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An assessment of global net irrigation water requirements from various water supply sources to sustain irrigation: rivers and reservoirs (1960–2050)

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Abstract. Water supply sources for irrigation (e.g. rivers and reservoirs) are critically important for agricultural productivity. The current rapid increase in irrigation water use is considered unsustainable and threatens food production. In this study, we estimated the time-varying dependence of irrigation water requirements from water supply sources, with a particular focus on variations in irrigation area during past (1960–2001) and future (2002–2050) periods using the global water resources model, H08. The H08 model can simulate water requirements on a daily basis at a resolution of $1.0° \times 1.0°$ latitude and longitude. The sources of irrigation water requirements in the past simulations were specified using four categories: rivers (RIV), large reservoirs (LR) with a storage capacity greater than $1.0 \times 10^9\,m^3$, medium-size reservoirs (MSR) with storage capacities ranging from $1.0 \times 10^9\,m^3$ to $3.0 \times 10^6\,m^3$, and non-local non-renewable blue water (NNBW). The simulated results from 1960 to 2001 showed that RIV, MSR and NNBW increased significantly from the 1960s to the early 1990s globally, but LR increased at a relatively low rate. After the early 1990s, the increase in RIV declined as it approached a critical limit, due to the continued expansion of irrigation area. MSR and NNBW increased significantly, during the same time period, following the expansion of the irrigation area and the increased storage capacity of the medium-size reservoirs. We also estimated future irrigation water requirements from the above four water supply sources and an additional water supply source (ADD) in three future simulation designs; irrigation area change, climate change, and changes in both irrigation area and climate. ADD was defined as a future increase in NNBW. After the 2020s, MSR was predicted to approach the critical limit, and ADD would account for 11–23 % of the total requirements in the 2040s.

1 Introduction

Irrigation is crucial to satisfying increasing food demands (Bruinsma, 2003; De Fraiture et al., 2007). In many countries, food production requires intensive levels of water withdrawal for irrigation, which can deplete water supply sources or even cause them to run dry. When these sources are depleted, a decline in future food production is expected (Hanjra and Qureshi, 2010). It is highly unlikely that we will be able to depend on existing irrigation water sources (e.g. rivers, reservoirs and aquifers) in the future, for two main reasons.

First, many major rivers, including the Yellow River, the Colorado River, the Rio Grande, the Syr Darya and the Amu Darya, are now diminished in their lower reaches due to diversions and impoundments for irrigation. For example, the Yellow River experienced a persistent decline in observed annual runoff from 1960 to 2000 (Piao et al., 2010), which was largely attributed to water use for irrigation (Tang et al., 2008). Diversion of water to support cotton plantations via an inefficient irrigation system has led to the retreat of the Aral Sea (Peachey, 2004).

Second, many countries are excessively using groundwater (Gleeson et al., 2012) as they struggle to satisfy their

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growing water demands. Critical groundwater depletion has been detected by the NASA Gravity Recovery and Climate Experiment satellites (GRACE) in northwestern India (Rodell et al., 2009) and many other basins where intensive irrigation is prevalent (Famiglietti et al., 2011; Döll et al., 2012).

A number of global-scale water resource models have been used to estimate spatial and temporal variations in water resources in the 20th century due to changes in irrigated areas as well as atmospheric forcing conditions (e.g. Haddeland et al., 2006; Hanasaki et al., 2006, 2008a, b, 2010; Rost et al., 2008; Döll et al., 2009; Liu et al., 2009; Wisser et al., 2010; Biemans et al., 2011; Wada et al., 2011; Pokhrel et al., 2012b). The results of these model simulations have indicated that an expansion of irrigation and/or the construction/operation of reservoirs in a typical catchment would have a gradual and significant influence on the hydrological cycle. Those studies showed that water use and the construction/operation of reservoirs caused a significant change in the seasonal pattern of water flow at continental and global scales. Thus, the change affected the amount of water available from various water supply sources for irrigation.

Global-scale water resource models have also simulated irrigation water requirements from various water supply sources. Döll et al. (2012) quantified the effects of irrigation water requirements from surface water and groundwater on variations in water storage for the period from 1901 to 2002 using the global water resources model Water GAP. Wada et al. (2012b) calculated the contribution of different water sources (i.e. blue water (renewable surface water and groundwater), non-renewable groundwater and non-local water resources) to irrigated crops, over the period from 1960 to 2000, using the global water resources model PCR-GLOBWB. Biemans et al. (2011) estimated the irrigation water supply from surface water, reservoirs and other sources using the dynamic global vegetation and hydrology model LPJmL, with a particular focus on the reservoir module based on Haddeland et al. (2006) and Hanasaki et al. (2006). Hanasaki et al. (2010) estimated the irrigation water requirements from different sources for major crops and livestock products and the level of global virtual water exports using the global water resources model H08 (Hanasaki et al., 2008a, b; hereafter, "H08 model"). In Hanasaki et al. (2010), the virtual water supply source was specified using two categories, green water and blue water, which were involved in the global hydrological cycle. Blue water was further divided into three subcategories: rivers, medium-size reservoirs, and non-renewable non-local blue water (NNBW).

Concerning future water use simulations, the change in total irrigation water requirements under climate change and the irrigation water use scenario for the 21st century have been discussed previously (e.g. Haddeland et al., 2014; Hagemann et al., 2013; Hanasaki et al., 2013a, b; Liu et al., 2013a; Schewe et al., 2014; Wada et al., 2014). Hanasaki et al. (2013b) projected global total water requirements under the water use scenarios and the latest climate change scenarios for the 21st century using the H08 model. Hanasaki et al. (2013a) developed water use scenarios depicting five global situations under the latest socio-economic scenarios. Wada et al. (2014) quantified the impact of projected global climate change on total irrigation water requirements among the multi-water resource models described above and among several global climate models (GCMs) under the highest greenhouse gas emission scenario (Van Vuuren et al., 2011). However, to our knowledge, no study has estimated irrigation water requirements from various water supply sources, in terms of spatial and temporal analyses for past and future conditions.

In this study, we estimated the time-varying dependence of irrigation water requirements from various water supply sources on a global scale, accounting for variations in the irrigation area and meteorological forcing conditions from 1960 to 2050, using the H08 model. For the past period of 1960–2001, the sources of irrigation water were classified into the following four categories: rivers, large reservoirs, medium-size reservoirs, and NNBW. For the future period from 2002 to 2050, an estimate was made of irrigation water requirements from the four water supply sources and a newly defined water supply source, termed "additional water supply source" (ADD), which is defined as an increase in NNBW from the past to the future.

The structure of this study is as follows. Section 2 presents a brief description of the model and the data collected. Sections 3 and 4 describe settings of model simulations and the validation of our model outputs. Sections 5 and 6 present the results of our analysis (global and country-based dependence of net irrigation water requirements on water supply sources), including sensitivity analyses. Section 7 comprises the discussion and concluding remarks.

2 Methods and data

In this section, we gave descriptions of the model and required data (Fig. 1 and Table 1), which include two types of input, meteorological forcing and geographical data, to drive the H08 model.

2.1 Model description

We used the H08 model to estimate net irrigation water requirements (Hanasaki et al., 2008a, b). This model can simulate both natural hydrological water flows and anthropogenic water withdrawals globally on a daily basis at a resolution of $1.0^\circ \times 1.0^\circ$ latitude and longitude using meteorological and geographical input data (Fig. 1). The meteorological variables used in the H08 model are air temperature (K), specific humidity ($\mathrm{kg\,kg^{-1}}$), wind speed ($\mathrm{m\,s^{-1}}$), surface pressure (Pa), downward shortwave and longwave radiation ($\mathrm{W\,m^{-2}}$) and precipitation ($\mathrm{kg\,m^{-2}\,s^{-1}}$). The model consists of five

Table 1. Description of data from the five simulations.

			Past (1960–2001)				Future (2002–2050)					
			(Sect. 3.1.1)		(Sect. 3.1.2)		IC simulation (Sect. 3.2.1)		CC simulation (Sect. 3.2.2)		IC + CC simulation (Sect. 3.2.3)	
			Data source	Temporal resolution	Data source	Temporal resolution	Data source	Temporal resolution	Data source	Temporal resolution	Data source	Temporal resolution
Meteorological forcing data	Air temperature (K) Specific humidity ($kg\,kg^{-1}$) Wind speed ($m\,s^{-1}$) Surface pressure (Pa) Downward shortwave and longwave radiation ($W\,m^{-2}$) Precipitation ($kg\,m^{-2}\,s^{-1}$)		WFD (Weedon et al., 2011)	6 hourly	WDD (Hagemann et al., 2011)	Daily	WDD (Hagemann et al., 2011)	Daily (1990–2000)	WDD (Hagemann et al., 2011)	Daily (2002–2050)	WDD (Hagemann et al., 2011)	Daily (2002–2050)
Geographical data	Irrigation areas		HIM (Sect. 2.3.1)	Yearly	HIM (Sect. 2.3.1)	Yearly	Irrigation scenario	Yearly	HIM (Sect. 2.3.1)	2000	Irrigation scenario	Yearly
	Base map	Irrigation area	Siebert et al. (2007)	2000	Siebert et al. (2007)	2000	Siebert et al. (2007)	2000	Siebert et al. (2007)	2000	Siebert et al. (2007)	2000
		Crop type	Leff et al. (2004)	1990	Leff et al. (2004)	1990	Leff et al. (2004)	1990	Leff et al. (2004)	1990	Leff et al. (2004)	1990
		Crop intensity	Döll and Siebert (2002)	1990	Döll and Siebert (2002)	1990	Döll and Siebert (2002)	1990	Döll and Siebert (2002)	1990	Döll and Siebert (2002)	1990
	Large reservoirs		Pokhrel et al. (2012b)	Yearly	Pokhrel et al. (2012b)	Yearly	Pokhrel et al. (2012b)	2000	Pokhrel et al. (2012b)	2000	Pokhrel et al. (2012b)	2000
	Medium-size reservoirs		This study (Sect. 2.3.2)	Yearly	This study (Sect. 2.3.2)	Yearly	This study (Sect. 2.3.2)	2000	This study (Sect. 2.3.2)	2000	This study (Sect. 2.3.2)	2000
	Industrial and domestic water withdrawal		This study (Sect. 2.3.3)	Yearly	This study (Sect. 2.3.3)	Yearly	This study (Sect. 2.3.3)	2000	This study (Sect. 2.3.3)	2000	This study (Sect. 2.3.3)	2000

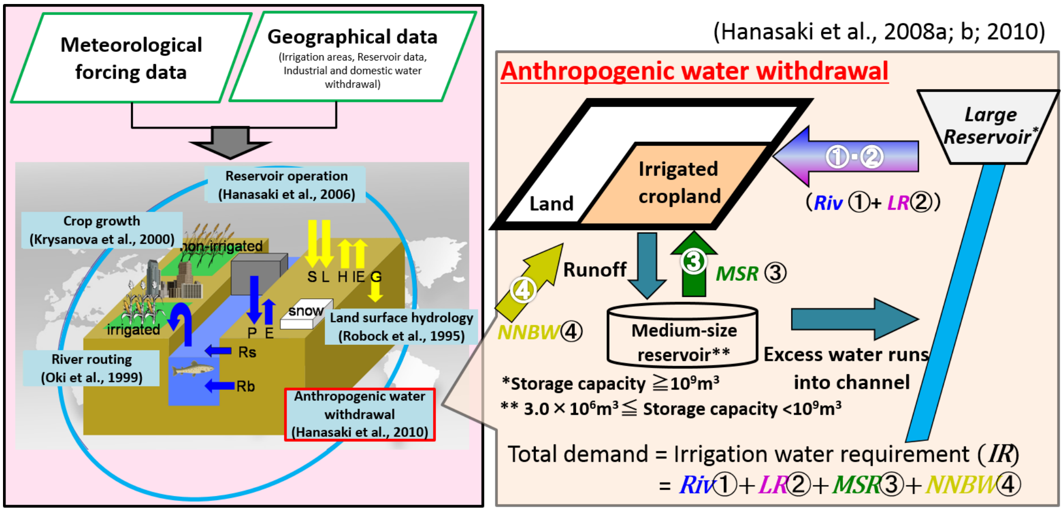

Figure 1. Schematic diagram of irrigation water requirements from various water supply sources in the H08 model.

sub-models for land surface hydrology (Robock et al., 1995), crop growth (Krysanova et al., 2000), river routing (Oki and Sud, 1998), reservoir operation (Hanasaki et al., 2006) and anthropogenic water withdrawal (Hanasaki et al., 2010). The crop growth sub-model estimates planting and harvesting dates, and the land surface hydrology sub-model calculates daily evapotranspiration from irrigated cropland. The consumption-based irrigation water demand is determined as the irrigation water requirement for maintaining soil moisture at 60 % in the top 1 m of irrigated cropland during the cropping period. In the case of paddy fields, soil moisture is maintained at 100 % of the field capacity to meet the condition of paddy inundation. Here, we set the soil moisture to be maintained at 60 % of the field capacity for crops other than rice, because wheat, a major global crop, is grown with soil moisture at 50–60 % of field capacity in many irrigated areas (Allen et al., 1998). The irrigation water requirement is set to begin 30 days before the planting date, increasing the soil moisture content linearly from 0 to 60 % or 100 %. The total irrigation water requirement defined in the above way is known as the "net irrigation water requirement" (IR) (Smith, 1992). It should be noted that return flow and delivery loss are not included in this model.

