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An assessment of global net irrigation water requirements from various water supply sources to sustain irrigation: rivers and reservoirs (1960–2000 and 2050)

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An assessment of global net irrigation water requirements

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Abstract

Water supply sources for irrigation, such as rivers, reservoirs, and groundwater, are critically important for agricultural productivity. The current rapid increase in irrigation water use threatens sustainable food production. In this study, we estimated the time-varying dependency of the supply of irrigation water from rivers, large reservoirs with a greater than 1.0 km^3 storage capacity, medium-size reservoirs with storage capacities ranging from 1.0 km^3 to 3.0 Mm^3, and non-local non-renewable blue water (NNBW), particularly taking into account variations in irrigation area during the period 1960–2000. We also estimated the future irrigation water requirements from water supply sources in addition to these four sources, using an irrigation area scenario. The net irrigation water requirements from various supply sources were assessed using the global H08 water resources model. The H08 model simulates water requirements on a daily basis at a resolution of $1.0^{\circ} \times 1.0^{\circ}$. We obtained net irrigation water from rivers and medium-size reservoirs, and determined that the NNBW increased continuously from 1960 to 1985, but the net irrigation water from large reservoirs increased only marginally. After 1985, the net irrigation water from rivers approached a critical limit with the continued expansion of the irrigation area. The irrigation water requirements from medium-size reservoirs and NNBW increased significantly following the expansion of the irrigation area and the increased storage capacity of medium-size reservoirs. Under the irrigation area scenario without climate change, global net irrigation water requirements from additional water supply sources will account for 26 % of the total requirements in the year 2050. We found that expansion of irrigation areas due to population growth will generate an enormous demand for irrigation water from additional resources.

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1 Introduction

Irrigation is crucial to satisfy increasing food demand (Buruinsma, 2003; De Fraiture et al., 2007). In many countries, food production requires intensive levels of water withdrawal, which could deplete water supply sources or even cause them to run dry. When these sources are depleted, a future drop in food production would be expected (Munir et al., 2010). Irrigation water use accounted for about 70 % of global total water withdrawal in the twentieth century (Shiklomanov, 2000; Döll, 2009; FAO, 2012). It is highly unlikely that we will be able to depend on existing irrigation water sources, for two main reasons.

First, many major rivers, including the Yellow, the Colorado, 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 has experienced a persistent decline in observed annual runoff from 1960 to 2000 (Piao et al., 2010) that was significantly affected by irrigation withdrawals (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 et al., 2004).

Second, many countries are over-utilising groundwater (Gleeson et al., 2012) as they struggle to satisfy their growing water demands. 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 very intensive irrigation is prevalent, including northwestern India (Döll et al., 2011; Famiglietti et al., 2011). Such groundwater depletion has contributed to a global rise in sea-levels (Pokhrel et al., 2012a; Wada et al., 2012a).

A number of global-scale water resource models have been used to estimate spatial and temporal variations in the world's irrigated areas together with climatic conditions (e.g., Biemans et al., 2011; Döll et al., 2009; Hanasaki et al., 2010; Pokhrel et al., 2012b; Rost et al., 2008; Wada et al., 2011; Wisser et al., 2010). The results of these models indicate that expanded irrigation by the construction/operation of reservoirs in

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a typical catchment would have a gradual but significant influence on the hydrological cycle. Döll et al. (2009) and Hanasaki et al. (2006) determined the the expansion of irrigation by the construction/ operation of reservoirs caused a change in the seasonal pattern of water flow, particularly for irrigation from water supply sources (e.g., rivers, lakes, and aquifers).

Various global-scale water resource models have been used in simulations. Wada et al. (2012b) calculated net irrigation water requirements and groundwater recharge to estimate non-renewable groundwater abstraction over the period 1960–2000 using the global water resources model PCR-GLOBWB. Döll et al. (2012) considered the effects of water withdrawals on variation in water storage and on the net abstraction of groundwater and surface water for irrigation, as well as domestic and industrial uses, for the period of 1901–2002 using the global water resources model Water GAP. Bienamas et al. (2011) estimated the impact of large reservoirs on the global water cycle by using a dynamic global vegetation and hydrology model, with a particular focus on the reservoir module based on Haddeland et al. (2006) and Hanasaki et al. (2006). In Döll et al. (2009), Wisser et al. (2010), and van Beek et al. (2011), large reservoirs with a greater than 0.5×10^9 m^3 storage capacity worldwide were individually geo-referenced to the routes of rivers, and the effects of their operation on river flow was determined. In a modelling study, Biemans et al. (2011) considered all individually geo-referenced dams using a geographically explicit and reliable database of dams (Lehner et al., 2011). These models have been used to determine how dams control the supply of irrigation water to rivers.

