7412

Ngo-Duc, T., Polcher, J., and Laval, K.: A 53-year forcing data set for land surface models, J. Geophys. Res., 110, D06 116, doi:10.1029/2004JD005434, 2005. 7441

Oki, T. and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068–1072, doi:10.1126/science.1128845, 2006. 7408, 7409

Oki, T., Agata, Y., Kanae, S., Saruhashi, T., Yang, D., and Musiake, K.: Global assessment of current water resources using total runoff-integrating pathways, Hydrol. Sci. J., 46, 983–996, 2001. 7401, 7440

Portmann, F., Siebert, S., Bauer, C., and Döll, P.: Global data set of monthly growing areas of 26 irrigated crops, Frankfurt Hydrology Paper 06, Tech. rep., Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 2008. 7441

Portmann, F., Siebert, S., Bauer, C., and Döll, P.: MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modelling, Global Biogeochem. Cy., 24, GB1011, doi:10.1029/2008GB003435, 2010. 7405, 7407

Postel, S.: Pillar of Sand: Can the Irrigation Miracle Last?, ISBN0-393-31937-7, W. W. Norton, New York, USA, 1999. 7443

Ramankutty, N., Evan, A. T., Monfreda, C., and Foley, J. A.: Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cy., 22, GB1003, doi:10.1029/2007GB002952, 2008. 7405

Robock, A., Vinnikov, K. Y., Schlosser, C. A., Speranskaya, N. A., and Xue, Y. K.: Use of mid-latitude soil-moisture and meteorological observations to validate soil-moisture simulations with biosphere and bucket models, J. Clim., 8, 15–35, 1995. 7441

Rohwer, J., Gerten, D., and Lucht, W.: Development of functional types of irrigation for improved global crop modelling, PIK Report 104, Tech. rep., Potsdam Institute for Climate Impact Research, Potsdam, Germany, 2007. 7407, 7415

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., 44, W09 405, doi:10.1029/2007WR006331, 2008. 7407, 7415, 7427, 7428, 7441, 7443

Sandu, I. and Mateescu, E.: Monitoring soil drought in Romania and the impact on agriculture, in: Inter-regional workshop on indices and yearly warning systems for drought, 8–11 December, Lincoln, Nebraska, USA, 2009. 7425

Shah, T., Molden, D., Sakthivadivel, R., and Seckler, D.: The global groundwater situation: overview of opportunities and challenges, Tech. rep., International Water Management Institute, Colombo, Sri Lanka, 2000. 7443

Sheffield, J. and Wood, E. F.: Characteristics of global and regional drought, 1950–2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle, J. Geophys. Res., 112, D17 115, doi:10.1029/2006JD008288, 2007. 7421

Shen, C., Wang, W. C., Hao, Z., and Gong, W.: Exceptional drought events over eastern China during the last five centuries, Clim. Change, 85, 453–471, 2007. 7421, 7424

Shen, Y., Oki, T., Utsumi, N., Kanae, S., and Hanasaki, N.: Projection of future world water resources under SRES scenarios: water withdrawal, Hydrol. Sci. J., 53, 11–33, 2008. 7408, 7445

Shiklomanov, I. A. (Ed.): Assessment of water resources and water availability in the world.





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

Comprehensive assessment of the freshwater resources of the world, World Meteorological Organization and the Stockholm Environment Institute, 1997. 7409
Shiklomanov, I. A.: World Water Scenarios Analyses, chap. World water resources and water use: Present assessment and outlook for 2025, Earthscan, London, UK, 2000a. 7417, 7445, 7446, 7449, 7455
Shiklomanov, I. A.: Appraisal and assessment of world water resources, Water Int., 25, 11–32, 2000b. 7417, 7428, 7445, 7446, 7449, 7455
Siebert, S. and Döll, P.: The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops, Frankfurt Hydrology Paper 07, Tech. rep., Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 2008. 7441
Siebert, S. and Döll, P.: Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, J. Hydrol., 384, 198–217, 2010. 7407, 7427, 7441
Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K., and Feick, S.: Development and validation of the global map of irrigation areas, Hydrol. Earth Syst. Sci., 9, 535–547, doi:10.5194/hess-9-535-2005, 2005. 7405, 7427, 7441
Siebert, S., D. P., Feick, S., Hoogeveen, J., and Frenken, K.: Global Map of Irrigation Areas Version 4.0.1., Tech. rep., Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 2007. 7427, 7441
Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T.: Groundwater use for irrigation - a global inventory, Hydrol. Earth Syst. Sci., 14, 1863–1880, doi:10.5194/hess-14-1863-2010, 2010. 7443
Simon, A. and Mohankumar, K.: Spatial variability and rainfall characteristics of Kerala, Proc. Indian Acad. Sci., 113, 211–221, 2004. 7423
Smith, M.: CROPWAT – a computer program for irrigation planning and management, FAO Irrigation and Drainage Paper 46, FAO, Rome, Italy, 1992. 7407
Stahle, D. W., Cook, E. R., Villanueva, D. J., Fye, F. K., Burnette, D. J., Griffin, R. D., Soto, R. A., Seager, R., and Richard, R. R.: Early 21st-Century Drought in Mexico, Eos, Trans. Amer. Geophys. Union, 90, 89–90, 2009. 7422, 7423
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., and de Haan, C.: Livestocks long shadow: Environmental issues and options, FAO, Rome, Italy, iSBN 978-92-5-105571-7, 2006. 7406, 7417, 7444
Sulser, T., Ringler, C., Zhu, T., Msangi, S., Bryan, E., and Rosegrant, M. W.: Green and blue





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

water accounting in the Ganges and Nile basins: implications for food and agricultural policy, J. Hydrol., 384, 276–291, 2010. 7407, 7441

Takeuchi, K. and Murthy, V. V. N.: Water lifting devices and groundwater management for irrigation: Report of the Expert Consultation of the Asian Network on Water Lifting Devices for Irrigation, chap. Overview of water lifting devices and groundwater management for irrigation in the Asia-Pacific region, FAO, Rome, Italy, 1994. 7443

The 2030 Water Resources Group: Charting Our Water Future: Economic frameworks to inform decision-making, Tech. rep., The 2030 Water Resources Group, 2009. 7413

Thenkabail, P. S., Biradar, C. M., Turral, H., Noojipady, P., Li, Y. J., Vithanage, J., Dheeravath, V., Velpuri, M., Schull, M., Cai, X. L., and Dutta, R.: An Irrigated Area Map of the World (1999) derived from Remote Sensing, Res., Rep., 105, Tech. rep., International Water Management Institute, Colombo, Sri Lanka, p. 74, 2006. 7405, 7427, 7441

Thenkabail, P. S., Biradar, C. M., Noojipady, P., Dheeravath, V., Li, Y. J., Velpuri, M., Reddy, G. P. O., Cai, X. L., Gumma, M., Turral, H., Vithanage, J., Schull, M., and Dutta, R.: A Global Irrigated Area Map (GIAM) Using Remote Sensing at the End of the Last Millennium., Tech. rep., International Water Management Institute, Colombo, Sri Lanka, p. 63, 2008. 7405