In the anthropogenic water withdrawal sub-model (Fig. 1), irrigation water requirements from various water supply sources were abstracted in the following order of priority to meet the IR:

a. the river flow (RIV), which is a naturalised flow regime;

b. large reservoirs (LR), which are determined by subtracting the river flow including large reservoirs with a storage capacity greater than 1.0×10^9 m^3, from those without large reservoirs;

c. medium-size reservoirs (MSR) with storage capacities ranging from 1.0×10^9 m^3 to 3.0×10^6 m^3; and

d. non-renewable non-local blue water (NNBW), which comprises the remaining demand and can be determined by assuming an unlimited water supply source. Hanasaki et al. (2010) originally added this term as a conceptual water supply source; it was termed NNBW by Rost et al. (2008) and Hanasaki et al. (2010). In this study we defined NNBW as an unlimited supply source, which is available everywhere without limit.

IR can be supplied from the four possible sources above as follows:

$$\mathrm{IR} = \mathrm{RIV} + \mathrm{LR} + \mathrm{MSR} + \mathrm{NNBW}. \quad (1)$$

First, RIV and LR are supplied to fulfil IR. When RIV becomes unavailable as a water supply source, IR is, in turn, derived from MSR. When the MSR are depleted, water is withdrawn from NNBW to fulfil IR.

We should note that reservoir treatments differed from reservoir to reservoir depending on the storage size. Large reservoirs control river discharge in the model and set operating rules for individual reservoirs along each river. For large reservoirs where the primary purpose was not irrigation water supply, the reservoir operating rule was set to minimise inter-annual and sub-annual river discharge variation. For large reservoirs in which irrigation water supply was the primary purpose, daily release from the reservoirs was proportional to the irrigation water requirement in the lower reaches. Medium-size reservoirs were not treated individually. Instead, their storage capacities were aggregated for each calculated grid cell. Runoff produced by the land surface hydrology module initially runs into the medium-size reservoirs in the same grid. Then excess water beyond the storage capacity of the medium-size reservoir flows into the river channel after runoff, as determined by the land surface hydrology module. Here, we assumed that medium-size reservoirs used 100 % of their storage capacity. Finally, the river discharge was calculated from the gridded runoff and the remaining river discharge, which was routed through the TRIP (Oki and Sud, 1998) river routing map.

2.2 Meteorological forcing data

To prepare the meteorological forcing data for the past period (1960–2001), we used two data sets. One was WATCH (WATer and global CHange project) forcing data (Weedon et al., 2011, hereafter, "WFD data set") based on the 40-year European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40), which consists of 6 hourly near-surface meteorological forcing data for 1958–2001, with a spatial resolution of $0.5° \times 0.5°$. For validation and sensitivity analysis, we used the WFD data set. The other data set used was the WATCH driving data (hereafter, "WDD data set") of three GCMs, namely CNRM, ECHAM5 and IPSL (Hagemann et al., 2011). The period covered by these data is 1960–2001, and the same forcing variables are available as for the WFD data set. For the past period, the WDD data set was based on the 20C3M experiment, which was performed in the third phase of the Coupled Model Intercomparison Project (CMIP3). We used the WDD data set to calculate future increase in NNBW from simulation results of the past with those of future.

For the future period from 2002 to 2050, we also used the WDD data set based on the IPCC AR4 high-emission A2 scenario of CMIP3 (Nakicenvoic et al., 2000), which contains daily near-surface meteorological forcing data with a spatial resolution of $0.5° \times 0.5°$. Daily precipitation and air temperature data in the WDD data set were bias-corrected to make them consistent with those of the WFD data set using the method described by Piani et al. (2010). All variables (precipitation, air temperature, downward shortwave and longwave radiation, specific humidity, and wind speed) in the WDD data set were interpolated from the spatial resolution of the climate model using a combination of bilinear and inverse distance interpolation. Both the WFD and WDD data sets represent a spatially aggregated median value with a $1.0° \times 1.0°$ grid resolution.

2.3 Geographical data

2.3.1 Irrigation areas

We prepared annual irrigation area distribution maps (spatial resolution: $1.0° \times 1.0°$) for the period of 1960–2001 to estimate irrigation water requirements. Data of "areas equipped for irrigation" are available from the University of Frankfurt's Food and Agriculture Organisation (FAO) Global Map of Irrigation Areas (GMIA) for 1998–2002 at a spatial resolution of 5 arcmin (Siebert et al., 2007). Time series data of areas equipped for irrigation per country are available from national statistics from 1900 to 2003 (Freydank and Siebert, 2008).

First, to prepare the data set of changes in the annual irrigation area, we used the GMIA as a base map. Second, we obtained the annual rate of change from 1960–2001 using data from Freydank and Siebert (2008). Finally, we rescaled each grid in the aggregated map on a country-by-country basis using the annual rate of change, denoted as historical irrigation map (HIM) data. This method is similar to that used by Wisser et al. (2010) and Pokhrel et al. (2012b). We confirmed whether the irrigation areas were constrained within croplands using a historical evolution of cropland areas (Ramankutty and Foley, 1999), which was calibrated using a remotely sensed global land-cover classification data set (Loveland et al., 2000).

We prepared an irrigation area scenario for the future period (2002–2050). In this scenario, we assumed that to meet food requirements, the future irrigation area will increase in proportion to population growth on a global scale (Oki and Kanae, 2006; Shen et al., 2008). This irrigation area scenario is based on the "medium scenario" from among the three population growth scenarios of the United Nations Population Division (UN, 2011). We used a future population growth rate of 0.9 % per year on a global scale according to the method of Shen et al. (2008).

Figure 2a shows the change in total irrigation area from 1960 to 2050. The HIM reflects the large-scale dynamics of development of the irrigated area over the 20th century, revealing an expansion in area from 1.6×10^6 km^2 in 1960 to 2.7×10^6 km^2 in 2000. Furthermore, our irrigation scenario was 3.9×10^6 km^2 in the year 2050. Figure 2b shows the difference in irrigation area between 1960 and 2000. Irrigation areas have been increasing in India, China, Pakistan and the United States. Subdivision of the HIM into single- and double-cropping irrigated areas was achieved by multiplying HIM data by the irrigation intensity data published by Döll and Siebert (2002).

2.3.2 Reservoir data

We estimated the storage capacity of large- and medium-size reservoirs in each grid to determine the impact of a change in water supply in each year. The International Commission on Large Dams (ICOLD, 1998) defines a large reservoir as one having a storage capacity greater than 1.0×10^9 m^3 and provides information on geophysical location, construction year, maximum storage capacity and function. In this study, we used 548 large reservoirs based on ICOLD (2003) data (Hanasaki et al., 2006; Pokhrel et al., 2012b).

We prepared the historical development and spatial distributions of storage capacity data for medium-size reservoirs from 1960 to 2001. We determined the geophysical location, dam construction year, and storage capacity of 6862 reservoirs from the Global Reservoir and Dam database (GRanD; Lehner et al., 2011). We spatially aggregated the

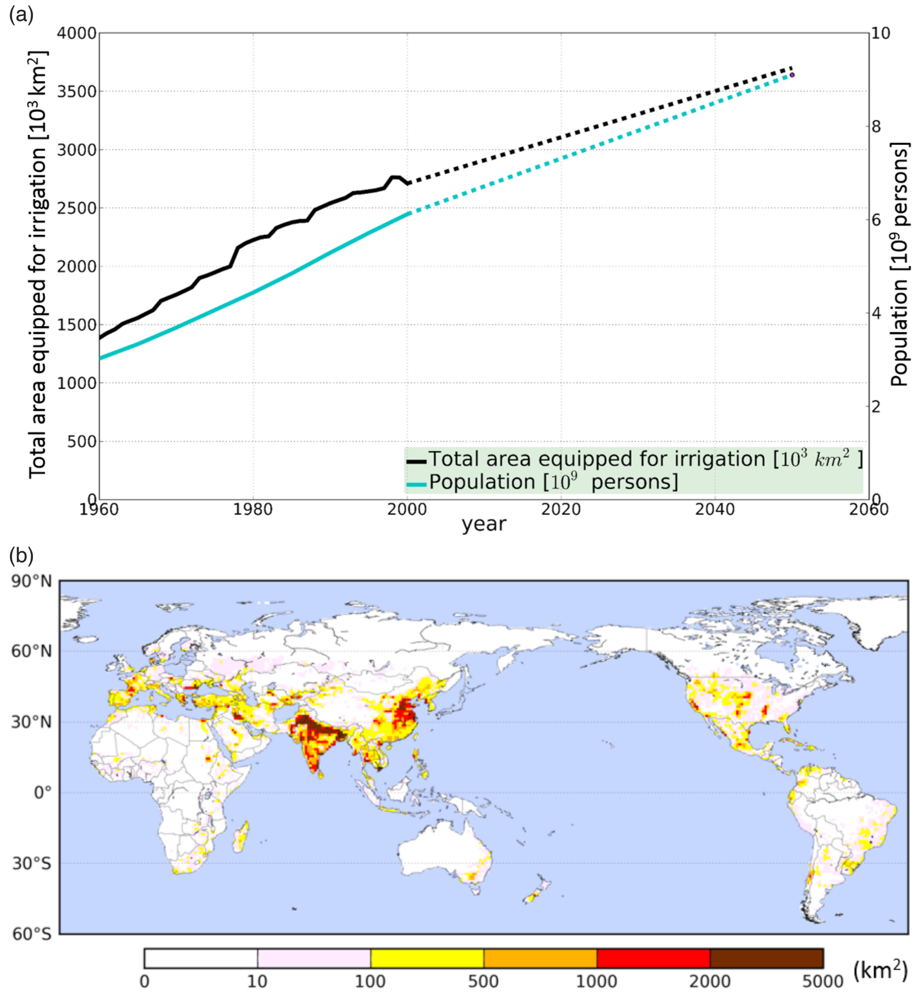

Figure 2. Global total area equipped for irrigation under historical irrigation map (HIM) data (10^3 km^2) during the period of 1960–2000 and irrigation scenarios due to population growth during the period of 2000–2050 and global total population **(a)**, and the difference in area equipped for irrigation (km^2) for the years 2000–1960 **(b)**.

storage capacity of medium-size reservoirs from the GRanD database in each year at a $1.0° \times 1.0°$ grid resolution and country scale. ICOLD (1998) defines medium-size reservoirs as those with a storage capacity ranging from 1.0×10^9 m^3 to 3.0×10^6 m^3 and provides the only total national capacity of global medium-size reservoirs. If the total capacity in ICOLD (2003) was greater than the aggregated storage capacity of medium-size reservoirs from the GRanD database at the national scale, the geographical distribution of the remaining storage within each country was then weighted in proportion to population (Klein Goldewijk et al., 2011). This procedure is supported by Hanasaki et al. (2010), who demonstrated a positive correlation between the total population of a country and the storage capacity of its reservoirs. Finally, we obtained the time-dependent storage capacity of medium-size reservoirs by incorporating the distribution map of the aggregated storage capacity from the GRanD database and the remaining storage. In contrast, if the aggregated storage capacity of medium-size reservoirs from the GRanD database at the national scale was greater than the total capacity in ICOLD (2003), we used the distribution map of the aggregated storage capacity at the grid scale.

Figure 3a presents the change in global total cumulative storage capacity of large and medium-size reservoirs, from 1240 and 1385 km^3 in 1960 to 4427 and 3084 km^3 in 2000, respectively. The cumulative storage capacity of large reservoirs for irrigation increased little after the 1970s, and was less than the increase for hydropower capacity in Fig. 3a. Figure 3b shows the difference in the storage capacity of medium-size reservoirs for the years 2000–1960. In China, storage capacities have increased substantially.