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 their simulation, the virtual water supply source was specified using two categories (green water and blue water), which were consistent with the global hydrological cycle. Blue water was further divided into three subcategories: stream flow, medium-size reservoirs, and nonrenewable and nonlocal blue water (NNBW). In the

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H08 model, large reservoirs with a greater than 1.0×10^9 m^3 storage capacity are individually geo-referenced to the river route. Medium-size reservoirs with storage capacities ranging from 1.0×10^9 m^3 to 3.0×10^6 m^3 are not treated individually: their storage capacities are accumulated in each calculated grid cell to use as a direct water supply source.

In this study, we estimated the time-varying dependency of irrigation water from various sources on a global scale, particularly taking into account variations in the irrigation area from 1960 to 2000, using the H08 model. In this simulation, the sources of irrigation water were specified using four categories: rivers, large reservoirs, medium-size reservoirs, and NNBW. Our treatment of medium-size reservoirs differed from that in other models. By investigating the model outputs year by year for the period 1960–2000, we obtained variations of the irrigation requirements from each of various sources due to both changes in irrigation practices and climate change. We also estimated future irrigation water requirements from new additional water supply sources using an irrigation area scenario for the year 2050.

Section 2 presents a brief description of the model and the data collected. Section 3 describes the validation and calibration of our model outputs. Section 4 presents the results of our analysis (dependency of net irrigation water requirements on water supply sources and country-based dependency of net irrigation water requirements). Sections 5 and 6 present a discussion and concluding remarks, respectively.

2 Model and data

2.1 Model description

We used the H08 model to estimate net irrigation water requirements (Hanasaki et al., 2008a, b). This model simulates both natural hydrological water flows and anthropogenic water withdrawals globally on a daily basis at a resolution of $1.0^{\circ} \times 1.0^{\circ}$ using meteorological and geographical input data. The model consists of the sub-models of

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land surface hydrology (Robock et al., 1995), crop growth (Krysanova et al., 2000), river routing (Oki et al., 1999), 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 supply of irrigated water is determined as the level at which soil moisture capacity on irrigated land remains above 75 % during the cropping period. In the case of paddy fields, soil moisture is maintained at 100 % of field capacity to meet the condition of paddy inundation. In this study, we set soil moisture to be maintained at 100 % and 60 % of field capacity for paddy and other crops, because wheat, as a major global crop, is grown at 50–60 % of field capacity in many irrigated areas (Allen et al., 1998). Irrigation supply was set to begin 30 days before the planting date, increasing the soil moisture content linearly from 0 % to 60 % or 100 % for paddy fields.

The total irrigation water requirement defined in this way is known as the "net irrigation water requirement" (IR) (Smith, 1992). The IR is determined from the anthropogenic water withdrawal sub-model, in the order of priority of water supply sources as follows: (1) the river flow (Riv), which does not include large reservoirs with a greater than 1.0×10^9 m^3 storage capacity; (2) large reservoirs (LR), which are determined by subtracting river flow with large reservoirs from that without large reservoirs; (3) medium-size reservoirs (MSR) with storage capacities ranging from 1.0×10^9 m^3 to 3.0×10^6 m^3; and (4) non-sustainable and non-local blue water (NNBW), which comprise 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 later defined as NNBW by Rost et al. (2008) and Hanasaki et al. (2010). Pokhrel et al. (2012a) defined NNBW as unsustainable water withdrawal from non-renewable fossil groundwater. However, 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 Eq. (1):

$$\mathrm{IR} = \mathrm{Riv} + \mathrm{LR} + \mathrm{MSR} + \mathrm{NNBW}. \tag{1}$$

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First, Riv and LR are supplied to fulfil IR. When Riv becomes unavailable as a water supply, IR is, in turn, derived from MSR. Excess water beyond the storage capacity of the MSR flows into the river channel after runoff, as determined by the land surface hydrology module, initially runs into the medium-size reservoirs in the same grid. When the MSR are depleted, water will be withdrawn from NNBW. Two types of input data (meteorological forcing and geographical data) are required to drive the H08 model. Table 1 summarises the two types of input data; further details are presented in the following sections.