Türkes, M.: Meteorological Drought in Turkey: A Historical Perspective, 1930-93, Drought Network News (1994–2001), Tech. rep., Drought - National Drought Mitigation Center, 1996. 7424

Tyagi, B. K., Hiriyan, J., Samuel, P., Tewari, S. C., and Paramasivan, R.: Dengue in Kerala: A Critical Review, ICMR Bulletin, 36, 13–22, 2006. 7423

UNEP: Groundwater: A threatened resource, UNEP Environment Library No. 15, Tech. rep., UNEP, Nairobi, Kenya, p. 36, 1996. 7402

United States Department of Agriculture: Cubas Food & Agriculture Situation Report, Tech. rep., United States Department of Agriculture, p. 68, 2008. 7426

Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J. F., Morcrette, J. J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Quart. J. Roy. Meteorol. Soc., 131, 2961–3012, 2005. 7412





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

Van Beek, L. P. H. and Bierkens, M. F. P.: The Global Hydrological Model PCR-GLOBWB: Conceptualization, Parameterization and Verification, Report, Tech. rep., Department of Physical Geography, Utrecht University, Utrecht, The Netherlands, http://vanbeek.geo.uu.nl/suppinfo/vanbeekbierkens2009.pdf/, 2009. 7411

Van Beek, L. P. H., Wada, Y., and Bierkens, M. F. P.: Global monthly water stress: I. Water balance and water availability, Water Resour. Res., 47, W07 517, doi:10.1029/2010WR009791, 2011. 7407, 7411, 7412, 7419, 7420, 7440

Vörösmarty, C. J., Sharma, K. P., Fekete, B. M., Copeland, A. H., Holden, J., Marble, J., and Lough, J. A.: The storage and aging of continental runoff in large reservoir systems of the world, Ambio, 26, 210–219, 1997. 7440

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: Vulnerability from climate change and population growth, Science, 289, 284–288, 2000. 7411, 7440, 7443

Vörösmarty, C. J., Leveque, C., and Revenga, C.: Millennium Ecosystem Assessment Volume 1: Conditions and Trends, chap. 7: Freshwater ecosystems, 165–207, Island Press, Washington DC, USA, 2005. 7401, 7409, 7413, 7415, 7428, 7443

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., and Bierkens, M. F. P.: Global depletion of groundwater resources, Geophys. Res. Lett., 37, L20 402, doi:10.1029/2010GL044571, 2010. 7414, 7415, 7420, 7443

Wada, Y., van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R., and Bierkens, M. F. P.: Global monthly water stress: II. Water demand and severity of water, Water Resour. Res., 47, W07 518, doi:10.1029/2010WR009792, 2011. 7401, 7402, 7403, 7407, 7409, 7410, 7411, 7413, 7414, 7427, 7428, 7440, 7441

Widén-Nilsson, E., Halldin, S., and Xu, C.: Global water-balance modelling with WASMOD-M: Parameter estimation and regionalization, J. Hydrol., 340, 105–118, 2007. 7411

Wilhite, D. and Glantz, M. H.: Understanding the drought phenomenon: the role of definitions, Water Int., 10, 111–120, 1985. 7422

Wint, G. R. W. and Robinson, T. P.: Gridded livestock of the world 2007, FAO, Rome, Italy, 2007. 7406

Wisser, D., Frolking, S., Douglas, E. M., Fekete, B. M., Vörösmarty, C. J., and Schumann, A. H.: Global irrigation water demand: Variability and uncertainties arising from agricultural and climate data sets, Geophys. Res. Lett., 35, L24 408, doi:10.1029/2008GL035296, 2008. 7403, 7427, 7441

Wisser, D., Fekete, B. M., Vörösmarty, C. J., and Schumann, A. H.: Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network- Hydrology (GTN-H), Hydrol. Earth Syst. Sci., 14, 1–24, doi:10.5194/hess-14-1-2010, 2010. 7408, 7415, 7427, 7428, 7443

World Resources Institute: World Resources: A Guide to the Global Environment 1998–1999, World Resources Institute, Washington DC, USA, 1998. 7409

World Water Assessment Programme: Water for people: Water for life, The United Nations World Water Development Report, UNESCO, Paris, France, 2003. 7413

World Water Assessment Programme: Water in a Changing World, The United Nations World Water Development Report 3, UNESCO, Paris, France, 2009. 7401

Yildiz, O.: Assessing temporal and spatial characteristics of droughts in the Hirfanli dam basin, Turkey, Sci. Res. Essays, 4, 249–255, 2009. 7424

You, L., Wood, S., and Wood-Sichra, U.: Generating global crop distribution maps: from census to grid, in: Selected paper at IAAE 2006 Conference, Brisbane, Australia, 2006. 7441

Zavoianu, I.: Romania's Water Resources and Their Use, GeoJournal, 29, 19–30, 1993. 7425

Zektser, I. S. and Everett, L. G. (Eds.): Groundwater Resources of the World and Their Use, IHP-VI, Series on Groundwater No. 6, UNESCO, Paris, France, 2004. 7443

Zhuguo, M. A., Li, D. N., and Yuewen, H. U.: The extreme dry/wet events in northern China during recent 100 years, J. Geogr. Sci., 14, 275–281, 2004. 7421, 7424