2.3.3 Industrial and domestic water withdrawal

Although we focused on global changes in the IR, we also estimated industrial and domestic water withdrawals because

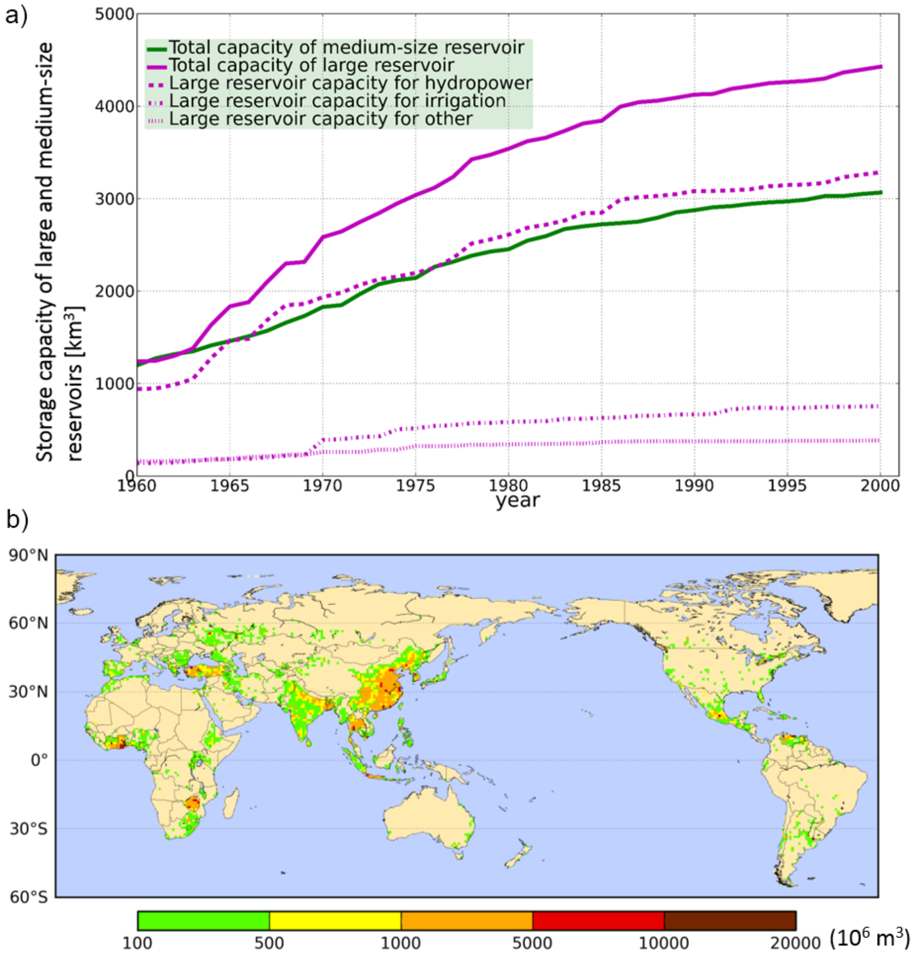

Figure 3. Total cumulative storage capacity of large and medium-size reservoirs (km^3) and the cumulative storage capacity of large reservoirs for hydropower, irrigation and other uses during the period 1960–2000 **(a)**, and a distribution map showing the difference in storage capacity ($10^6\ m^3$) of medium-size reservoirs for the years 2000–1960 **(b)**. In **(a)**, the magenta short-dashed line shows the storage capacity of large reservoirs for irrigation. If a reservoir has multiple functions, the most important function was counted.

they commonly share the same water supply sources as irrigation withdrawals.

The total water withdrawals for industrial and domestic use were estimated on a grid scale, primarily based on statistical data for the period 1960–2001. First, at the country scale, the water withdrawals for each sector (i.e. irrigation, industrial, and domestic use) from FAO (2012) were used as base data. Some countries provide time series data, some provide discontinuous data, and others provide only single-year data. For countries in which time series data were available, we conducted a linear interpolation to fill the gaps between data. Elsewhere, discontinuous data or data for a single year were calculated by multiplying the regionally scaled evolving ratio of withdrawal from Shiklomanov (1999). In this manner, we prepared water withdrawal data for various countries for 1960–2001.

The water withdrawal data (1960–2001) were then downscaled to a resolution of $1.0° \times 1.0°$. Infrastructure areas for the year 2000, from the global land use data published by Erb et al. (2007), were used as a proxy for the gridded distribution of industrial water withdrawal because Otaki et al. (2008) found that industrial water consumption correlated well with the extent of urban areas in an analysis in Japan and China. The adjusted total population (Klein Goldewijk et al., 2011) was used as a proxy for the gridded distribution of domestic water withdrawal, as in previous studies (Vörösmarty et al., 2000; Oki et al., 2001; Shen et al., 2008).

3 Model simulations

Table 1 summarises the input data of five simulation settings; further input data details are given in Sect. 2. Past simulations for the period of 1960–2001 were executed using two different sets of meteorological forcing data (the WFD and WDD data sets). Future simulations for the period of 2002–2050 were also performed for three different future scenario settings, using the outputs of three different GCMs, based on the WDD data set. These settings are discussed in the following two sections.

3.1 Past simulations for the period of 1960–2001

3.1.1 Simulations using WATCH forcing data

We computed the irrigation water requirements from various water supply sources using the WFD data set and geographical data such as the irrigation area data, reservoir data, and the industrial and domestic water withdrawal (as described in Sect. 2) during the past period from 1960 to 2001. The total irrigation water requirement of this simulation ($IR_{WFD,y}$, where y means year) were defined as value of IR, and the irrigation water requirements from various water supply sources of this simulation ($RIV_{WFD,y}$, $LR_{WFD,y}$, $MSR_{WFD,y}$ and $NNBW_{WFD,y}$) were defined as value of RIV, LR, MSR and NNBW in each year. Throughout the entire period, the crop types and crop intensity were unchanged from those used by Leff et al. (2004) and Döll and Siebert (2002) for the year 1990. For results of annual irrigation water requirement from various water supply sources during the past period (1960–2001) in Sect. 5, the simulations relied mainly on the WFD data set. For validation in Sect. 4 and sensitivity analysis in Sect. 6, we also used the WFD data set.

3.1.2 Simulations using WATCH driving data

To determine the change from the past to future conditions, a continuous simulation using consistent meteorological forcing data is required. As discussed in Sect. 2.2, the WFD data set is inconsistent with the WDD data set, with the exception of air temperature and precipitation values. Therefore, we simulated irrigation water requirements from various water supply sources using the WDD data set ($RIV_{WDD,y}$, $LR_{WDD,y}$, $MSR_{WDD,y}$ and $NNBW_{WDD,y}$) for the past period (1960–2001). Geographical data were identical to the WFD simulation in Sect. 3.1.1. These simulation results were used to calculate the difference between the future and past periods.

3.2 Future simulations for the period of 2002–2050

3.2.1 Simulations with a sole scenario of irrigation area change

First, we estimated whether RIV, LR, MSR and NNBW would increase with future changes in the irrigation area for the future period of 2002–2050. In these simulations of irrigation area change only (hereafter, "IC" simulations), we used the WDD data set for the period of 1990–2000 as the meteorological forcing data. The total irrigation water requirement of the IC simulations ($IR_{IC,y}$) was defined as the ensemble median value of IR on the basis of three GCMs, estimated from the irrigation area scenario in each year of the future period (2002–2050) and the storage capacity of reservoirs in 2000. We assumed that the storage capacities of large and medium-size reservoirs, as well as those of industrial and domestic water withdrawals, remained unchanged between 2000 and 2050.

For both future and past simulation periods, $IR_{IC,y}$ were met by four water supply sources: $RIV_{IC,y}$, $LR_{IC,y}$, $MSR_{IC,y}$, and $NNBW_{IC,y}$, listed in order of priority (described in Sect. 2.1). Because we fixed the storage capacities of large and medium-size reservoirs at those of the year 2000, the growth in water requirement was mainly sustained by $NNBW_{IC,y}$ in our future simulation. In other words, the growth in $NNBW_{IC,y}$ can be partly attributed to the fixed capacities of large and medium-size reservoirs. Hence, we defined an additional water supply source, termed "$ADD_{IC,y}$" (determined from Eq. 2 below), as $NNBW_{IC,y}$–$NNBW_{WDD,1990s}$ and separated the $NNBW_{IC,y}$ into two components. In this study, $ADD_{IC,y}$ is considered as the additional NNBW in the future compared with the 1990s, and possibly and partly allocable into $LR_{IC,y}$ and $MSR_{IC,y}$ if reservoir capacity increases. Although we could set construction of new reservoirs in the future, subdivision of $ADD_{IC,y}$ into $LR_{IC,y}$, $MSR_{IC,y}$ and $NNBW_{IC,y}$ requires development of scenarios based on the future construction of spatially explicit reservoirs, which is beyond the scope of this study.

3.2.2 Simulations with a sole climate change scenario

Second, we estimated RIV, LR, MSR, NNBW and ADD using a sole climate change scenario for the future period 2002–2050. In these experimental simulations (hereafter, "CC" simulations), we used the WDD data set projected by three GCMs for the future period of 2002–2050 as the metrological forcing data. The total irrigation water requirements of the CC simulations ($IR_{CC,y}$) were defined as the ensemble medians of IR values on the basis of three GCMs. In the CC simulations, the irrigation areas remained unchanged between 2000 and 2050. All other settings were identical to those in Sect. 3.2.1.

3.2.3 Simulations with both irrigation area and climate change scenarios

Third, we also estimated RIV, LR, MSR, NNBW and ADD the future water supply source components using both the irrigation area and climate change scenarios for the period 2002–2050. In the simulation with the scenarios of irrigation area and climate change (hereafter, "IC + CC" simulations), for metrological forcing data we used the WDD data set from three GCMs with future changes in irrigation areas for the period 2002–2050. The total irrigation water requirements of the IC + CC simulations ($IR_{IC+CC,y}$) were also defined as the ensemble median IR of the three GCMs. All other settings were identical to those described in Sects. 3.2.1 and 3.2.2.

The new water supply source in each year of the future period (2002–2050) for three future simulations, termed $\mathrm{ADD}_{\mathrm{SIM},y}$, was defined as

$$\mathrm{IR}_{\mathrm{SIM},y} = \mathrm{RIV}_{\mathrm{SIM},y} + \mathrm{LR}_{\mathrm{SIM},y} + \mathrm{MSR}_{\mathrm{SIM},y} + \mathrm{NNBW}_{\mathrm{WDD,1990s}} + \mathrm{ADD}_{\mathrm{SIM},y} \quad (2)$$

$$\begin{pmatrix} \mathrm{ADD}_{\mathrm{SIM},y}=\mathrm{NNBW}_{\mathrm{SIM},y}-\mathrm{NNBW}_{\mathrm{WDD,1990s}} & \text{and } \mathrm{NNBW}_{\mathrm{SIM},y}=\mathrm{NNBW}_{\mathrm{WDD,1990s}} & \text{if } \mathrm{NNBW}_{\mathrm{SIM},y}>\mathrm{NNBW}_{\mathrm{WDD,1990s}} \\ \mathrm{ADD}_{\mathrm{SIM},y}=0 & \text{and } \mathrm{NNBW}_{\mathrm{SIM},y}=\mathrm{NNBW}_{\mathrm{SIM},y} & \text{if } \mathrm{NNBW}_{\mathrm{SIM},y}\leq\mathrm{NNBW}_{\mathrm{WDD,1990s}} \end{pmatrix},$$

where the subscript SIM denotes the simulation, namely, IC, CC or IC + CC, as discussed above.

4 Validation

Figure 4 compares the $\mathrm{IR}_{\mathrm{WFD,2000}}$ results from our H08 simulation with irrigation water requirements from three previous studies. The previous studies (Siebert and Döll, 2008; Liu and Yang, 2010; FAO, 2012) assumed that the total irrigation water requirements could be estimated based on the dependence on blue water use, which is defined as extraction from surface and/or subsurface water bodies (e.g. rivers, reservoirs, and aquifers). Even though there were different degrees of uncertainty between the previous models and the H08 model (e.g. inconsistencies among input data or parameterisations), the correlations between our $\mathrm{IR}_{\mathrm{WFD,2000}}$ and the results of these previous studies were high: 0.99 for FAO (2012) ($N = 90$), 0.89 for Liu and Yang (2010) ($N = 172$) and 0.98 for Siebert and Döll (2008) ($N = 39$). In particular, we found that our $\mathrm{IR}_{\mathrm{WFD,2000}}$ values in both the United States and China agreed well with those of the previous studies. The $\mathrm{IR}_{\mathrm{WFD,2000}}$ values for India and Pakistan (which typically have high water use) were overestimated compared with previous results. On the other hand, most countries with an $\mathrm{IR}_{\mathrm{WFD,2000}} < 100\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ had lower correlation coefficients. The distributions of over- and underestimates did not depend on the experimental period.