2.2 Meteorological forcing data

To prepare meteorological forcing data for the 40-yr simulation period (1960–2000), we used the NCC dataset (based on the National Centers for Environmental Prediction/National Center for Atmospheric Research, NCEP/NCAR; reanalysis project, corrected by data from the Climate Research Unit, CRU) (Ngo-Duc et al., 2005), which are 6-hourly near-surface meteorological data with a spatial resolution of $1.0^\circ \times 1.0^\circ$ for the period 1948–2000. The variables used in the H08 model are air temperature (K), specific humidity ($kg\,kg^{-1}$), wind speed ($m\,s^{-1}$), surface pressure (Pa), downward short and long wave radiation ($W\,m^{-2}$), and precipitation ($kg\,m^{-2}\,s^{-1}$).

2.3 Geographical data

2.3.1 Irrigation areas

We prepared an annual irrigation area distribution map (spatial resolution: $1.0^\circ \times 1.0^\circ$) for the period 1960–2000 to estimate irrigation water requirements. Data for equipped irrigation areas are available from the University of Frankfurt's Food and Agriculture Organization (FAO) Global Map of Irrigation Areas (GMIA) (Siebert et al., 2005, 2007) for 1998–2002 at a spatial resolution of five arc minutes. Time series data for equipped

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irrigation areas per country are available from national statistics from 1900–2003 (Freydank and Siebert, 2008).

First, to prepare the dataset of changes in the annual irrigation area, we used the Global Map of Irrigated Area (GMIA) as a base map. The GMIA is a spatially aggregated land-sea mask map with a $1.0^{\circ} \times 1.0^{\circ}$ grid resolution. Second, we obtained the annual rate of change from 1960–2000 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 equipped area 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 Foly, 1999), calibrated by a remotely sensed global land cover classification dataset (Loveland et al., 2000). Figure 1a shows the change in total irrigation area from 1960 to 2000. The HIM reflects the large-scale dynamics of the development of the irrigated area over the twentieth century, revealing an expansion in area from 1.6×10^6 km^2 in 1960 to 2.7×10^6 km^2 in 2000. Figure 1b shows the difference in irrigation area between 1960 and 2000. Irrigation areas have been increasing in India, China, Pakistan, and the United States.

Additionally, 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). The distribution of crop types and crop intensity were derived from Leff et al. (2004) and Döll and Siebert (2002) for the year 1990.

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 studied. 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 geographical

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information and specifications. In this study, we used a total of 548 large reservoirs based on ICOLD (2003) data (Hanasaki et al., 2006; Pokhrel et al., 2012b).

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 comprehensive inventory of global medium-size reservoirs, but geographical information is not available. Hanasaki et al. (2010) and Pokhrel et al. (2012b) aggregated the storage capacity distribution of medium-size reservoirs for each grid. The geographical distribution of medium-size reservoirs within each country was then weighted in proportion to population in the year 2000.

In this study, we investigated temporal variations and spatial distributions of storage capacity data for medium-size reservoirs from 1960–2000. 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 storage capacity of medium-size reservoirs in each year at a $1.0^\circ \times 1.0^\circ$ grid resolution and country scale. The remaining storage capacity was calculated from the difference between the comprehensive inventory in ICOLD (2003) and the aggregated storage capacity at the country scale. The geographical distribution of the remaining storage within each country was then weighted in proportion to population (Klein et al., 2011); see Fig. 1b for annual data based on the methods set out by Hanasaki et al. (2010) and Pokhrel et al. (2012b). Finally, we obtained the time-dependent storage capacity of medium-size reservoirs by incorporating the distribution map of the aggregated storage capacity and the remaining storage. Figure 1c presents the change in global total storage capacity of medium-size reservoirs, from 1385 km^3 in 1960 to 3084 km^3 in 2000. Figure 2b presents the variations in the storage capacity of medium-size reservoirs between 1960 and 2000. In China, storage capacities have been increasing substantially.