HESSD

8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

**Table 1.** Previous global assessments of blue water stress.

| Previous studies | Global hydrological model (spatial resolution) | Reservoir/River routing scheme | Gross/Net water demand (Livestock, Irrigation, Industry, Domestic) | Additional components | Population under high water stress (billion; % of total) | Year | Spatial resolution | Temporal resolution |
|---|---|---|---|---|---|---|---|---|
| Arnell (1999) | Macro-PDM (0.5°) | – | Irr., Ind. Dom. (Gross) | Future scenario (Conventional development scenario) | 0.4 (8 %) | 1990 | Country | Annual |
| Vörösmarty et al. (2000) | WBM (0.5°) | Reservoir routing scheme (Vörösmarty et al., 1997) | Irr., Ind., Dom. (Gross) | Future scenarios (Sc1, Sc2, Sc3) | 1.8 (31 %) | 1995 | 0.5° | A nnual |
| Alcamo et al. (2000) | WaterGAP (0.5°) | – | Irr., Ind., Dom. (Gross) | Future scenarios (Business-as-usual) | 2.1 (37 %) | 1995 | Watershed | Annual |
| Oki et al. (2001) | TRIP (0.5°) | Exogenous runoff scheme | Irr., Ind., Dom. (Gross) | – | 1.7 (30 %) | 1995 | 0.5° | Annual |
| Arnell (2004) | Macro-PDM (0.5°) | – | Irr., Ind., Dom. (Gross) | Future scenarios (A1, A2, B1, B2) | 1.4 (25 %) | 1995 | Watershed | Annual |
| Islam et al. (2007) | TRIP (0.5°) | Exogenous runoff scheme (Oki et al., 2001) | Unit water requirements to produce crop and livestock commodities (Gross) | Virtual water flow | 1.2 (20 %) | 2000 | 0.5° | Annual |
| Alcamo et al. (2007) | WaterGAP (0.5°) | Lake and wetland scheme (Döll et al., 2003) | Liv., Irr., Ind., Dom. (Gross) | Future scenarios (A2, B2) | 2.3 (40 %) | 1995 | 0.5° | Annual |
| Hanasaki et al. (2008a,b) | H07 (1.0°) | Reservoir routing scheme (Hanasaki et al., 2006) | Irr., Ind., Dom. (Gross) | Environmental flow requirements | 1.9 (37 %) | 1995 | 1.0° | Subannual |
| Kummu et al. (2010) | STREAM (0.5°) | – | Per capita water withdrawal (Gross) | Millennial assesment (Years: 0-2005) | 2.3 (35 %) | 2005 | FPUs (Food Producing Units) | Several decades |
| Wada et al. (2011) | PCR-GLOBWB (0.5°) | Reservoir routing scheme (Van Beek et al., 2011) Exogeneous runoff scheme | Liv., Irr., Ind., Dom. (Net) | Groundwater abstraction Desalinated water use | 1.1 (18 %)$^{annual}$ 1.7 (28 %)$^{subannual}$ | 2000 | 0.5° | Annual Subannual |





HESSD
8, 7399–7460, 2011

Table 2. Previous global studies to estimate irrigation water demand.

| Previous studies | Climate input | Reference evapotranspiration | Irrigated area | Crop | Crop calendar | Additional components | Gross/Net demand ($km^3 yr^{-1}$) | 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 | 2452/1091.5 | Average of 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 | 2254/1127 | Average of 1987-1988 | 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 | 2555/1364[IPOT] 1161/636[ILIM] | Average of 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] Thenkabail et al. (2006)[WMI] | Monfreda et al. (2008) | Optimal growth | Irrigation efficiency Flooding applied to paddy irrigation | 3000-3400[CRU_FAO] 3700-4100[CRU_IWMI] 2000-2400[NCEP_FAO] 2500-3000[NCEP_IWMI] | Average of 1963-2002 | 0.5° |
| Siebert and Döll (2010) | CRU TS 2.1 | FAO Penman-Monteith[PM] Priestley and Taylor[PT] | Portmann et al. (2008) | 26 crops | Portmann et al. (2008) | Green water use | 2099/1180[PM] 2404/1448[PT] | Average of 1998-2002 | 0.5° |
| 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 H08 (Hanasaki et al., 2008b) | Irrigation efficiency Virtual water flow | 2380/1530 | Average of 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) | 3128/1423[2000] 4060/1603[2025] 4396/1785[2050] | 2000 2025 2050 | 281 Food Producting Units |
| Wada et al. (2011) | CRU TS 2.1 | FAO Penman-Monteith | Portmann et al. (2008) | 26 crops | Portmann et al. (2008) Siebert and Döll (2008) | Green water use Irrigation efficiency | 2057/1176 | Average of 1958-2001 | 0.5° |



HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

**Table 3.** Past desalinated water use with the largest user (%) from 1960 to 2000 based on the FAO AQUASTAT data base.

| 1960 | 1970 | 1980 | 1990 | 2000 |
|---|---|---|---|---|
| | | Globe ($km^3\ yr^{-1}$) | | |
| 0.26 | 0.42 | 0.94 | 2.74 | 4.41 |
| | | Largest user | | |
| Saudi Arabia (62 %) | Saudi Arabia (55 %) | Saudi Arabia (40 %) | Saudi Arabia (25 %) | Kazakhstan (31 %) |





HESSD
8, 7399–7460, 2011

**Table 4.** Global estimates of groundwater abstraction.

| $km^3 yr^{-1}$ | Total/Non-renewable | Year | Gross/Net | Runoff/Recharge | Sources |
|---|---|---|---|---|---|
| | | Data based estiamtes | | | |
| Postel (1999) | NA/around 200 | NA | – | – | Based on various literature and statistics |
| IGRAC-GGIS | 734/NA | 2000 | – | – | Based on various literature and country statistics |
| Shah et al. (2000) | 750–800/NA | Contemporary conditions | – | – | FAO AQUASTAT, Llamas et al. (1992), Takeuchi and Murthy (1994) |
| Zektser and Everett (2004) | 600–700/NA | Contemporary conditions | – | – | Based on various country statistics |
| | | Model based estiamtes | | | |
| Vörösmarty et al. (2005) | NA/389$^{Irr.}$–830$^{Total}$ | Average of 1995–2000 | 3557$^{Total}$/1206$^{Irr.}$ | 39 294/NA | Implicitly simulated by WBM (0.5°) (Vörösmarty et al., 2000, 2005; Fekete et al., 2002) |
| Rost et al. (2008) | NA/730 | Average of 1971–2000 | 2534–2566 /1353–1375 | 36,921/NA | Implicitly simulated by LPJmL (0.5°) with four different precipitation inputs |
| Döll (2009) | 1100/NA | 2000 | 4020/1300 | 38,800/NA | Implicitly calculated based on water withdrawals and a fraction of groundwater to water withdrawals |
| Wisser et al. (2010) | 1708/1199 | Contemporary conditions | 2997/NA | 37,401/NA | Implicitly simulated by WBMplus (0.5°) |
| Hanasaki et al. (2010) | NA/703 | Average of 1985–1999 | NA/1690 | 41,820/NA | Implicitly simulated by H08 (1.0°) (Hanasaki et al., 2008a,b) |
| Siebert et al. (2010) | 545/NA | 2000 | NA/1277 | 39 549/12 600 | Based on statistics of 15,038 national or sub-national administrative units for irrigation purpose only |
| Wada et al. (2010) | 734(±82)/283(±40) | 2000 | NA/NA | 36 200/15 200 | Explicitly calculated based on IGRAC-GGIS data and simulated groundwater recharge (0.5°) |





HESSD
8, 7399–7460, 2011
Modelling global water stress of the recent past
Y. Wada et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