On a global scale, $\mathrm{IR}_{\mathrm{WFD,2000}}$ ($1302\,\mathrm{km}^3\,\mathrm{yr}^{-1}$) was overestimated when compared to the range of results reported previously, namely 824 to $1181\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ (Siebert and Döll, 2008; Liu and Yang, 2010; FAO, 2012; Wada et al., 2012b). $\mathrm{IR}_{\mathrm{WFD,2000}}$ was ∼ 30 % larger than the average of previous results. This inconsistency may be due to differences in the physical processes and boundary conditions used in the models. Given that lower correlations were most apparent for Asian countries, which are dominated by paddy cultivation (e.g. Thailand, Bangladesh, Indonesia, Japan), it is recommended that the water body of paddy fields be considered when using the model to predict agricultural water use.

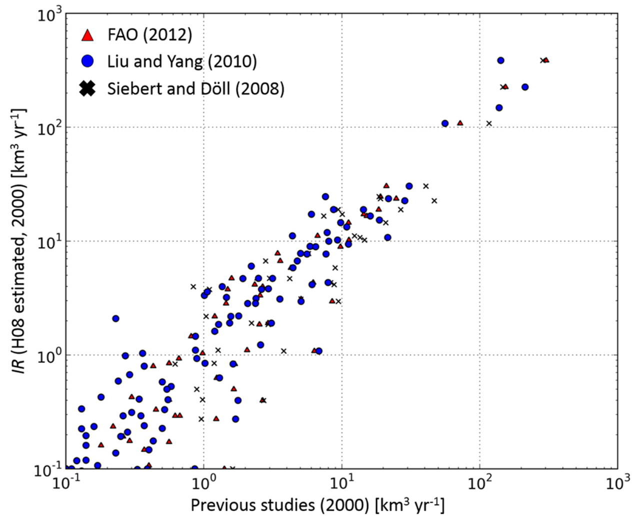

Figure 4. Comparison of $\mathrm{IR}_{\mathrm{WFD,2000}}$ ($\mathrm{km}^3\,\mathrm{yr}^{-1}$) with previous studies (crosses: Siebert and Döll, 2008; circles: Liu and Yang, 2010; triangles: FAO, 2012).

5 Results

5.1 Global-based dependence of net irrigation water requirements on water supply sources

Figure 5a and b show annual changes and ratios in the global net irrigation water requirements from four water supply sources for 1960–2001 and from five water supply sources for 2002–2050. The estimated and projected net irrigation water requirements from various water supply sources using the WFD and WDD data sets in the 1960s, 1990s and 2040s are presented in Table 2. There were only small differences (−1.9 to 9 %) between the 10-year average requirements using the WDD and WFD data sets in the 1960s and 1990s. We only described the results using the WFD data set in the past period.

Concerning simulations of the past period of 1960–2001 using the WFD data set, estimated water requirements increased as follows: from 340 km to $480\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ for $\mathrm{RIV}_{\mathrm{WFD}}$, from 16 to $29\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ for $\mathrm{LR}_{\mathrm{WFD}}$, from 218 to $423\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ for $\mathrm{MSR}_{\mathrm{WFD}}$ and from 163 to $259\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ for $\mathrm{NNBW}_{\mathrm{WFD}}$. The $\mathrm{IR}_{\mathrm{WFD}}$ showed a continuously increasing trend. The $\mathrm{RIV}_{\mathrm{WFD}}$ displayed a continuously increasing trend to the early 1990s, but $\mathrm{LR}_{\mathrm{WFD}}$ increased very little due to the limited capacity of large reservoirs for irrigation (see Fig. 3a). The increasing trend for $\mathrm{RIV}_{\mathrm{WFD}}$ stabilised after the early 1990s. Compared with the other water supply sources, the dependence on $\mathrm{RIV}_{\mathrm{WFD}}$ was at its highest level from the 1960s to the 1990s. $\mathrm{MSR}_{\mathrm{WFD}}$ also displayed a continuous increasing trend. Construction of medium-size reservoirs may have increased to meet the growing $\mathrm{IR}_{\mathrm{WFD}}$ caused by the expansion of irrigated areas. There was not much difference in the total values of $\mathrm{MSR}_{\mathrm{WFD}}$ and $\mathrm{RIV}_{\mathrm{WFD}}$ at the end of the

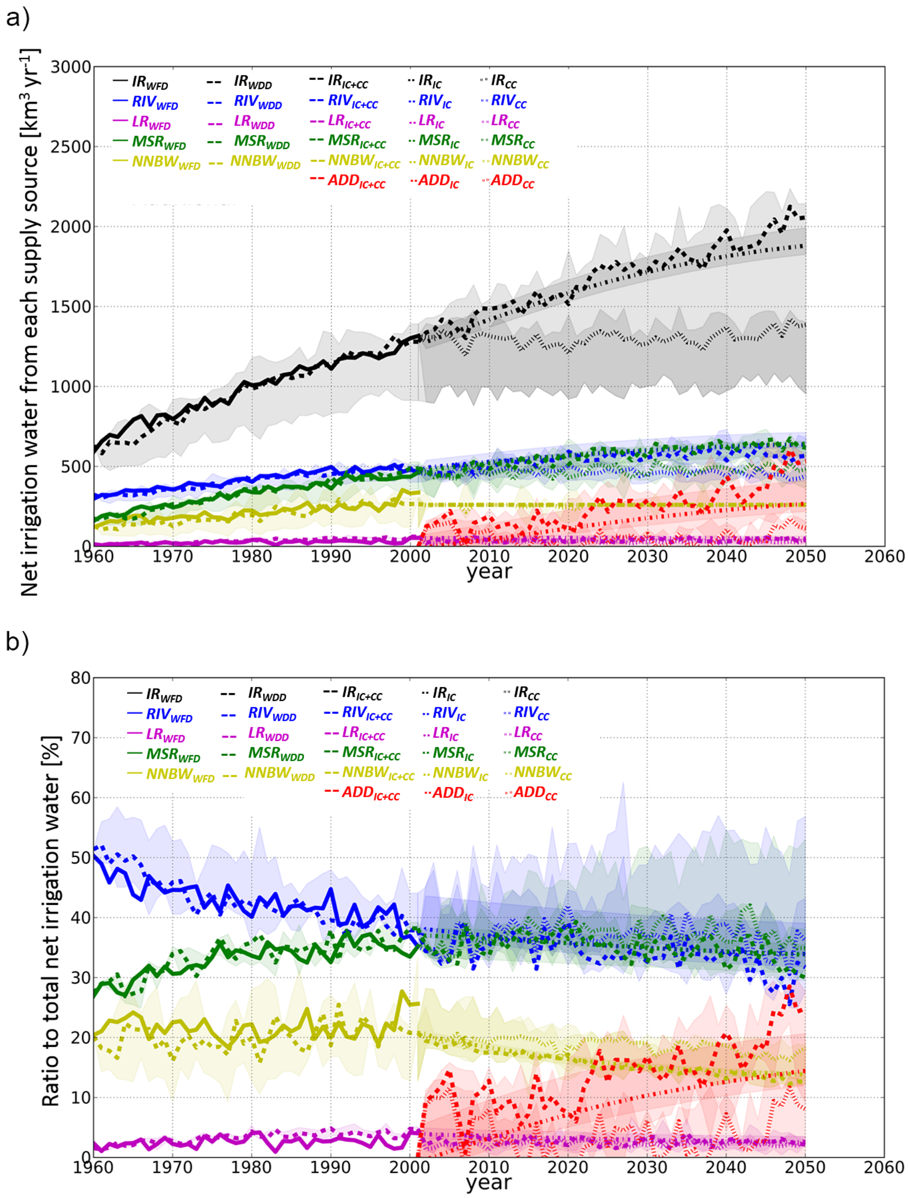

Figure 5. Annual changes in global net irrigation water requirements ($km^3\ yr^{-1}$) from four water supply sources (RIV, LR, MSR and NNBW) using the WFD and WDD data sets for 1960–2001, and global net irrigation water requirements ($km^3\ yr^{-1}$) from five water supply sources according to the IC simulation (RIV_{IC}, LR_{IC}, MSR_{IC}, $NNBW_{IC}$ and ADD_{IC}), the CC simulation (RIV_{CC}, LR_{CC}, MSR_{CC}, $NNBW_{CC}$ and ADD_{CC}) and the IC + CC simulation (RIV_{IC+CC}, LR_{IC+CC}, MSR_{IC+CC}, $NNBW_{IC+CC}$ and ADD_{IC+CC}) for the period 2002–2050 **(a)**; the percentage contributions (%) of different water supply sources to the total IR **(b)**. In the past and future periods, results of the ensemble median for the WDD data set of three GCMs are provided. Outer shades show the maximum and minimum for the all meteorological forcing data.

past period. $NNBW_{WFD}$ increased gradually from the 1960s on a global scale. The growth rate of $NNBW_{WFD}$ as an irrigation water supply source increased noticeably after the 1970s. Due to atmospheric forcing conditions and an expansion of the global irrigation area from the 1960s to the 1990s, $NNBW_{WFD}$ increased by 1.6 times. The reason for this is that RIV_{WFD}, LR_{WFD} and MSR_{WFD} were depleted previously, due to the order of priority of water supply sources. The $NNBW_{WFD}$ increased substantially from 1997 to 2000 (see more details in Sect. 6.2 and Table 5). The $NNBW_{WFD,2000}$, which approached $RIV_{WFD,2000}$ and $MSR_{WFD,2000}$, met the larger demand for global water supply in terms of irrigation water use.

Figure 6a shows the spatial distribution of the difference in MSR_{WFD} between 1960 and 2000. The largest increases are due to the doubling in size of the storage capacities of

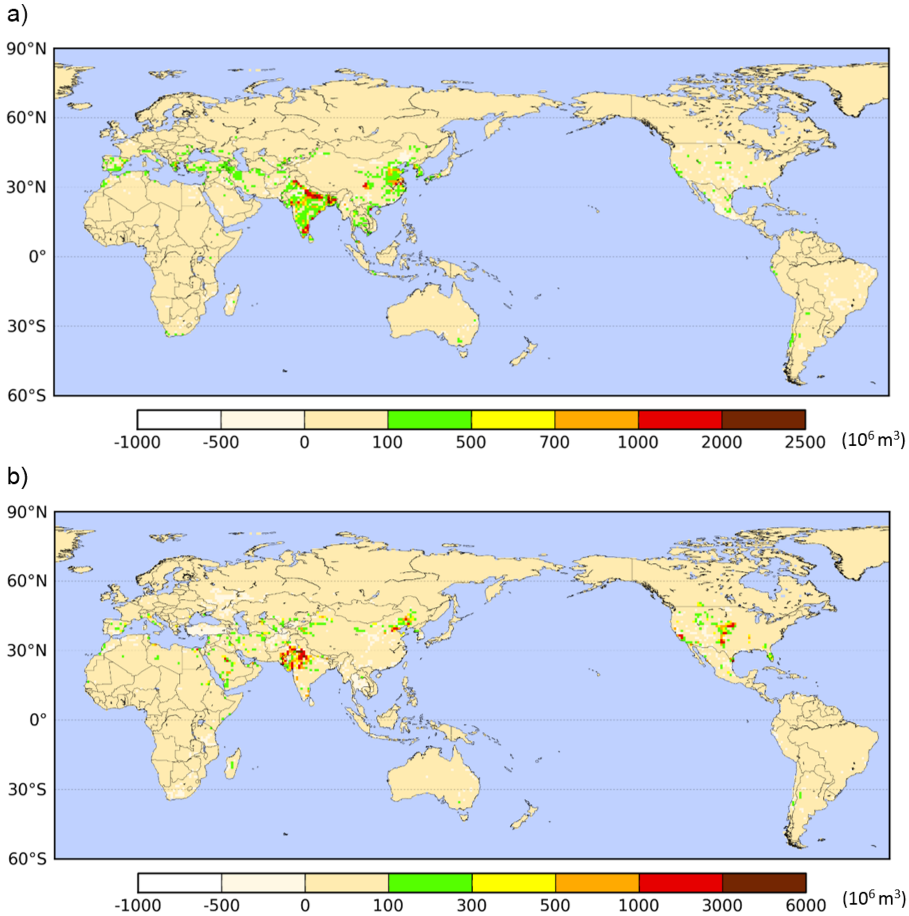

Figure 6. Distributions of the differences in MSR_{WFD} (10^6 m^3) between 1960 and 2000 **(a)** and the differences in $NNBW_{WFD}$ (10^6 m^3) between 1960 and 2000 **(b)**.

medium-size reservoirs and irrigation areas from 1960 to 2000 in northern India and the Yellow River basin in China (Figs. 2b and 3b). Figure 6b shows the spatial distribution of the difference in $NNBW_{WFD}$ between 1960 and 2000. The largest increase occurred because the irrigation areas doubled from 1960 to 2000 in the High Plains aquifer region of the United States, northwestern India, Pakistan, and north-eastern China (Fig. 2b); however, the storage capacities of medium-size reservoirs did not increase (Fig. 3b).