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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 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 1960–2000. 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 where 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 1960–2000.

The water withdrawal data (1960–2000) were then downscaled to a resolution of $1.0^{\circ} \times 1.0^{\circ}$. 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 et al., 2011) was used as a proxy for the gridded distribution of domestic water withdrawal, as in previous studies (Oki et al., 2001; Shen et al., 2008; Vörösmarty et al., 2000).

2.4 Future simulation without climate change

We estimated whether Riv, LR, MSR, and NNBW will increase with future changes only in irrigation area. For meteorological forcing data for the year 2050, we used the NCC dataset for the period 1990–2000. IR_{2050} was defined as the mean IR from 1990 to 2000, estimated from the irrigation area in the year 2050 and the storage capacity

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of reservoirs in 2000. We prepared an irrigation area scenario for the year 2050. In this scenario, we assumed that to meet food requirements, the future irrigation area will increase proportionally with population growth (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 population growth rate per country of 0.9 % yr^{-1} on a global scale.

In this experiment, we assumed that the storage capacity of large- and medium-size reservoirs, as well as industrial and domestic water withdrawals, were unchanged between the years 2000 and 2050. To indicate future water supply source changes perspicuously, a new water supply source, termed “Additional” (determined from the Eq. 2 below), was defined as the difference between NNBW in the year 2050 and NNBW in 2000, because the use of other water supply sources (LR, MSR or NNBW) in 2050 is difficult to predict:

$$IR_{2050} = Riv_{2050} + LR_{2050} + MSR_{2050} + NNBW_{2000} + Additional_{2050} \quad (2)$$

$(Additional_{2050} = NNBW_{2050} - NNBW_{2000})$.

3 Validation and calibration

For model validation, we employed a strategy that has been used in three previous studies to validate IR. Figure 3 compares the results of previous studies and the IR from our H08 simulation. These previous studies (FAO, 2012; Liu and Yang, 2011; Siebert and Döll, 2008) defined blue water use as extraction from surface or subsurface water bodies (e.g., rivers, reservoirs, lakes, aquifers). They assumed that the demand for irrigation could be estimated based on dependency on blue water. There was uncertainty in the estimations produced by all the previous models, and the H08 model also has limitations regarding input data and parameterisation. Despite this, the correlations between our present model outputs and these previous studies have high coefficients (0.76–0.99) for each country. We found relatively strong correlations

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between our present model outputs and these previous studies for the United States and China (which have the highest global irrigation water requirements). The data for India and Pakistan (which typically have high water use) were overestimated. Additionally, most countries with an IR < 100 $km^3 yr^{-1}$ had lower correlation coefficients. The distributions of over- and under-estimation errors did not depend on the experimental period. To evaluate the total IR by the model simulation, we validated the output of our model against previously reported simulations.

The overall trend was a persistent increase, from 671 $km^3 yr^{-1}$ in 1960 to 1358 $km^3 yr^{-1}$ in 2000, i.e., the total IR almost doubled during this period. The value estimated from the model simulation for year 2000 was considerably overestimated when compared to the range of results reported previously, namely 824–1,181 $km^3 yr^{-1}$ (FAO, 2012; Liu and Yang, 2011; Siebert and Döll, 2008; Wada et al., 2012b). The range of results reported in the literature is ~ 30 %. The uncertainty may be due to differences in the physical processes and boundary conditions used in the various models.

With regard to our sensitivity results (see Table A1 in Appendix A), discrepancies between previous studies and the H08 estimation may have been caused by the parameterisation of field capacity, albedo, and double-cropping. However, given that lower correlations were most apparent for Asian countries, dominated by paddy cultivation (e.g., Thailand, Bangladesh, Indonesia, Japan, etc.), it is recommended that the water body of paddy fields should be considered when using the model to predict agricultural water use. We also evaluated factors affecting model performance for estimating MSR (see Table B1 in Appendix B). When MSR decreased due to a decrease in storage capacity, Riv and NNBW increased. The storage capacity of medium-size reservoirs strongly influences the calculation of not only MSR but also Riv and NNBW.