**Table 5.** Computed livestock water demand from 1960 to 2000 with the estimates of Steinfeld et al. (2006) for 2000.

| Year | $km^3 yr^{-1}$ | Cattle | Buffaloes | Sheep | Goats | Pigs | Poultry | Total |
|---|---|---|---|---|---|---|---|---|
| 1960 | This study | 8.05 (75.9 %) | 0.85 (8.0 %) | 1.13 (10.6 %) | 0.24 (2.3 %) | 0.15 (1.4 %) | 0.19 (1.8 %) | 10.61 (100.0 %) |
| 1970 | This study | 9.06 (74.8 %) | 0.96 (7.9 %) | 1.28 (10.6 %) | 0.31 (2.6 %) | 0.26 (2.1 %) | 0.24 (2.0 %) | 12.11 (100.0 %) |
| 1980 | This study | 10.25 (73.7 %) | 1.14 (8.2 %) | 1.29 (9.3 %) | 0.42 (3.0 %) | 0.47 (3.4 %) | 0.33 (2.4 %) | 13.90 (100.0 %) |
| 1990 | This study | 11.23 (71.5 %) | 1.39 (8.8 %) | 1.46 (9.3 %) | 0.53 (3.4 %) | 0.51 (3.2 %) | 0.59 (3.8 %) | 15.71 (100.0 %) |
| 2000 | This study | 10.86 (68.1 %) | 1.63 (10.2 %) | 1.21 (7.6 %) | 0.71 (4.5 %) | 0.61 (3.8 %) | 0.92 (5.8 %) | 15.94 (100.0 %) |
| | Steinfeld et al. (2006) | 11.40 (70.1 %) | 1.36 (8.6 %) | 1.11 (9.0 %) | 0.77 (3.4 %) | 0.69 (3.0 %) | 0.93 (3.6 %) | 16.26 (100.0 %) |





HESSD
8, 7399–7460, 2011

**Table 6.** Computed sectoral and total water demand compared with reported values from the FAO AQUASTAT and other estimates from 1960 to 2000.

| $km^3 yr^{-1}$ | Gross/Net demand | 1960 | 1970 | 1980 | 1990 | 2000 |
|---|---|---|---|---|---|---|
| | | | Agriculture (Irrigation) | | | |
| FAO AQUASTAT | Withdrawal | – | – | 1463 | 1996 | 2659 |
| Shen et al. (2008) | Gross | – | – | 1857 | 2271 | 2658 |
| Shiklomanov (2000a,b) | Withdrawal/Consumption | 1481/1005 | 1743/1186 | 2112/1445 | 2425/1691 | 2605/1834 |
| This study | Gross/Net | 1268/645 | 1519/756 | 1900/958 | 2258/1089 | 2628/1376 |
| | | | Industry | | | |
| FAO AQUASTAT | Withdrawal | – | – | 499 | 629 | 777 |
| Shen et al. (2008) | Gross | – | – | 543 | 642 | 777 |
| Shiklomanov (2000a,b) | Withdrawal/Consumption | 339/31 | 547/51 | 713/71 | 735/79 | 776/88 |
| This study | Gross/Net | 356/116 | 452/143 | 607/191 | 692/210 | 752/257 |
| | | | Domestic | | | |
| FAO AQUASTAT | Withdrawal | – | – | 189 | 260 | 377 |
| Shen et al. (2008) | Gross | – | – | 217 | 275 | 390 |
| Shiklomanov (2000a,b) | Withdrawal/Consumption | 118/21 | 160/29 | 219/38 | 305/45 | 384/50 |
| This study | Gross/Net | 85/57 | 119/77 | 201/126 | 262/157 | 328/198 |
| | | | Total | | | |
| FAO AQUASTAT | Withdrawal | – | – | 2151 | 2885 | 3812 |
| Shen et al. (2008) | Gross | – | – | 2615 | 3187 | 3824 |
| Shiklomanov (2000a,b) | Withdrawal/Consumption | 1968/1086 | 2526/1341 | 3175/1686 | 3633/1982 | 3973/2182 |
| This study | Gross/Net | 1709/818 | 2090/976 | 2708/1275 | 3212/1456 | 3708/1831 |





HESSD
8, 7399–7460, 2011

**Table 7.** Correlation between computed gross water demand and reported water withdrawal from the FAO AQUASTAT data base and between computed gross and net water demand and estimated water withdrawal and water consumption of Shiklomanov (2000a,b) per country. $R^2$ and $\alpha$ denote the coefficient-of-determination and the slope of regression line respectively.

| FAO AQUASTAT | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sector | | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 |
| Agriculture | $R^2$ | 0.98 | 0.98 | 0.96 | 0.97 | 0.97 | 0.99 | 0.98 |
| | $\alpha$ | 1.12 | 1.08 | 0.96 | 0.92 | 0.99 | 0.90 | 1.01 |
| Industry | $R^2$ | 0.98 | 0.99 | 0.98 | 0.97 | 0.97 | 0.92 | 0.98 |
| | $\alpha$ | 1.03 | 1.06 | 1.20 | 0.99 | 0.99 | 1.20 | 1.10 |
| Domestic | $R^2$ | 0.97 | 0.98 | 0.95 | 0.97 | 0.98 | 0.96 | 0.95 |
| | $\alpha$ | 0.85 | 0.98 | 0.95 | 0.88 | 0.90 | 1.10 | 0.92 |
| Total | $R^2$ | 0.96 | 0.98 | 0.99 | 0.96 | 0.96 | 0.98 | 0.96 |
| | $\alpha$ | 0.85 | 1.09 | 0.89 | 0.95 | 0.99 | 0.91 | 0.99 |

| Shiklomanov (2000a,b) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sector | | 1960 | 1970 | 1980 | 1990 | 1995 | 2000 |
| Total (gross) | $R^2$ | 0.92 | 0.91 | 0.94 | 0.97 | 0.95 | 0.95 |
| | $\alpha$ | 0.88 | 0.85 | 0.90 | 0.98 | 1.01 | 1.04 |
| Total (net) | $R^2$ | 0.96 | 0.97 | 0.96 | 0.97 | 0.95 | 0.94 |
| | $\alpha$ | 0.84 | 0.85 | 0.89 | 0.88 | 0.90 | 0.95 |





HESSD
8, 7399–7460, 2011

**Table 8.** Computed total and non-renewable groundwater abstraction for major groundwater users from 1960 and 2000.

| $km^3\ yr^{-1}$ | Total [1] | | Non-renewable [2] | | [2]/[1] (%) | | Increase in ratio (%) |
|---|---|---|---|---|---|---|---|
| Country | 1960 | 2000 | 1960 | 2000 | 1960 | 2000 | 1960–2000 |
| India | 87 | 190 | 21 | 75 | 24 | 40 | 67 |
| USA | 63 | 115 | 20 | 37 | 32 | 32 | 0 |
| China | 46 | 97 | 10 | 25 | 22 | 26 | 18 |
| Pakistan | 36 | 55 | 18 | 38 | 50 | 69 | 38 |
| Iran | 31 | 53 | 12 | 28 | 39 | 53 | 36 |
| Mexico | 18 | 38 | 5 | 12 | 28 | 32 | 14 |
| Saudi Arabia | 5 | 21 | 2 | 15 | 40 | 71 | 78 |
| Globe | 312 | 734 | 98 | 275 | 31 | 38 | 23 |