Concerning future simulations for the period of 2002–2050 using the WDD data set, estimated water requirements increased as follows: 629, 449 and 576 km^3 yr^{-1} for $RIV_{IC,2040s}$, $RIV_{CC,2040s}$ and $RIV_{IC+CC,2040s}$, respectively; 50, 31 and 44 km^3 yr^{-1} for $LR_{IC,2040s}$, $LR_{CC,2040s}$, and $LR_{IC+CC,2040s}$, respectively; 635, 448 and 638 km^3 yr^{-1} for $MSR_{IC,2040s}$, $MSR_{CC,2040s}$, and $MSR_{IC+CC,2040s}$, respectively; and 275, 153 and 443 km^3 yr^{-1} for $ADD_{IC,2040s}$, $ADD_{IC,2040s}$, and $ADD_{IC+CC,2040s}$, respectively (Table 2). IR_{IC+CC} and IR_{IC} also rose substantially, by ∼63 and ∼54 %, in future simulations. However, IR_{CC} projected an increasing trend of ∼11 %, and the differences among the three GCMs were relatively large. These results imply that future water increases will be relatively large due to the increasing irrigation area rather than the effect of climate change. $RIV_{IC,2040s}$, $RIV_{CC,2040s}$ and $RIV_{IC+CC,2040s}$ increased only marginally compared to $RIV_{WFD,1990s}$. This result indicates that current RIV and LR have already nearly reached their critical limits for irrigation water use. MSR_{IC}, MSR_{CC} and MSR_{IC+CC} as well as RIV_{IC}, RIV_{CC} and RIV_{IC+CC} did not increase significantly. MSR_{IC}, MSR_{CC} and MSR_{IC+CC} exceeded RIV_{IC}, RIV_{CC} and RIV_{IC+CC} (Fig. 5a) after the 2020s. Therefore, compared with other water supply sources, the dependence on $MSR_{IC+CC,2040s}$ was highest, accounting for almost 33 % of the $IR_{IC+CC,2040s}$ in Fig. 5b and Table 2. $MSR_{IC,2040s}$ and $MSR_{IC+CC,2040s}$ were both 1.5 times greater than $MSR_{WDD,1990s}$.

ADD_{IC} and ADD_{IC+CC}, which were highlighted future increases in $NNBW_{IC}$ and $NNBW_{IC+CC}$ from $NNBW_{WDD,1990s}$, were predicted to increase significantly along with an increase in IR_{IC} and IR_{IC+CC}. In contrast, ADD_{CC} was relatively small along with the approximately constant IR_{CC}. In addition, the annual variations in ADD_{CC}

Table 2. Contributions of global average net irrigation water requirements from various water supply sources to the total net irrigation water requirement ($km^3\,yr^{-1}$ and %) using the WFD and WDD data sets, and irrigation areas ($10^6\,km^2\,yr^{-1}$) in the 1960s, 1990s and 2040s. IC, CC, and IC + CC denote simulations with a sole scenario of irrigation area change, a sole scenario of climate change and a scenario with both irrigation area and climate change, respectively.

Simulations			Meteorological forcing data	Irrigation areas ($10^6\,km^2\,yr^{-1}$)	IR	RIV	LR ($km^3\,yr^{-1}$, %)	MSR	NNBW	ADD
1960s	Past		WFD	1.5	737 (100)	340 (46)	16 (2)	218 (30)	163 (22)	–
			WDD		669 (100)	327 (49)	12 (2)	197 (29)	133 (20)	
1990s	Past		WFD	2.6	1191 (100)	480 (40)	29 (2)	423 (36)	259 (22)	–
			WDD		1200 (100)	473 (39)	33 (3)	434 (36)	260 (22)	
2040s	Future	IC	WDD	3.9	1849 (100)	629 (34)	50 (3)	635 (34)	260 (14)	275 (15)
		CC	WDD	2.6	1341 (100)	449 (34)	31 (2)	448 (33)	260 (20)	153 (11)
		IC + CC	WDD	3.9	1961 (100)	576 (29)	44 (2)	638 (33)	260 (13)	443 (23)

and ADD_{IC+CC} were significant. With an increase in temperature and precipitation variability due to the anticipated climate change scenario of CMIP3, additional water supply sources could be needed during specific seasons when water shortages become more prominent.

5.2 Country-based dependence of net irrigation water requirements on water supply sources

Figure 7a and b present annual changes and ratios in the net irrigation water requirements from four water supply sources (RIV, LR, MSR and NNBW) for 1960–2050, and an additional water supply source (ADD) for 2002–2050 in China, India, Pakistan, the United States, Mexico and Iran (the countries with the highest levels of irrigation water use worldwide). These changes had large variations. The results of sensitivity tests (shown in Sect. 6.2) indicated that this is primarily due to climate variation.

The IR_{WFD} for all countries increased from the 1960s to 1990s. The RIV_{WFD} supply for IR_{WFD} in all countries increased very little after the early 1990s. Pakistan and China had the highest dependence on RIV_{WFD}. MSR_{WFD} showed an increasing trend. India, Mexico and Iran had the highest dependence on MSR_{WFD}. $NNBW_{WFD}$ also displayed an increasing trend, particularly after the early 1980s in China and India, the early 1990s in Mexico and the late 1990s in Iran. These temporal changes in NNBW are associated with the expansion of irrigated areas in these countries. Compared with other water supply sources, $NNBW_{WFD}$ increased the most in the United States. The RIV_{WFD}, LR_{WFD} and MSR_{WFD} values in the United States were generally small, and they stagnated after the 1960s. Thus, the increased IR generated by the expansion of the irrigation area was replenished with $NNBW_{WFD}$.

Concerning future simulations for the period of 2002–2050, IR_{IC} and IR_{IC+CC} increased according to the expansion of the irrigation area, whereas IR_{CC} decreased, compared to $IR_{WDD,2000}$ due to climate change in India, Pakistan and Iran. Conversely, IR_{IC} increased, whereas IR_{CC} and IR_{IC+CC} decreased, compared to $IR_{WDD,2000}$ due to climate change in the United States, China and Mexico. $ADD_{IC+CC,2040s}$ in India and Pakistan accounted for 28 and 45 % of $IR_{IC+CC,2040s}$, respectively. $ADD_{IC,2040s}$ in India, Pakistan and the United States, accounted for 14, 26 and 16 % of $IR_{IC,2040s}$, respectively. $ADD_{CC,2040s}$ in India and Pakistan accounted for 14 and 25 % of $IR_{CC,2040s}$, respectively. These results imply that additional water would be needed in any cases of irrigation area change and/or anticipated climate change in India and Pakistan. Compared with India, Pakistan, Mexico and Iran, additional water would not be needed as much in the United States when the impacts of climate change are affected. However, in China, there was little need for additional water in any of the cases, because the simulation results indicated that China could still use the enormous storage capacity of its medium-size reservoirs.

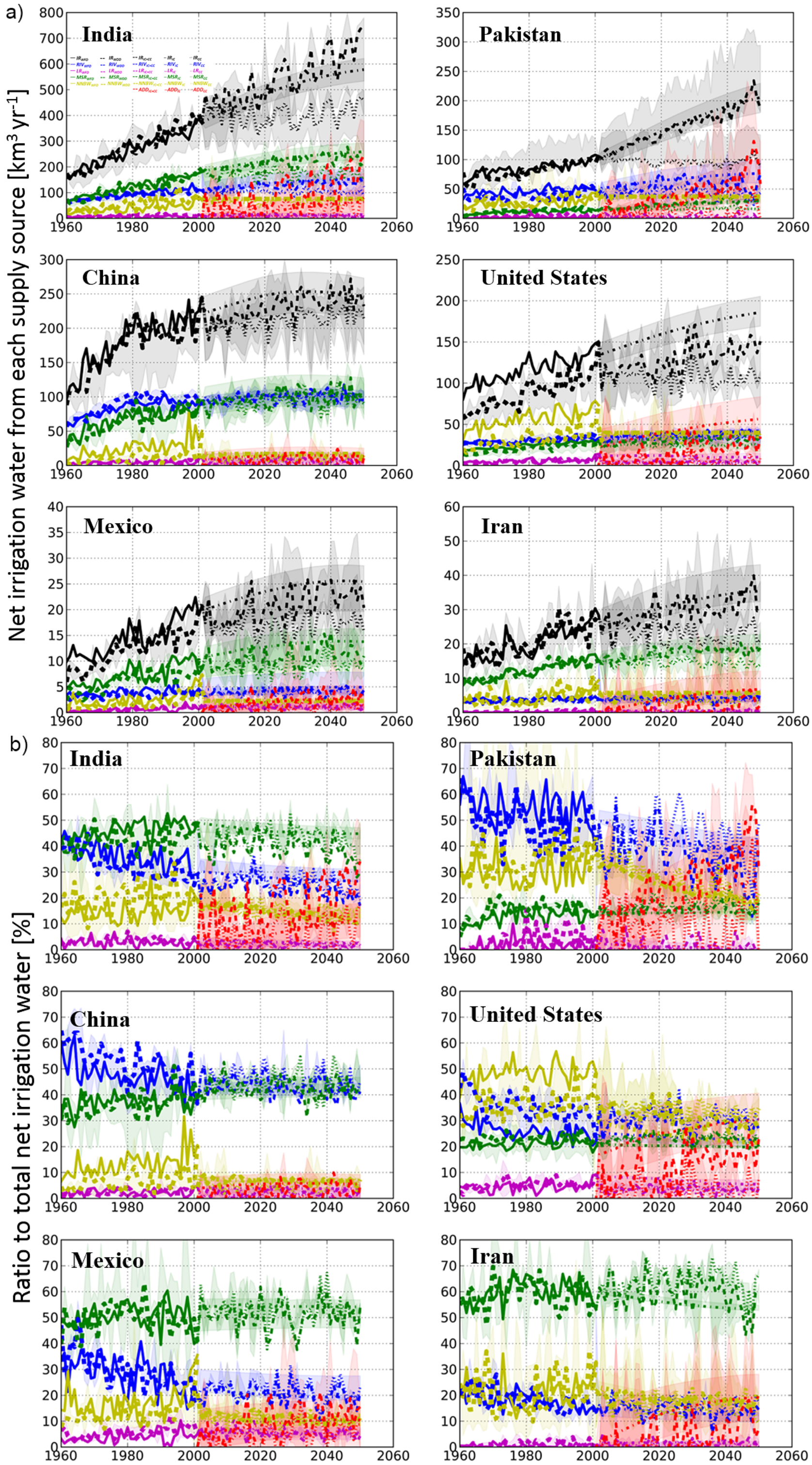

Figure 7. Annual changes in net irrigation water requirements from four water supply sources (RIV, LR, MSR and NNBW) using the WFD and WDD data sets during 1960–2001, and global net irrigation water requirements from five water supply sources according to the IC simulation (RIV_{IC}, LR_{IC}, MSR_{IC}, $NNBW_{IC}$ and ADD_{IC}), the CC simulation (RIV_{CC}, LR_{CC}, MSR_{CC}, $NNBW_{CC}$ and ADD_{CC}) and the IC + CC simulation (RIV_{IC+CC}, LR_{IC+CC}, MSR_{IC+CC}, $NNBW_{IC+CC}$ and ADD_{IC+CC}) for 2002–2050 in India, Pakistan, China, the United States, Mexico and Iran **(a)**. The percentage contribution of the different water supply sources to IR for the six countries **(b)**. In the past and future periods, results of the ensemble median for the WDD data set from the three GCMs are provided. Outer shades show the maximum and minimum for all the meteorological forcing data.

Table 3. Sensitivity study of the total global net irrigation water requirements in the year 2000 with regard to target soil moisture levels, surface albedo and double-cropping.

Experimental designs	Conditions	$IR_{WFD,2000}$ ($km^3\,yr^{-1}$)	Change rate (%)
This study			
1. Target soil moisture level of irrigation (except paddy)	60 %	1302	–
2. Land surface albedo	Seasonal change		
3. Cropping option	Double		
Sensitivity tests			
1. Target soil moisture levels of irrigation (except paddy)	75 %	1585	+21.7
2. Land surface albedo	Fixed at 0.23	1211	−7.0
3. Cropping option	Single	1081	−7.1

6 Sensitivity tests

6.1 Uncertainties in net irrigation water requirements from various water supply sources

6.1.1 Target soil moisture levels, land surface albedo and option for double-cropping

Evaluations of model performance based on sensitivity tests can be helpful in determining the uncertainty of estimated results. Target soil moisture levels, land surface albedo, and option for double-cropping are the most critical parameters with regard to model performance for estimating the total water requirements (Döll and Siebert, 2002). Thus, we investigated the sensitivity of these three parameters to $IR_{WFD,2000}$.