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4 Results

4.1 Dependency of net irrigation water requirement on water supply sources

Figure 4a shows annual changes in the global net irrigation water requirements from four water supply sources from 1960–2000 and the global net irrigation water requirements from five water supply sources in the year 2050. The estimated water requirements (in Table 2) increased from 1960 to 2000 as follows: from 245 $km^3 yr^{-1}$ to 345 $km^3 yr^{-1}$ for Riv; from 16 $km^3 yr^{-1}$ to 31 $km^3 yr^{-1}$ for LR; from 194 $km^3 yr^{-1}$ to 472 $km^3 yr^{-1}$ for MSR; and from 216 $km^3 yr^{-1}$ to 510 $km^3 yr^{-1}$ for NNBW. The contribution of global net irrigation water requirements from various water supply sources to total net irrigation water requirement increased from 1960 to 2000 (Fig. 4b) as follows: from 29 % to 35 % for MSR and from 32 % to 38 % for NNBW. In 2050, the estimated water requirements (in Table 2) are 451 $km^3 yr^{-1}$ (19 %) for Riv_{2050}, 52 $km^3 yr^{-1}$ (2 %) for LR_{2050}, 737 $km^3 yr^{-1}$ (31 %) for MSR_{2050}, 510 km^3/year (22 %) for $NNBW_{2050}$, and 605 $km^3 yr^{-1}$ (26 %) for $Additional_{2050}$.

Riv, MSR, and NNBW displayed a continuously increasing trend from 1960 to 2000, but LR increased very little. The increasing trend for Riv stabilised after 1985. In the irrigation scenario for 2050, Riv_{2050} and LR_{2050} increased only marginally compared to 2000. This result indicates that Riv and LR have already reached their critical limits for irrigation water use.

MSR exceeded Riv (green and blue lines, respectively, in Fig. 4) after 1976. This may be because construction of MSR has increased to meet the growth in demand for irrigation water caused by the expansion of irrigated areas. Thus, in comparison with the other water supply sources, the dependency on MSR was highest during the 1980s and 1990s, when it contributed almost 35 % of the total IR. MSR_{2050} was 1.6 times greater than MSR in the year 2000.

Total NNBW was estimated as 368 (±33) $km^3 yr^{-1}$ in the 1990s, i.e., 38 % of the IR on a global scale. In comparison with values reported in previous studies (ranging from

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464–940 $km^3 yr^{-1}$; see Biemans et al., 2011; Rost et al., 2008; Wada et al., 2012b), this value is not overestimated. It should be noted that the results vary within a range of −20 % ∼ +21 % depending on the storage capacity set for reservoirs and parameterisation in the H08 model (see Sect. 3, Appendices A and B). In 2000, the total contribution from NNBW surpassed that from MSR, making NNBW the largest global water supply source in terms of irrigation water use. The growth rate of NNBW as an irrigation water supply source increased rapidly after 1980. Due to climatic conditions and an expansion of the global irrigation area from 1960–2000, Riv, LR, MSR, and NNBW increased by 1.4, 1.9, 2.4, and 2.4 times respectively. However, because of the insufficiency of Riv, LR, and MSR as water supply sources, a larger NNBW was required to satisfy the increase in total irrigation water demand. In 2050, $Additional_{2050}$ is predicted to increase significantly along with an increase in IR_{2050}. With the expansion of irrigation area to meet future food demand, additional water supply sources will have to be utilised.

Figure 5a shows the spatial distribution of the difference in MSR between 1960 and 2000. The largest increases occurred in north India, north Pakistan, and the Yellow River basin in China. The storage capacity of MSR has doubled from 1960 to 2000 in these regions.

Figure 5b shows the spatial distribution of the difference in NNBW between 1960 and 2000. The largest increase occurred in the High Plains aquifer region in the United States, northwestern India, Pakistan, and northeastern China. Wada et al. (2010) and Wada et al. (2012b) predicted groundwater depletion in all of these areas. The amount of precipitation in India and Pakistan has decreased since 1997, as shown in NCC data. NNBW increased substantially from 1997–2000.