HESSD
8, 7399–7460, 2011

**Table 9.** Simulated results of the global population under different degrees of water stress with those of Kummu et al. (2010) from 1960 to 2000. Per class, population is given in billions and the corresponding fraction of the global population (%).

| Magnitude | No stress | Low stress | Moderate stress | High stress | Total | Year |
|---|---|---|---|---|---|---|
| Per capita water availability ($m^3$ $capita^{-1}$ $yr^{-1}$) | >1700 | 1700-1000 | <1000 | | | |
| WSI | WSI<0.1 | 0.1≤WSI<0.2 | 0.2≤WSI<0.4 | 0.4≥ WSI | | |
| Kummu et al. (2010) | 1.52 (92 %) | 0.10 (6 %) | | 0.03 (2 %) | 1.7 | 1900 |
| | 1.98 (81 %) | 0.23 (10 %) | | 0.09 (5 %) | 2.3 | 1940 |
| | 2.41 (81 %) | 0.29 (10 %) | | 0.28 (9 %) | 3.0 | 1960 |
| | 2.76 (62 %) | 0.97 (22 %) | | 0.71 (16 %) | 4.4 | 1980 |
| | 3.21 (50 %) | 0.95 (15 %) | | 2.30 (35 %) | 6.5 | 2005 |
| This study (annual assessment) | 2.4 (90 %) | 0.3 (10 %) | 0.1 (3 %) | 0.2 (7 %) | 3.0 | 1960 |
| | 2.8 (76 %) | 0.3 (8 %) | 0.2 (5 %) | 0.4 (11 %) | 3.7 | 1970 |
| | 3.2 (73 %) | 0.4 (9 %) | 0.3 (7 %) | 0.5 (11 %) | 4.4 | 1980 |
| | 3.7 (70 %) | 0.5 (9 %) | 0.4 (8 %) | 0.7 (13 %) | 5.3 | 1990 |
| | 3.8 (62 %) | 0.6 (10 %) | 0.5 (8 %) | 1.2 (20 %) | 6.1 | 2000 |
| This study (subannual assessment) | 1.9 (63 %) | 0.3 (10 %) | 0.3 (10 %) | 0.5 (17 %) | 3.0 | 1960 |
| | 2.2 (59 %) | 0.4 (11 %) | 0.4 (11 %) | 0.7 (19 %) | 3.7 | 1970 |
| | 2.4 (55 %) | 0.5 (11 %) | 0.5 (11 %) | 1.0 (23 %) | 4.4 | 1980 |
| | 2.8 (53 %) | 0.6 (11 %) | 0.7 (13 %) | 1.2 (23 %) | 5.3 | 1990 |
| | 2.9 (47 %) | 0.6 (10 %) | 0.8 (13 %) | 1.8 (30 %) | 6.1 | 2000 |





HESSD
8, 7399–7460, 2011

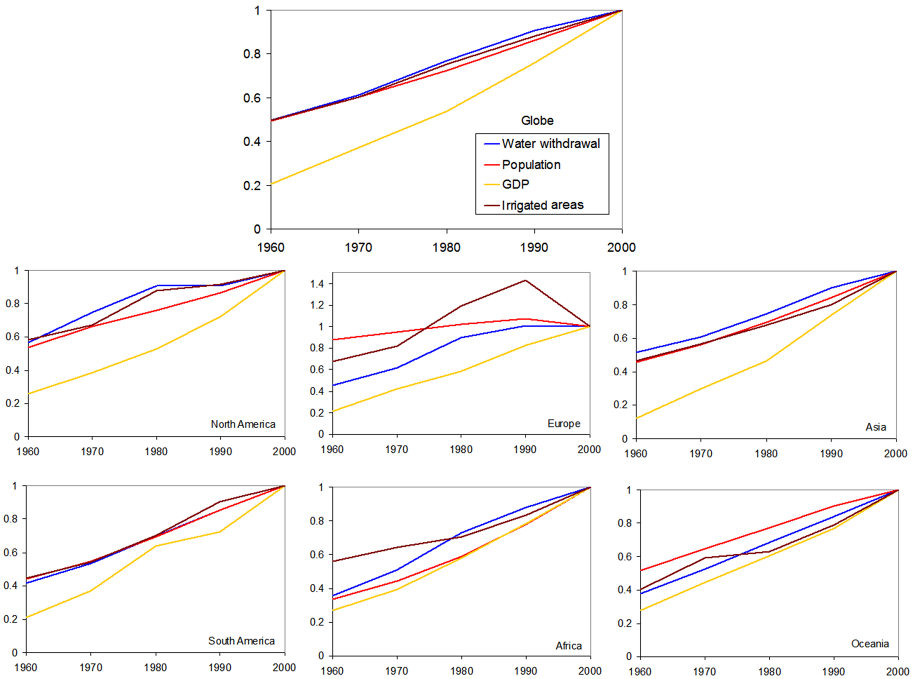


**Fig. 1.** Past trends of water withdrawal, population, GDP and irrigated areas from 1960 to 2000 over the Globe and for each continent. They are all indexed to 2000 to characterize their development against water withdrawal. Water withdrawal, population, GDP and irrigated areas were taken from Shiklomanov (2000a,b), World Bank and FAOSTAT, respectively.