In the H08 model, the target soil moisture level strongly influences irrigation water use because it determines the level of soil moisture for consumption-based irrigation water demands. With the exception of rice, all crops in the original H08 model set the target soil moisture level to 75 % during the growing season. However, in this study we used a target soil moisture level of 60 %.

Surface albedo is a critical parameter related to evaporation, due to alterations in surface-available energy. Previous studies using water resource models (Siebert and Döll, 2008; Liu and Yang, 2010; Wada et al., 2012b) have adopted an albedo value of 0.23 for all seasons because they selected the FAO Penman–Monteith method (Allen et al., 1998). In this study, we followed Hanasaki et al. (2008a, b) and used albedo data from the second Global Soil Wetness Project, in which albedo values vary from 0.1 to 0.3, according to the stage of the cropping season (Hanasaki et al., 2008a, b, 2010).

The double-cropping schedule is important for water resource management. The H08 model has a double cropping option based on crop intensity data published by Döll and Siebert (2002). We took this into account, but some other studies did not include this factor (Siebert and Döll, 2008; Liu and Yang, 2010; Wada et al., 2012b).

Table 3 lists the results from our H08 model with regard to the target soil moisture level, land surface albedo and the option for double-cropping. In the year 2000, an increase in the target soil moisture level from 60 to 75 % resulted in a 21.7 % increase in $IR_{WFD,2000}$. When the albedo value was fixed at 0.23, the $IR_{WFD,2000}$ was reduced by 7.0 %. Furthermore, when the model considered only single-cropping, $IR_{WFD,2000}$ decreased by 17.0 %. Thus, changes in these three parameters could increase or decrease the total water requirement by $\sim$ 20 %.

6.1.2 Storage capacity of medium-size reservoirs

Although we assumed that the entire capacity of medium-size reservoirs is useable for storing water, this is unrealistic: a considerable fraction of the capacity should be spared for dead and surcharge storage. Table 4 lists the results of our H08 model reducing the storage capacity of medium-size reservoirs by 90, 70, 50, 30 and 10 %. When storage capacity use declined from 90 to 10 %, $MSR_{WFD,2000}$ was decreased from −2.8 to −47.7 %, while $RIV_{WFD,2000}$ and $NNBW_{WFD,2000}$ increased from 10.4 and 4.8 % to 16.2 and 55.4 %, respectively. Our findings indicate that storage capacity strongly influences the calculation not only of MSR but also of RIV and NNBW.

6.2 Contributions of changes in irrigation areas and the WFD data set to the NNBW increase from 1997 to 2000

In our past simulations using the WFD data set, we found an increase in $NNBW_{WFD}$ in the period from 1997 to 2000, as shown in Fig. 5a. The difference between $NNBW_{WFD,2000}$ (332 $km^3\,yr^{-1}$) and $NNBW_{WFD,1997}$ (268 $km^3\,yr^{-1}$) from our past simulations was 64 $km^3\,yr^{-1}$. This could be

Table 4. Sensitivity study of $MSR_{WFD,2000}$ with regard to 90, 70, 50, 30 and 10 % storage capacity in medium-size reservoirs.

	Storage capacity of medium-size reservoirs	$MSR_{WFD,2000}$ ($km^3\,yr^{-1}$)	Change rate (%)	$RIV_{WFD,2000}$ ($km^3\,yr^{-1}$)	Change rate (%)	$NNBW_{WFD,2000}$ ($km^3\,yr^{-1}$)	Change rate (%)
This study	100 %	436	–	481	–	332	–
Sensitivity tests	90 %	424	−2.8	531	+10.4	348	+4.8
	70 %	404	−7.4	534	+11.0	366	+10.2
	50 %	373	−14.4	538	+11.9	392	+18.1
	30 %	322	−26.1	544	+13.1	437	+31.6
	10 %	228	−47.7	559	+16.2	516	+55.4

Table 5. Sensitivity analysis for the contribution of $NNBW_{WFD}$ using combinations of irrigation areas and meteorological forcing conditions in the years 1997 and 2000 for the globe, India and Pakistan.

		Year	$NNBW_{WFD}$ (km^3) in simulation setting of irrigation areas		Difference 2000–1997	Contribution of irrigation area changes (%)
			1997	2000		
Globe	$NNBW_{WFD}$ (km^3) in simulation setting of meteorological forcing conditions	1997	268	275	7	11 % (7/64)
		2000	330	332	–	
	Difference 2000–1997 (km^3)		62	–	64	
	Contribution of meteorological forcing conditions (%)		97 % (62/64)			
India	$NNBW_{WFD}$ (km^3) in simulation setting of meteorological forcing conditions	1997	35	44	9	19 % (9/48)
		2000	74	83	–	
	Difference 2000–1997 (km^3)		39	–	48	
	Contribution of meteorological forcing conditions (%)		81% (39/48)			
Pakistan	$NNBW_{WFD}$ (km^3) in simulation setting of meteorological forcing conditions	1997	23	23	0	0 % (0/20)
		2000	43	43	–	
	Difference 2000–1997 (km^3)		20	–	20	
	Contribution of meteorological forcing conditions (%)		100 % (20/20)			

attributable to changes in irrigation area and climatic variability. In order to quantitatively investigate the contribution of these factors we performed sensitivity experiments to evaluate the contribution ratios of the changes in irrigation area and the variations in the WFD data set. We undertook two simulations: in the first, only irrigation areas were changed, whereas in the second, only meteorological forcing data between 1997 and 2000 were changed. We estimated the $NNBW_{WFD}$ according to these experiments, as shown in Table 5. The contribution of meteorological forcing was 62 $km^3\,yr^{-1}$ globally. The contribution of changes in irrigation area was 7 $km^3\,yr^{-1}$ when the global irrigation area was fixed to the 1997 value. The difference in the meteorological forcing data contributed 97 % of the increased $NNBW_{WFD}$ in both the meteorological forcing data and irrigation area. In India, expansion of the irrigation area contributed 19 % of the increased $NNBW_{WFD}$ between 1997 and 2000. The difference in the WFD data set contributed 81 % of the increased $NNBW_{WFD}$. In Pakistan, the difference in meteorological forcing data contributed all of the increased $NNBW_{WFD}$ between 1997 and 2000. In both two countries, variations in the WFD meteorological forcing data set contributed to increases in $NNBW_{WFD}$ from 1997 to 2000.

7 Discussion and concluding remarks

7.1 General findings

In this study, by using the H08 model and taking into account variations in the irrigation area for the period of 1960–2001, we estimated the time-varying dependence of net irrigation water requirements from various water supply sources. Estimation of RIV, LR, MSR and NNBW on a global scale (Fig. 5a and b) revealed that RIV, MSR and NNBW increased continuously from the 1960s to the early 1990s, but LR increased only marginally. After the early 1990s, RIV was almost constant, whereas MSR and NNBW continued to increase significantly. This finding suggests that RIV has almost reached its critical limit as the irrigation area has continually expanded. This indicates that there would not be enough river water to meet irrigation water requirements during irrigation periods. MSR increased according to the increasing storage capacity of medium-size reservoirs. NNBW increased under the conditions of increased irrigation area because RIV and MSR could not fulfil the required supply of water needed for the increased IR. In addition, we projected the future dependence on RIV, LR, MSR, NNBW and ADD for the period of 2002–2050 according to three future simulations (IC, CC and IC + CC simulations). In this study, ADD was defined as an increase in NNBW from the 1990s. In any of the simulations, there were no further increases in RIV, LR and MSR after the 2020s.

Our results, which showed that IR_{CC} increased by $\sim 10\,\%$ from the 1990s to 2040s under the IPCC AR4 high emission scenario of CMIP3, are consistent with those of Wada et al. (2014), who predicted the increase of irrigation water withdrawal under the IPCC AR5 highest greenhouse gas emission scenario of CMIP5. It should be noted that Wada et al. (2014) used multi-water resource models, whereas our study used a sole water resource model (the H08 model).

A continuous increase in irrigated areas would result in more ADD_{IC} and ADD_{IC+CC} on a global scale, particularly in India, Pakistan and the United States. Associated with the increases in IR_{CC}, a significant increase in ADD_{CC} would occur in India and Pakistan due to the insufficient water resources from $RIV_{CC,2040s}$, $LR_{CC,2040s}$ and $MSR_{CC,2040s}$. These requirements varied significantly under climate change, with an accompanying increase in the frequency and magnitude of the risk of floods and droughts (Kundzewicz et al., 2007; Hirabayashi et al., 2008, 2013). Climate change causes substantial increases in ADD_{CC} and ADD_{IC+CC} during specific seasons. This casts doubt on the steadiness and sustainability of regional future food production (Foley et al., 2011) and the likelihood of maintaining safe operating spaces for freshwater use by humanity (Rockström et al., 2009).

7.2 Comparison of LR and MSR in the past simulations with a previous work by Biemans et al. (2011)

To our knowledge, no reliable global report on irrigation water use has separated surface water into natural (RIV) and regulated flows (LR and MSR). Here, we discuss our results in comparison with the work of Biemans et al. (2011), as their work is largely comparable with ours. In our estimation, the ratio of the global annual average net irrigation water requirement from reservoirs to IR was 37.5 %, including a 2.7 % contribution from LR and a 34.8 % contribution from MSR, during the period from 1981 to 2000. Biemans et al. (2011) estimated 40 % global annual average irrigation extraction from reservoirs over the same period. Not only our numbers, but also the spatial distributions in India and China, agreed well with the results of Biemans et al. (2011). Although these values were very similar, computational processes between our results and Biemans et al. (2011) were different, and differences resulted from the following three factors.

First, this study presented results for IR, whereas Biemans et al. (2011) has presented results for water withdrawals, which include return flows and conveyance losses. Second, the difference in total storage capacity using large and medium-size reservoirs as input data may lead to different results. In this study, the time-varying distribution of the storage capacity of large and medium-size reservoirs was determined from the geographical location and year of dam construction based on data from Lehner et al. (2011) and ICOLD (2003). These methods were described by Hanasaki et al. (2010) and Pokhrel et al. (2012b). In 2000, the total storage capacity of these reservoirs had reached $7511\,km^3$ (Fig. 3a). However, Biemans et al. (2011) used $6300\,km^3$ for the total storage capacity, which was derived from Lehner et al. (2011). Finally, there are differences in the way reservoirs are described. In the H08 model, large reservoirs are treated individually and geo-referenced to the river network. Then, the river discharge from downstream to a large reservoir is regulated by large reservoirs for the purpose of irrigation and non-irrigation. LR contributed only to irrigation areas within the grid cells located downstream of the reservoirs. Medium-size reservoirs were accumulated in each calculated grid cell for use as direct water supply sources. The discharge in each grid cell is not regulated by medium-size reservoir operations. Consequently, medium-size reservoirs strongly influence the calculation of other water supply sources (described in Sect. 6.1.2) in the H08 model, whereas large reservoirs strongly influence the calculation of river discharge. In contrast, Biemans et al. (2011) considered all of the reservoirs individually, and found that most rivers, including tributaries, were regulated by reservoir operations. This means that irrigation water from reservoirs in Biemans et al. (2011) could be supplied to a much larger area than LR in this study.

7.3 NNBW in the past simulations

The simulated global total $NNBW_{WFD,2000}$ in this study ($332\,km^3\,yr^{-1}$) was underestimated compared with values reported in previous studies (ranging from 494 to $940\,km^3\,yr^{-1}$; see Rost et al., 2008; Biemans et al., 2011; Wada et al., 2012b). Potentially, this underestimation could have resulted from the different kinds of meteorological forcing data used. The previous studies performed NNBW using the Climatic Research Unit Global Monthly Time Series, Version 2.1 (CRU TS 2.1) meteorological forcing data set (New et al., 2000). Here, we used the WFD meteorological forcing data set, which is based on the ERA-40 product.

The key differences from the CRU TS 2.1 data set are that the WFD data set used ERA-40 and applied the gauging-undercatch correction of Adam and Lettenmaier (2003) to its precipitation products. Therefore, $RIV_{WFD,2000}$, $LR_{WFD,2000}$ and $MSR_{WFD,2000}$ may be overestimated compared with the actual values, and hence $NNBW_{WFD,2000}$ could have been underestimated.