4.2 Country-based dependency of net irrigation water requirement

Figure 6 presents annual changes in net irrigation water requirements from four water supply sources from 1960–2000 and the net irrigation water requirements from five

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water supply sources for the year 2050 in China, India, Pakistan, the United States, Mexico, and Iran (the countries with the highest levels of irrigation water use worldwide). The IR for all countries increased from 1960–2000. Riv for all countries increased very little after 1985. MSR displays an increasing trend. China, India, and Mexico have the highest dependency on MSR. NNBW also displays an increasing trend, particularly after 1980 in China, 1985 in India, and 1990 in Mexico. These temporal changes in NNBW are associated with the expanded irrigation areas in these countries. Compared with other water supply sources, NNBW increased most in Pakistan, the United States, and Iran. In these countries, Riv, LR, and MSR values were generally small, and stagnated after the 1960s. Thus, the increased IR generated by the expansion of the irrigation area has been replenished by NNBW in Pakistan and the United States. The contribution from Riv_{2050} in India and Pakistan is not significantly larger than the Riv contribution in 1990. The contribution of each water resource requirement differs among the six countries considered here, because of variations in climate conditions, infrastructure construction, geological conditions, and irrigation area management.

Figure 7 shows the additional net irrigation water requirement in 2050. Many new water supply sources ($Additional_{2050}$) will likely be obtained: $Additional_{2050}$ in India and Pakistan will account for 28 % and 47 % of IR, respectively. In China and the United States, $Additional_{2050}$ will account for 8 % and 10 % of IR, respectively, because the results of simulation indicate that China can still use the enormous storage capacity of its medium-size reservoirs.

5 Discussion and concluding remarks

In this study, we determined the time-varying dependency of net irrigation water requirements from rivers, large reservoirs, medium-size reservoirs, and non-local and non-renewable blue water, taking into account variations in irrigation area for the period 1960–2000, using the H08 model. We used estimates of the blue water contribution to

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water supplied to irrigated crops from previous studies (Biemans et al., 2011; Döll et al., 2009; Hanasaki et al., 2010; Liu and Yang, 2011; Pokhrel et al., 2012b; Rost et al., 2008; Siebert and Döll, 2008; Wada et al., 2011, 2012b; Wisser et al., 2010), and then estimated the net irrigation water requirement from four water supply sources for irrigation (Riv, LR, MSR, and NNBW). We found that Riv, MSR, and NNBW increased continuously from 1960 to 1985, but LR increased only marginally. After 1985, 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 means that there is not enough river water to meet their irrigation 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.

We also conducted a simulation to investigate dependency on Riv_{2050}, LR_{2050}, MSR_{2050}, and $\mathrm{Additional}_{2050}$ in the year 2050. $\mathrm{Additional}_{2050}$ will account for one-half of the IR_{2050} in Pakistan (Fig. 7) and one-third of the IR_{2050} in India. If irrigation area continuously increases in India and Pakistan, we can confidently state that more irrigation water will be required from additional water supply sources. Additionally, if further medium-size reservoirs are not built in the future, MSR might approach the critical limit in countries such as Pakistan and the United States. Total Riv and MSR might not be able to provide sufficient irrigation water without construction of new reservoirs. As a result, the net irrigation water requirements from Additional will become greater than NNBW under the scenario in which only irrigation area expansion is considered. Increasing the net irrigation water requirement from Additional may contribute to groundwater depletion (Wada et al., 2010) and sea level rise (Pohkrel et al., 2012a; Wada et al., 2012a).

Riv, LR, MSR, and NNBW are controlled mainly by irrigation area and climatic conditions. Our results demonstrate that temporal trends in the water requirements of the six countries (China, India, Iran, Mexico, the United States, and Pakistan) are associated

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with expansion of the irrigation area. However, seasonal fluctuations in water requirements are strongly dependent on variations in climatic conditions, because the importance of each water supply source is easily altered by climate-induced surface hydrology changes (e.g., runoff and discharge).