HESSD
8, 7399–7460, 2011

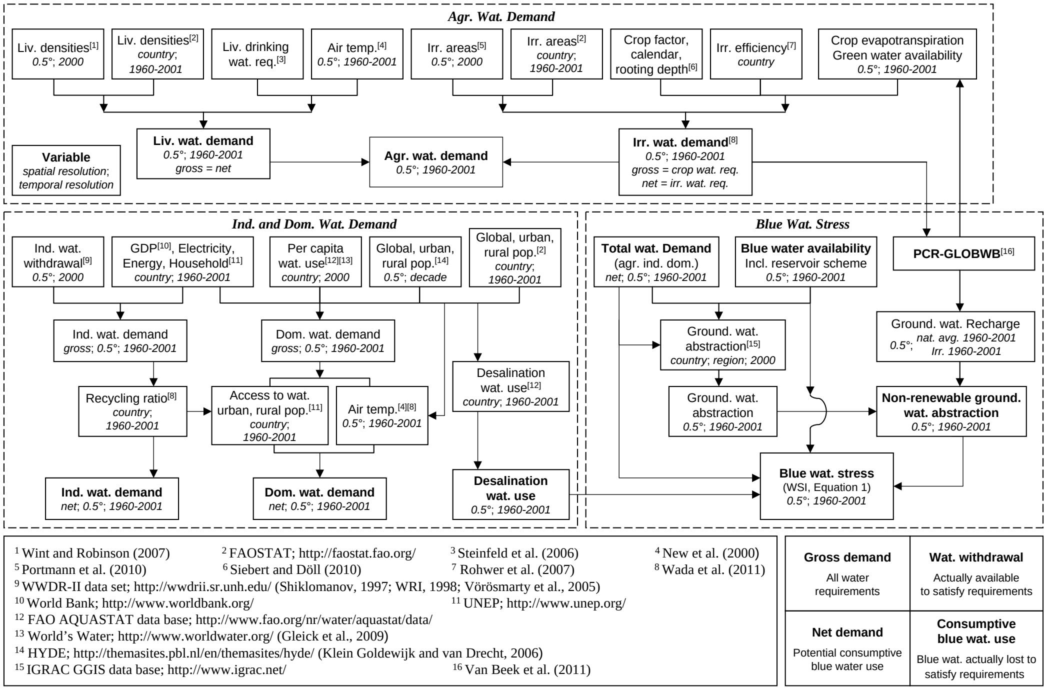


**Fig. 2.** Schematic diagram of computation of sectoral water demand and blue water stress with input data sources.





HESSD
8, 7399–7460, 2011

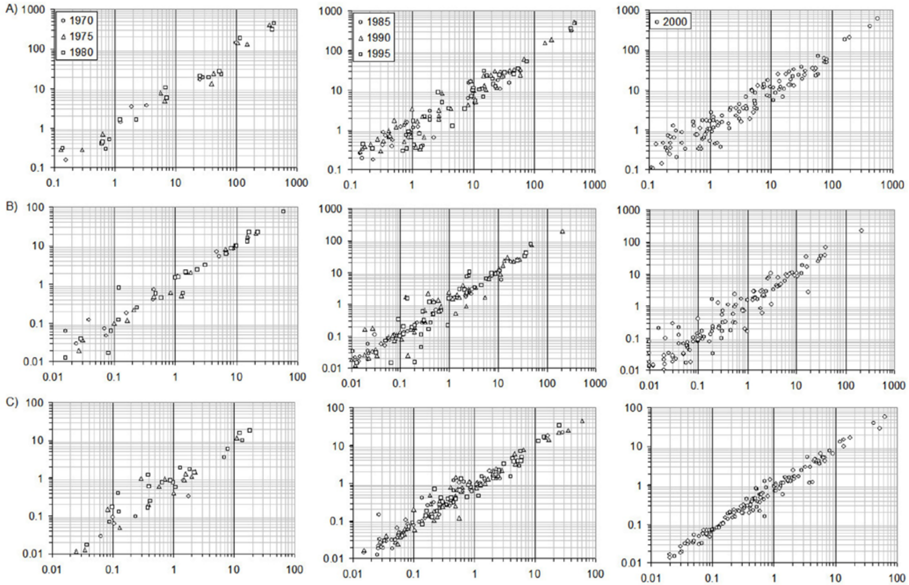


**Fig. 3.** Comparison between computed gross water demand (Y-axis) and reported water withdrawal (X-axis) for **(a)** agricultural, **(b)** industrial and **(c)** domestic sector per country from 1970 to 2000. The reported water withdrawals were taken from the FAO AQUASTAT data base.



HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

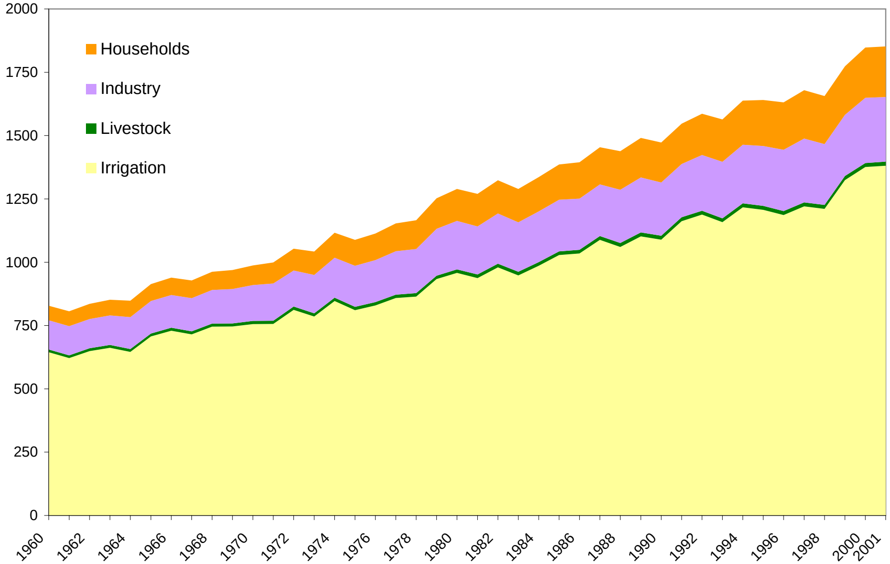


**Fig. 4.** Computed net sectoral and total water demand from 1960 to 2001 in $km^3\,yr^{-1}$.





HESSD
8, 7399–7460, 2011

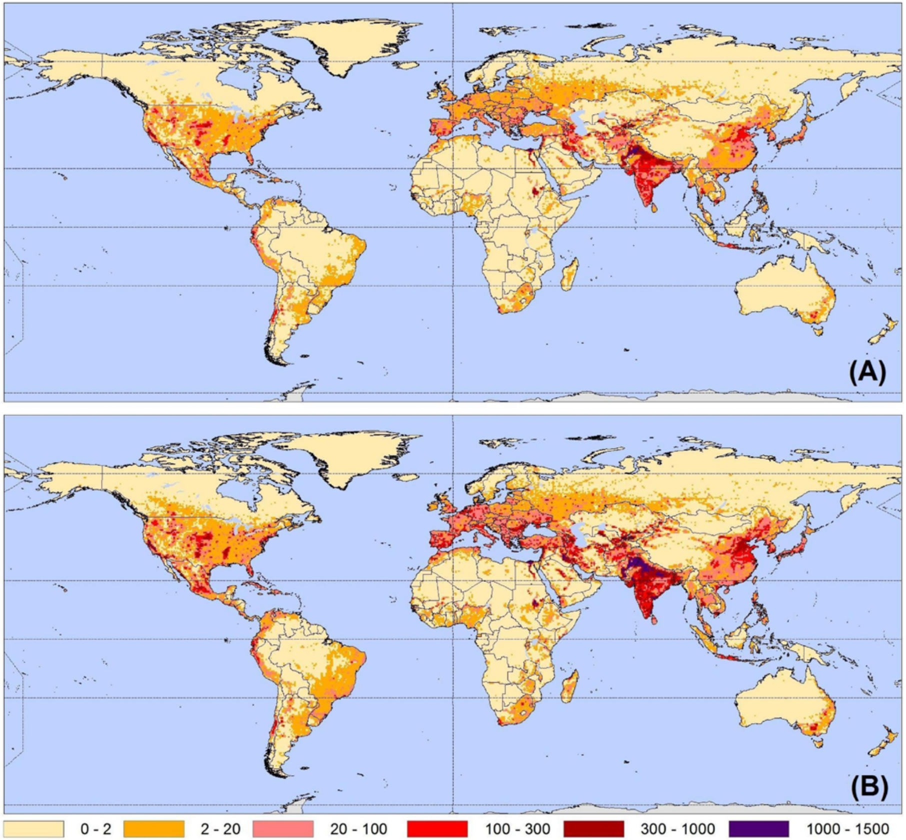


**Fig. 5.** Computed net total water demand for **(a)** 1960 and **(b)** 2000 in million $m^3\,yr^{-1}$.





HESSD
8, 7399–7460, 2011

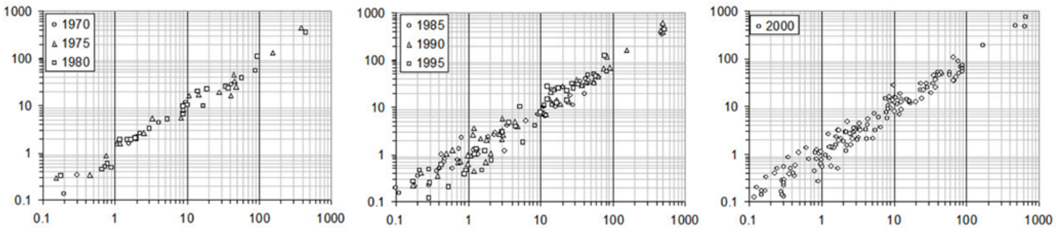


**Fig. 6.** Comparison between computed gross total water demand (Y-axis) and reported total water withdrawal (X-axis) per country from 1970 to 2000. The reported total water withdrawals were taken from the FAO AQUASTAT data base.





HESSD
8, 7399–7460, 2011

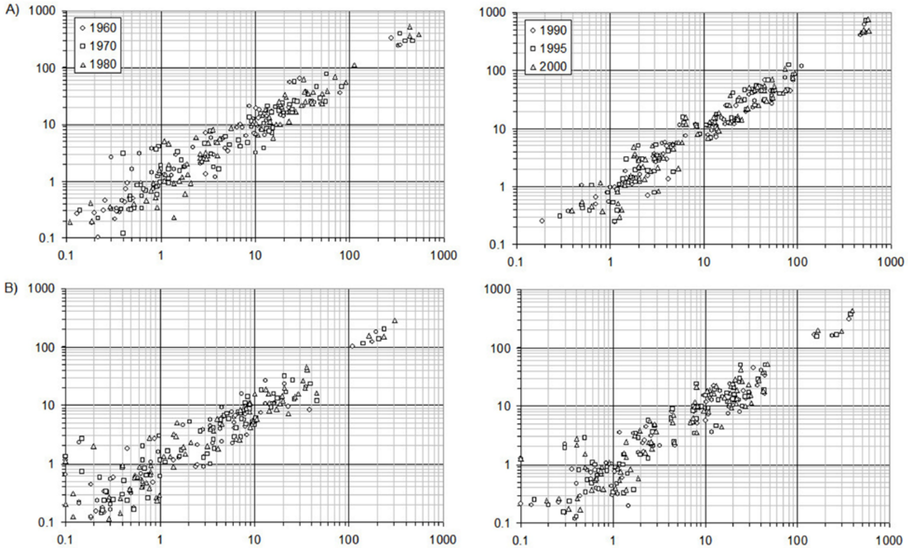


**Fig. 7.** Comparison between computed **(a)** gross and **(b)** net total water demand (Y-axis) and estimated **(a)** water withdrawal and **(b)** water consumption (X-axis) per country from 1960 to 2000. The estimated water withdrawals and water consumption were taken from Shiklomanov (2000a,b).

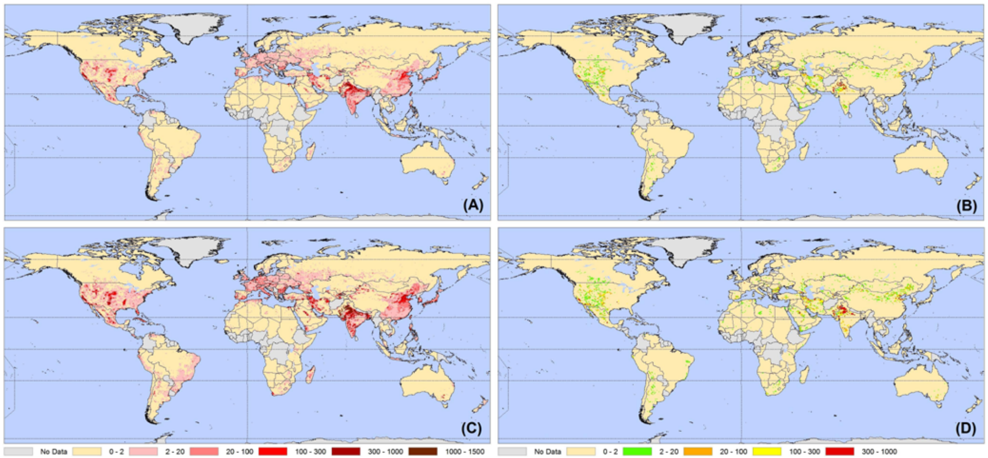


**Fig. 8.** Computed **(a, c)** total and **(b, d)** non-renewable groundwater abstraction for **(a, b)** 1960 and **(c, d)** 2000 in million $m^3\,yr^{-1}$.