The spatial distribution of the difference in $NNBW_{WFD,2000}$ (Fig. 6b) is similar to groundwater depletion predicted by Wada et al. (2010, 2012b). The Wada et al. (2010) estimated groundwater depletion values were obtained by assessing groundwater recharge using a global-scale hydrological model and subtracting estimates of groundwater abstraction based on statistical data. Another attempt was made to include groundwater in global-scale hydrological models (Döll and Fiedler, 2008; Döll et al., 2014). Even though NNBW is not an explicit representation of the fossil groundwater in the H08 model, the difference between the total of RIV, LR and MSR, and an unlimited total IR, could partly be attributable to groundwater abstraction. Therefore, we need further verification of the outputs and the hypothesis of the water resource model. Separate estimation of NNBW into non-renewable and non-local water use is required to improve the information available for water management.

Our results demonstrated that temporal trends in the irrigation water requirements of the six countries (China, India, Iran, Mexico, the United States and Pakistan) shown in Fig. 7a and b were associated with expansion of irrigation areas. However, the seasonal fluctuations in water requirements were strongly dependent on variations in meteorological forcing conditions because the importance of each water supply source was altered by changes in meteorological forcing-induced surface hydrology (e.g. runoff and discharge). For example, after 1997, $NNBW_{WFD}$ increased substantially in India and Pakistan (Table 5). We determined that almost all of the increase in $NNBW_{WFD}$ from 1997 to 2000 was due to variations in the meteorological forcing data. In these countries with the highest numbers of irrigation water users, different events occurred around the same time. In the year 1997, a heavy monsoon caused devastating floods in the Punjab region of Pakistan, near Northwest India (Abbas et al., 2014). The $NNBW_{WFD,1997}$ was relatively small because the H08 model stores heavy rainfall as soil moisture on land. Conversely, during the monsoon season of the year 2000, severe meteorological and vegetative drought occurred across Northwest India (Bhuiyan et al., 2006) due to a shortage of rainfall (Mall et al., 2006). In the worst case, only ∼ 40 % of the food production for a normal year was secured. $NNBW_{WFD,2000}$ was relatively large due to water shortages. Therefore, in India and Pakistan these events contributed to a sudden increase in NNBW from 1997 to 2000.

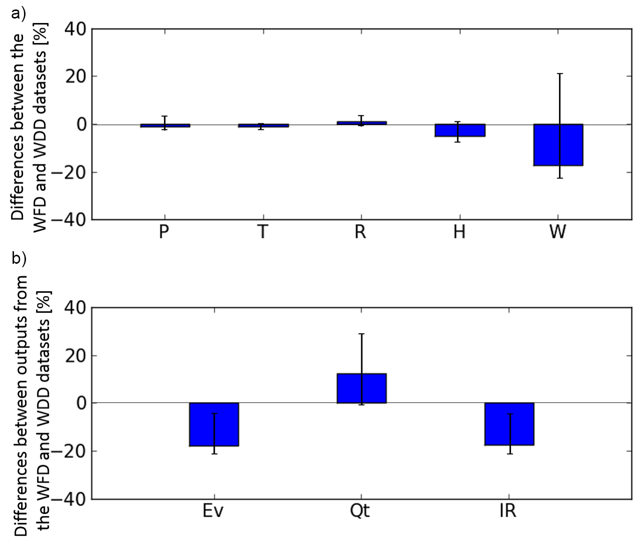

Figure 8. Global differences (%) in precipitation (P), temperature (T), downward longwave and shortwave radiation (R), humidity (H), and wind speed (W) as simulation inputs for the three GCMs of the WDD data set compared to the WFD data set **(a)**, and global differences (%) in evapotranspiration (ET), runoff (Q_t), and total irrigation requirement (IR) as simulation outputs for three GCMs of the WDD data set compared to those results using the WFD data set **(b)**. Blue bars and ranges show the average and the maximum and minimum for all the data.

7.4 Other uncertainties and limitations in the past simulations

The differences/inconsistencies in meteorological forcing data between the WDD data set taken from the three GCMs and the WFD data set based on observation should be noted. Precipitation and temperature data in the WDD data set were bias-corrected against the WFD data set (Piani et al., 2010). However, other forcing variables (e.g. radiation, humidity and wind speed) still have significant biases. We tested the error by comparing differences in the results simulated by the WDD and the WFD data sets. Figure 8 shows that there are small spreads (−1.6 to 5.5 %) among the three GCMs in global precipitation of the WDD data set compared to the WFD data set for the period of 1971–2000. On the other hand, the simulated evapotranspiration, runoff and IR using the three GCMs of the WDD data set had relatively large differences (−21.7 to −5.0 %, −1.3 to 33.0 % and −21.8 to −5.0 %, respectively) compared to those results of the WFD data set, respectively. These results are consistent with those of Haddeland et al. (2012) who tested the effects of radiation, humidity and wind variables on four large-scale hydrological models that used both bias-corrected forcing and non-bias-corrected forcing. They mentioned that the absolute values of simulated evapotranspiration and runoff had large differences before and after bias correction of the forcing variables.

According to Sect. 6.1, target soil moisture level, land surface albedo and the option for double-cropping were important to the accurate estimation of IR. Setting the storage capacity of medium-size reservoirs also appears to be important in the estimation of RIV, LR, MSR and NNBW. According to Sect. 6.2, storage capacities influenced the estimation of not only MSR but also RIV and NNBW. The reservoirs cannot be adequately represented given the available information regarding their size, purpose and characteristics. Therefore, the results of this study should be considered alongside the influence of limited geographical information on reservoirs.

7.5 Other uncertainties and limitations in the future simulations

In our future simulations, there could also be potential uncertainties in the parameterisations from the meteorological forcing data set. In the CC simulations and the IC + CC simulations, we used three GCMs of CMIP3 under only one scenario, although more than 40 GCMs of CMIP5 are readily available (Taylor et al., 2012). As suggested in other studies (e.g. Gosling et al., 2011; Haddeland et al., 2011, 2014; Hagemann et al., 2013; Hanasaki et al., 2013a, b; Schewe et al., 2014; Wada et al., 2014; Zhao et al., 2014), multi-meteorological forcing data and multi-scenario approaches may be preferable.

In the CC simulations and the IC + CC simulations, we designed the irrigation scenario according to the future global population growth rate. However, this study did not include changes in irrigation efficiency, crop intensity, or crop type over the entire period. All of the future simulations assumed that the storage capacity of large- and medium-size reservoirs, as well as industrial and domestic water withdrawals, are unchanged between 2000 and 2050. Hanasaki et al. (2013a) developed future scenarios of irrigation water use that incorporate five factors: irrigation area, crop intensity, irrigation efficiency and domestic and industrial water use. However, in Hanasaki et al. (2013a), there are no future scenarios of potential reservoir construction on a global scale. If large or medium-size reservoirs were to be constructed in the future, LR and MSR would increase, and ADD would decrease. For these reasons, there might still be large uncertainties associated with ADD.

The limitations of these simulations with regard to future conditions must also be quantified. We should note that the response of stomata to greenhouse gases and the related effects on evapotranspiration (Gerten et al., 2007) are not accounted for in this study. Additionally, environmental flow requirements were not accounted for in all of our simulations, although these requirements can influence all elements of water supply. In the H08 model, such values have been estimated, but without considering explicit linkages to freshwater ecosystem structure and function. Yoshikawa et al. (2014) suggested that there is a strong need to find ways to incorporate this linkage to more adequately determine environmental flows for each region at a global scale. Incorporating these factors into future simulations in the H08 model, while challenging, is critically important. Additionally, our approach does not fully reflect regional irrigation practices by which farmers may adapt several technical and political management approaches (e.g. Lazarova and Bahri, 2005; Gupta et al., 2011; Liu et al., 2013b) to increasing irrigation water use from various water supply sources.

7.6 Concluding remarks

In total, RIV, LR and MSR might not be able to provide sufficient irrigation water without the construction of new reservoirs in the future. If irrigation areas and climate change have impacts on future water requirements, more irrigation water will be required from additional water supply sources. Increasing ADD may contribute to groundwater depletion (Konikow and Kendy, 2005; Wada et al., 2010; Gleeson et al., 2012) and may result in sea level rise (Pohkrel et al., 2012a; Wada et al., 2012a). Otherwise, we may require the further development of water supply sources in order to sustain future irrigation.

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References

Abbas, F., Ahmad, A., Safeeq, M., Ali, S., Saleem, F., Hammad, H. M., and Farhad, W.: Changes in precipitation extremes over arid to semiarid and subhumid Punjab, Pakistan, Theor. Appl. Climatol., 116, 671–680, doi:10.1007/s00704-013-0988-8, 2014.

Adam, J. C. and Lettenmaier, D. P.: Adjustment of global gridded precipitation for systematic bias, J. Geophys. Res., 108, 4257, doi:10.1029/2002JD002499, 2003.

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.

Bhuiyan, C., Singh, R. P., and Kogan, F. N.: Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data, Int. J. Appl. Earth Obs. Geoinf., 8, 289–302, doi:10.1016/j.jag.2006.03.002, 2006.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R. W., Heinke, J., von Bloh, W., and Gerten, D.: Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resour. Res., 47, 1–15, 2011.

Bruinsma, J.: World Agriculture: Towards 2015/2030 – An FAO Perspective, Food and Agriculture Organization and Earthscan, London, 2003.

De Fraiture, C., Wichelns, D., Rockstrom, J., Kemp-Benedict, E., Eriyagama, N., Gordon, L. J., Hanjra, M. A., Hoogeveen, J., Huber-Lee, A., and Karlberg, L.: Looking ahead to 2050: Scenarios of alternative investment approaches, in: Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture London UK, edited by: Modlen, D., Earthscan, IWMI, Colombo, Sri Lanka, 91–145, 2007.

Döll, P. and Fiedler, K.: Global-scale modeling of groundwater recharge, Hydrol. Earth Syst. Sci., 12, 863–885, doi:10.5194/hess-12-863-2008, 2008.

Döll, P. and Siebert, S.: Global modeling of irrigation water requirements, Water Resour. Res., 38, 1037, doi:10.1029/2001WR000355, 2002.

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.

Döll, P., Hoffmann-Dobreva, H., Portmanna, F. T., Siebertb, S., Eickerc, A., Rodelld, M., Strassberge, G., and Scanlone, B. R.: Impact of water withdrawals from groundwater and surface water on continental water storage variations, J. Geodynam., 59–60, 143–156, 2012.

Döll, P., Schmied, H. M., Schuh, C., Portmann, F. T., and Eicker, A.: Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites, Water Resour. Res., 50, 5698–5720, doi:10.1002/2014WR015595, 2014.

Erb, K. H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., and Haberl, H.: A comprehensive global min resolution land-use data set for the year 2000 consistent with national census data, J. Land Use Sci., 2, 191–224, doi:10.1080/17474230701622981, 2007.

Famiglietti, J. S., Lo, M., Ho, S. L., Bethune, J., Anderson, K. J., Syed, T. H., Swenson, S. C., de Linage, C. R., and Rodell, M.: Satellites measure recent rates of groundwater depletion in California's Central Valley, Geophys. Res. Lett., 38, L03403, doi:10.1029/2010GL046442, 2011.

FAO – Food and Agriculture Organization of the United Nations/AQAUASTAT: AQUASTAT online database, available at: http://www.fao.org/nr/water/aquastat/dbase/index.stm, last access: 23 December 2012.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, G. D., and Zaks, D. P. M.: Solutions for a cultivated planet, Nature, 478, 337–342, doi:10.1038/nature10452, 2011.

Freydank, K. and Siebert, S.: Towards mapping the extent of irrigation in the last century: A time series of irrigated area per country, Frankfurt Hydrology Paper 08, Institute of Physical Geography, University of Frankfurt, Frankfurt, Germany, 2008.

Gerten, D., Schaphoff, S., and Lucht, W.: Potential future changes in water limitations of the terrestrial biosphere, Climatic Change, 80, 3–4, doi:10.1007/s10584-006-9104-8, 2007.

Gleeson, T., Wada, Y., Marc, F. P. B., and van Beek, L. P. H.: Water balance of global aquifers revealed by groundwater footprint, Nature, 488, 197–200, doi:10.1038/nature11295, 2012.

Gosling, S. N., Taylor, R. G., Arnell, N. W., and Todd, M. C.: A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models, Hydrol. Earth Syst. Sci., 15, 279–294, doi:10.5194/hess-15-279-2011, 2011.

Gupta, A. K., Tyagi, P., and Sehgal, V. K.: Drought disaster challenges and mitigation in India: Strategic appraisal, Current Sci., 100, 1795–1806, 2011.

Haddeland, I., Skaugen, T., and Lettenmaier, D. P.: Anthropogenic impacts on continental surface water fluxes, Geophys. Res. Lett., 33, L08406, doi:10.1029/2006GL026047, 2006.