Since 1997, NNBW has increased substantially following a decrease in precipitation in India and Pakistan. To confirm the effect of variations in climatic conditions, we performed sensitivity experiments using the H08 model to determine the contribution of the effects of changes in irrigation area and climate conditions to the increase of NNBW during the period 1997–2000. We undertook two simulations: in the first, only irrigation area was changed; in the second, only climate conditions were changed. The former used an irrigation area for 2000 and climate conditions for 1997. The latter used the irrigation area for 1997 and climate conditions for 2000. We estimated NNBW according to these experiments, as shown in Table 3. The contribution of climate was 77 $km^3 yr^{-1}$. The contribution of changes in irrigation area was 93 $km^3 yr^{-1}$ when the global irrigation area was fixed to the 1997 value. The difference between NNBW in 2000 (510 $km^3 yr^{-1}$) and NNBW in 1997 (510 $km^3 yr^{-1}$) from our simulation was 170 $km^3 yr^{-1}$. Furthermore, expansion of the global irrigation area contributed 55 % of the increased NNBW during 1997–2000. Climatic conditions contributed 45 % of increased NNBW.

In this study, the global annual average net irrigation requirement from reservoirs was estimated to be 469 $km^3 yr^{-1}$ (39 % of IR) which includes a 43 $km^3 yr^{-1}$ contribution from LR (3 % of IR) and a 426 $km^3 yr^{-1}$ contribution from MSR (36 % of IR) from 1981–2000. However, Biemans et al. (2011) estimated global annual average irrigation extraction from reservoirs (1981–2000) at 460 $km^3 yr^{-1}$ (40 % of the irrigation supply from surface water) using reservoirs with exact geographical locations determined from the GRanD database (Lehner et al., 2011). The reservoirs provided approximately 40 % of the irrigation supply from surface water. The reservoirs were treated individually and were geo-referenced to the river route. In the H08 model, large reservoirs are also treated individually and geo-referenced to the river route. Medium-size reservoirs are accumulated in each calculated grid cell for use as direct water supply sources. The

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time-varying distribution of the storage capacity of large- and medium-size reservoirs was determined from the geophysical location and date of dam construction based on data from Lehner et al. (2011) and ICOLD (2003) and the methods set out by Hanasaki et al. (2010) and Pokhrel et al. (2012b). In 2000, the total storage capacity of these reservoirs had reached 7764 km^3, consisting of 4680 km^3 in large reservoirs and 3084 km^3 in medium-size reservoirs, whereas Biemans et al. (2011) used 6300 km^3 for the total storage capacity.

The storage capacity of large- and medium-size reservoirs (4680 km^3 and 3084 km^3) corresponds to 94–111 % of the values reported by ICOLD (1998), Vörösmarty et al. (2003), and Chao et al. (2008), in which the total storage is in the range of 7000–8300 km^3. Although our original total storage capacity exceeds the value reported in ICOLD (1998), the reservoirs not included cannot be adequately represented given their limited size and catchment area, and the required information regarding their purpose and characteristics is unavailable. Thus, the results of this study should be considered alongside the influence of limited geographical information. We need further verification of the outputs and the hypothesis of the water resource model. Separate estimation of groundwater use and non-local water use is required to improve the information available for water management.

In conclusion, it is likely that increasing water stress conditions will occur in the future due to expanded irrigation area. Thus, more irrigation water will be required. However, we may not be able to obtain this water without using non-renewable groundwater (i.e., fossil groundwater) or building new reservoirs for irrigation. The increasing population and corresponding increases in food demand are likely to increase the amount of unsustainable water use and even more land area will require irrigation, particularly in emerging countries.

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Appendix A

Uncertainties in the net irrigation water requirement in these simulations

Evaluation of model performance based on sensitivity tests can be very helpful in determining the uncertainty of estimated results. The three most critical considerations with regard to model performance for estimating IR are field capacity, land surface albedo, and the option for double-cropping (Döll and Siebert, 2002).

In the model, field capacity in irrigated land strongly influences irrigation water use, because it determines the level of soil moisture for agricultural water demand. Furthermore, this differs regionally according to crop type, growing season, and soil properties. Previous model studies have used various crop-coefficient values for several crop types (e.g., Allen et al., 1998) to parameterise field capacity. With the exception of rice, all crops in the original H08 model had a 75 % field capacity during the growing season. However, in this study we used a field capacity of 60 %, because wheat (the globally dominant crop in irrigated areas) has a field capacity of 50–60 % (Allen et al., 1998).