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

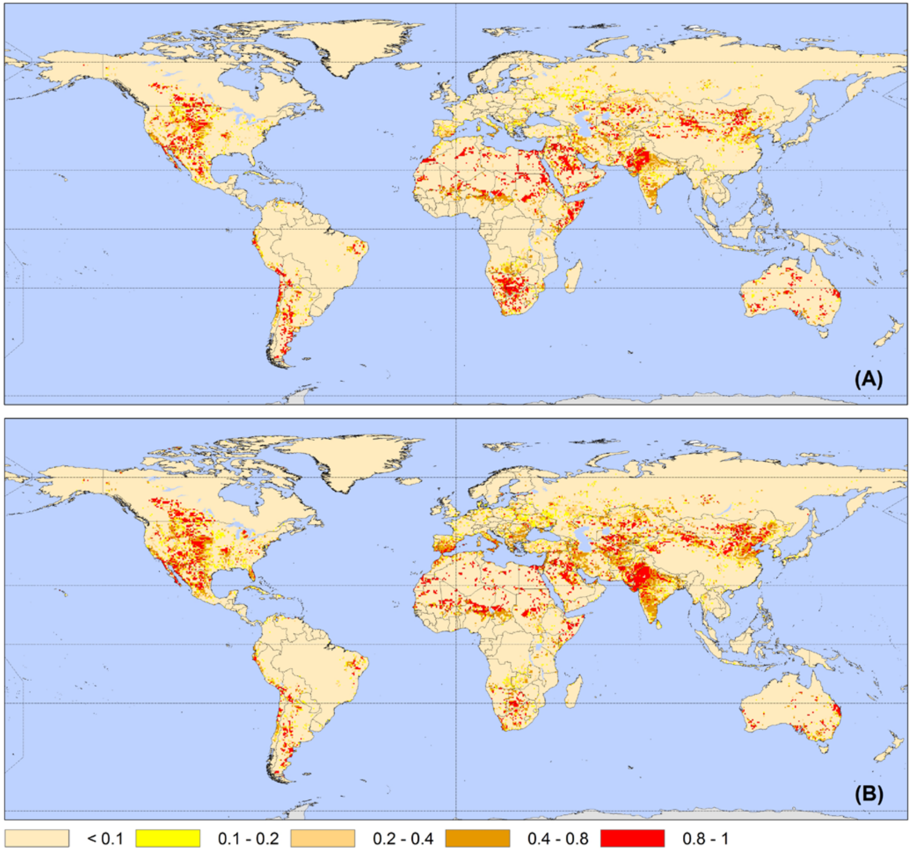


**Fig. 9.** Simulated global water stress (–) for **(a)** 1960 and **(b)** 2000.





HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

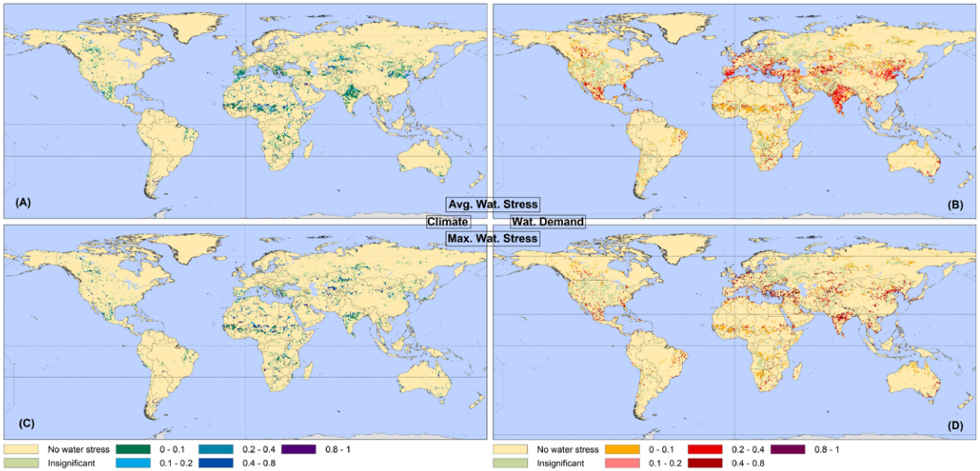


**Fig. 10.** Contribution to heightened water stress (–) due to **(a, c)** decreased water availability and **(b, d)** increased water demand. Yearly **(a, b)** average and **(c, d)** maximum water stress were used to estimate the trends between 1960 and 2001 by linear regression (two-tailed *t*-test with ± = 0.05).





HESSD
8, 7399–7460, 2011

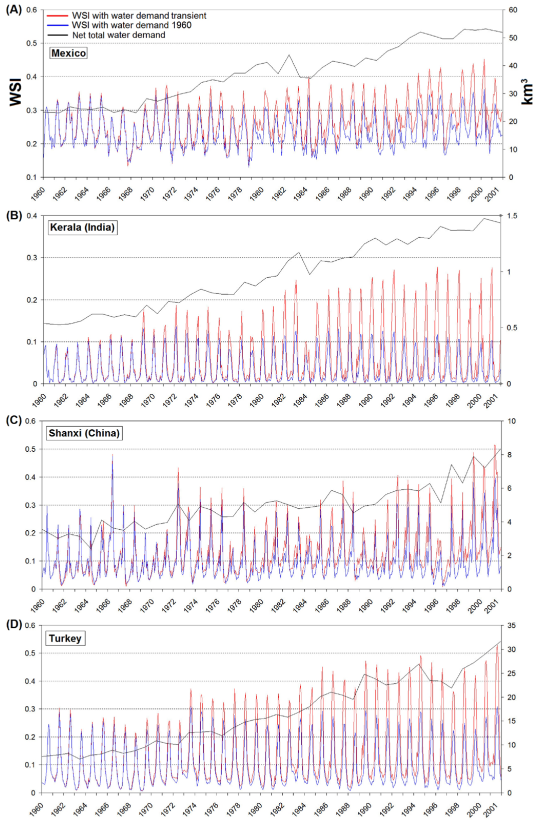


**Fig. 11.** Comparisons of simulated country-averaged monthly water scarcity index (WSI; left axis) between that with the estimated water demand for each year and that with the estimated water demand for 1960 over 1960–2001 for **(a)** Mexico, **(b)** Kerala (India), **(c)** Shanxi (China), **(d)** Turkey, **(e)** Romania **(f)** Bulgaria and **(g)** Cuba. The computed net total water demand is shown over the same period ($km^3\,yr^{-1}$; right axis).



HESSD
8, 7399–7460, 2011

Modelling global water stress of the recent past

Y. Wada et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

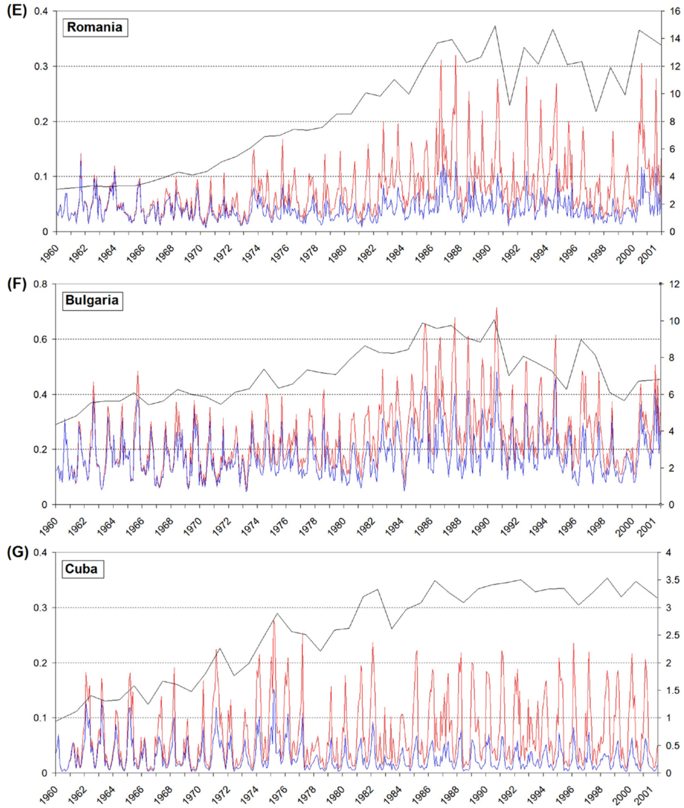


**Fig. 11.** Continued.



Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

8, 7399–7460, 2011