Haddeland, I., Clark, D., Franssen, W., Ludwig, F., Voss, F., Arnell, N., Bertrand, N., Best, M., Folwell, S., Gerten, D., Gomes, S., Gosling, S., Hagemann, S., Hanasaki, N., Harding, R., Heinke, J., Kabat, P., Koirala, S., Oki, T., Polcher, J., Stacke, T., Viterbo, P., Weedon, G., and Yeh, P.: Multimodel estimate of the global terrestrial water balance: Setup and first results, J. Hydrometeorol., 12, 869–884, doi:10.1175/2011JHM1324.1, 2011.

Haddeland, I., Heinke, J., Voß, F., Eisner, S., Chen, C., Hagemann, S., and Ludwig, F.: Effects of climate model radiation, humidity and wind estimates on hydrological simulations, Hydrol. Earth Syst. Sci., 16, 305–318, doi:10.5194/hess-16-305-2012, 2012.

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z. D., Wada, Y., and Wisser, D.: Global water resources affected by human interventions and climate change, P. Natl. Acad. Sci., 111, 3251–3256, doi:10.1073/pnas.1222475110, 2014.

Hagemann, S., Chen, C., Haerter, J. O., Heinke, J., Gerten, D., and Piani, C.: Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models, J. Hydrometeorol., 12, 556–578, doi:10.1175/2011JHM1336.1, 2011.

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F., and Wiltshire, A. J.: Climate change impact on available water resources obtained using multiple global climate and hydrology models, Earth Syst. Dynam., 4, 129–144, doi:10.5194/esd-4-129-2013, 2013.

Hanasaki, N., Kanae, S., and Oki, T.: A reservoir operation scheme for global river routing models, J. Hydrol., 327, 22–41, doi:10.1016/j.jhydrol.2005.11.011, 2006.

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, 2008a.

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, doi:10.5194/hess-12-1027-2008, 2008b.

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, doi:10.1016/j.jhydrol.2009.09.028, 2010.

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., and Kanae, S.: A global water scarcity assessment under Shared Socio-economic Pathways – Part 1: Water use, Hydrol. Earth Syst. Sci., 17, 2375–2391, doi:10.5194/hess-17-2375-2013, 2013a.

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., and Kanae, S.: A global water scarcity assessment under Shared Socio-economic Pathways – Part 2: Water availability and scarcity, Hydrol. Earth Syst. Sci., 17, 2393–2413, doi:10.5194/hess-17-2393-2013, 2013b.

Hanjra, M. A. and Qureshi, E. M.: Global water crisis and future food security in an era of climate change, Food Policy, 35, 365–377, doi:10.1016/j.foodpol.2010.05.006, 2010.

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., and Kimoto, M.: Global projections of changing risks of floods and droughts in a changing climate, Hydrolog. Sci. J. 53, 754–772, doi:10.1623/hysj.53.4.754, 2008.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., and Kanae, S.: Global flood risk under climate change, Nat. Clim. Change, 3, 816–821, doi:10.1038/nclimate1911, 2013.

ICOLD – International Commission on Large Dams: World Register of Dams, ICOLD, Paris, France, 1998.

ICOLD – International Commission on Large Dams: World Register of Dams, ICOLD, Paris, France, 2003.

Klein Goldewijk, K., Beusen, A., Van Drecht, G., and De Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Global Ecol. Biogeogr., 20, 73–86, doi:10.1111/j.1466-8238.2010.00587.x, 2011.

Konikow, L. F. and Kendy, E.: Groundwater depletion: A global problem, Hydrogeol. J., 13, 317–320, doi:10.1007/s10040-004-0411-8, 2005.

Krysanova, V., Wechsung, F., Arnold, J., Srinivasan, R., and Williams, J.: SWIM (Soil and Water Integrated Model) User Manual, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 2000.

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.: Freshwater resources and their management, in: Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E., Cambridge University Press, Cambridge, UK, 173–210, 2007.

Lazarova, V. and Bahri, A.: Water Reuse for Irrigation: Agriculture, Landscapes, and Turf Grass, CRC Press, Boca Raton, FL, 2005.

Leff, B., Ramankutty, N., and Foley, J. A.: Geographic distribution of major crops across the world, Global Biogeochem. Cy., 18, GB1009, doi:10.1029/2003GB002108, 2004.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., and Wisser, D.: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Front. Ecol. Environ., 9, 494–502, doi:10.1890/100125, 2011.

Liu, J. and Yang, H.: Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water, J. Hydrol., 384, 187–197, doi:10.1016/j.jhydrol.2009.11.024, 2010.

Liu, J., Folberth, C., Yang, H., Röckström, J., Abbaspour, K., and Zehbder, A. J. B.: A Global and Spatially Explicit Assessment of Climate Change Impacts on Crop Production and Consumptive Water Use, PLoS ONE, 8, e57750, doi:10.1371/journal.pone.0057750, 2013a.

Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B., and Zhang, M.: Water conservancy projects in China: achievements, challenges and way forward, Global Environ. Change, 23, 633–643, doi:10.1016/j.gloenvcha.2013.02.002, 2013b.

Liu, J., Zehbder, A. J. B., and Yang, H.: Global consumptive water use for crop production: The importance of green water and virtual water, Water Resour. Res., 45, W05428, doi:10.1029/2007WR006051, 2009.

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, Z., Yang, L., and Merchant, J. W.: Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data, Int. J. Remote Sens., 21, 1303–1365, doi:10.1080/014311600210191, 2000.

Mall, R. K., Singh, R., Gupta, A., Srinivasan, G., and Rathore, L. S.: Impact of climate change on Indian agriculture: a review, Climatic Change, 78, 2–4, 445–478, doi:10.1007/s10584-005-9042-x, 2006.

Nakicenovic, N. and Swart, R.: Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 612 pp., 2000.

New, M. G., Hulme, M., and Jones, P. D.: Representing twentieth century space-time climate variability, Part II: Development of a 1901–1996 monthly terrestrial climate field, J. Climate, 13, 2217–2238, doi:10.1175/1520-0442(1999)012<0829:RTCSTC>2.0.CO;2, 2000.

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

Oki, T. and Sud, Y. C.: Design of Total Runoff Integrating Pathways (TRIP) – A Global River Channel Network, Earth Interact., 2, 1–37, doi:10.1175/1087-3562(1998)002<0001:DOTRIP>2.3.CO;2, 1998.

Oki, T., Agata, Y., Kanae, S., Saruhashi, T., Yang, D., and Musiake, K.: Global assessment of current water resources using total runoff integrating pathways, Hydrolog. Sci. J., 46, 983–996, doi:10.1080/02626660109492890, 2001.

Otaki, Y., Otaki, M., and Yamada, T.: Attempt to establish an industrial water consumption distribution model, J. Water Environ. Tech., 6, 85–91, doi:10.2965/jwet.2008.85, 2008.

Peachey, E. J.: The Aral Sea basin crisis and sustainable water resource management in Central Asia, J. Publ. Int. Affairs, 15, 1–20, 2004.

Piani, C., Weedon, G., Best, M., Gomes, S., Viterbo, P., Hagemann, S., and Haerter, J.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models, J. Hydrol., 395, 199–215, doi:10.1016/j.jhydrol.2010.10.024, 2010.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., and Fang, J.: The impacts of climate change on water resources and agriculture in China, Nature, 467, 43–51, doi:10.1038/nature09364, 2010.

Pokhrel, Y. N., Hanasaki, N., Yeh, P. J.-F., Yamada, T., Kanae, S., and Oki, T.: Model estimates of sea level change due to anthropogenic impacts on terrestrial water storage, Nat. Geosci., 5, 389–392, doi:10.1038/ngeo1476, 2012a.

Pokhrel, Y. N., Hanasaki, N., Koirala, S., Cho, J., Yeh, P. J.-F., Kim, H., Kanae, S., and Oki, T.: Incorporating anthropogenic water regulation modules into a land surface model, J. Hydrometeorol., 13, 255–269, doi:10.1175/JHM-D-11-013.1, 2012b.

Ramankutty, N. and Foley, J. A.: Estimating historical changes in land cover: North American croplands from 1850 to 1992, Global Ecol. Biogeogr., 8, 381–396, doi:10.1046/j.1365-2699.1999.00141.x, 1999.

Robock, A., Vinnikov, K. Y., Schlosser, C. A., Speranskaya, N. A., and Xue, Y. K.: Use of midlatitude soil-moisture and meteorological observations to validate soil-moisture simulations with biosphere and bucket models, J. Climate, 8, 15–35, doi:10.1175/1520-0442(1995)008<0015:UOMSMA>2.0.CO;2, 1995.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A.: A safe operating space for humanity, Nature, 461, 472–475, doi:10.1038/461472a, 2009.

Rodell, M., Velicogna, I., and Famiglietti, J. S.: Satellite-based estimates of groundwater depletion in India, Nature, 460, 999–1002, doi:10.1038/nature08238, 2009.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., and Rohwer, J.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., 44, 1–17, doi:10.1029/2007WR006331, 2008.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnelld, N. W., Clarke, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., and Kabat, P.: Multimodel assessment of water scarcity under climate change, P. Natl. Acad. Sci., 111, 3245–3250, doi:10.1073/pnas.122246011, 2014.

Shen, Y., Oki, T., Utsumi, N., Kanae, S., and Hanasaki, N.: Projection of future world water resources under SRES scenarios: water withdrawal, Hydrolog. Sci. J., 53, 11–33, doi:10.1623/hysj.53.1.11, 2008.

Shiklomanov I. A.: World water resources and their use, a joint SHI/UNESCO product, available at: http://webworld.unesco.org/water/ihp/db/shiklomanov/ (last access: 23 December 2012), 1999.

Siebert, S. and Döll, P.: The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops. Frankfurt Hydrology Paper 07, Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 2008.

Siebert, S., Döll, P., Feick, S., Frenken, K., and Hoogeveen, J.: Global map of irrigation areas version 4.0.1, University of Frankfurt (Main), Germany and FAO, Rome, Italy, 2007.

Smith, M.: Irrigation and Drainage Paper 46 CROPWAT: A computer program for irrigation planning and management, FAO, Rome, Italy, 1992.

Tang, Q., Oki, T., Kanae, S., and Hu, H.: Hydrological cycles change in the Yellow river basin during the last half of the 20th century, J. Climate, 21, 1790–1806, doi:10.1175/2007JCLI1854.1, 2008.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.

UN – United Nations Department of Economic and Social Affairs Population Division, World Population Prospects: The 2010 Revision, New York, 2011.

van Beek, L. P. H., Wada, Y., and Bierkens, M. F. P.: Global monthly water stress: 1 Water balance and water availability, Water Resour. Res., 47, W07517, doi:10.1029/2010WR009791, 2011.

Van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., and Rose S.: The representative concentration pathways: an overview, Climatic Change, 109, 5–31, doi:10.1007/s10584-011-0148-z, 2011.

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, doi:10.1126/science.289.5477.284, 2000.

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, L20402, doi:10.1029/2010GL044571, 2010.

Wada, Y., van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R., and Bierkens, M. F. P.: Global monthly water stress: 2. Water demand and severity of water stress, Water Resour. Res., 47, W07518, doi:10.1029/2010WR009792, 2011.

Wada, Y., van Beek, L. P. H., Weiland, F. C. S., Chao, B. F., Wu, Y.-H., and Bierkens, M. F. P.: Past and future contribution of global groundwater depletion to sea-level rise, Geophys. Res. Lett., 39, L09402, doi:10.1029/2012GL051230, 2012a.

Wada, Y., van Beek, L. P. H., and Bierkens, M. F. P.: Nonsustainable groundwater sustaining irrigation: a global assessment, Water Resour. Res., 48, W00L06, doi:10.1029/2011WR010562, 2012b.

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F. T., Stacke, T., Tessler, Z., and Schewe, J.: Multi-model projections and uncertainties of irrigation water demand under climate change, Geophys. Res. Lett., 40, 4626–4632, doi:10.1002/grl.50686, 2014.

Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N., Boucher, O., and Best, M.: Creation of the WATCH Forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century, J. Hydrometerol., 12, 823–848, doi:10.1175/2011JHM1369.1, 2011.

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.

Yoshikawa, S., Yanagawa, A., Iwasaki, Y., Sui, P., Koirala, S., Hirano, K., Khajuria, A., Mahendran, R., Hirabayashi, Y., Yoshimura, C., and Kanae, S.: Illustrating a new global-scale approach to estimating potential reduction in fish species richness due to flow alteration, Hydrol. Earth Syst. Sci., 18, 621–630, doi:10.5194/hess-18-621-2014, 2014.

Zhao, Q., Liu, J., Khabarov, N., Obersteiner, M., and Westphal, M.: Impacts of climate change on virtual water content of crops in China, Ecol. Inform., 19, 26–34, doi:10.1016/j.ecoinf.2013.12.005, 2014.