Surface albedo is a critical parameter related to evaporation, due to alterations in surface-available energy. Previous studies using water resource models (Liu and Yang, 2010; Siebert and Döll, 2008; Wada et al., 2012b) have adopted an albedo value of 0.23 for all seasons. In this study, we followed the parameterisation scheme from the original H08 model, 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).

Agriculture is the largest water consumption sector worldwide, so the double-cropping schedule is important for water resource management. Most previous estimations have not considered the option of first and second crops (Liu and Yang, 2010; Siebert and Döll, 2008; Wada et al., 2012b). In this study, we established a double-cropping option based on crop-intensity data published by Döll and Siebert (2002).

Table A1 lists the results from our H08 model with regard to field capacity, albedo value, and double-cropping. In 2000, an increase in the field capacity from 60 % to

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75 % resulted in a 20 % increase in total global IR. When the albedo value was fixed at 0.23, the total global IR was reduced by 7 %. Furthermore, when the model considered only single-cropping, the total global IR was decreased by 21 %. Thus, changes in the three parameters can increase or decrease the total global IR by ∼ 20 %. Our findings indicate that previously recorded uncertainty values may not accurately reflect the various factors of field capacity, albedo, and double-cropping, because the models and meteorological forcing data also differed in our sensitivity test. The values given to these factors appear to be critical to accurate estimation of IR.

Appendix B

Uncertainties in the storage capacity of medium-size reservoirs

We assumed that the distribution of storage capacities of medium-size reservoirs is related to the population's geographical distribution, if the actual information provided from the GRanD database (Lehner et al., 2011) was less than the aggregated storage capacity of each country (ICOLD, 1998). Therefore, it is important to validate critical considerations with regard to model performance when estimating MSR. Table A2 lists the results of our H08 model with regard to a 90 %, 70 %, 50 %, 30 %, and 10 % storage capacity of medium-size reservoirs. When storage capacity use declined from 90 % to 10 %, MSR was reduced from −2.8 % to −50.0 %, while Riv and NNBW increased from 9.3 % and 1.8 % to 19.7 % and 39.0 %, respectively. Our findings indicate that storage capacity strongly influences the calculation of not only MSR but also Riv and NNBW. This suggests that updates to the GRanD database and improvements to this algorithm are needed.

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Table 1. Description of data.

		Data source (1960–2000)	Temporal resolution
Meteorological forcing data	Air temperature (K), Specific humidity ($kg\,kg^{-1}$) Wind speed ($m\,s^{-1}$) Surface pressure (Pa) Downward short and long Wave radiation ($W\,m^{-2}$) Precipitation ($kg\,m^{-2}\,s^{-1}$)	NCC (Ngo-Duc et al., 2005)	6 hourly
Geographical data	Irrigation areas Base map	HIM (Sect. 2.3.1)	Yearly
	Irrigation area	Siebert et al. (2005)	2000
	Crop type	Leff et al. (2004)	1990
	Crop intensity	Doll and Siebert (2002)	1990
	Large reservoirs	Pokhrel et al. (2012)	Yearly
	Medium-size reservoirs	This study (Sect. 2.3.2)	Yearly
	Industrial and domestic water	This study (Sect. 2.3.3)	Yearly

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Table 2. Contribution of global net irrigation water requirements from various water supply sources to total net irrigation water requirement ($km^3\ yr^{-1}$ and %) and irrigation area in major irrigated areas ($10^6\ km^2$) in the years 1960, 2000, and 2050.

	Irrigation area ($10^6\ km^2\ yr^{-1}$)	IR	Riv	LR	MSR	NNBW	Additional
		($km^3\ yr^{-1}$)					
1960	1.6	671 (100)	245 (37)	16 (2)	194 (29)	216 (32)	
2000	2.7	1358 (100)	345 (25)	31 (2)	472 (35)	510 (38)	
2050	3.9	2355 (100)	451 (19)	52 (2)	737 (31)	510 (22)	605 (26)

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Table 3. Sensitivity analysis for the contribution of global net irrigation water requirements from NNBW using a combination of irrigation area and climate condition simulations in the years 1997 and 2000.

NNBW (km^3)	(year)	Setting Irrigation area 1997	Setting Irrigation area 2000	Contribution of irrigation area change
Setting Climate condition	1997	340	433	93
	2000	417	510	(54.7 %)
Contribution of climate condition change		77 (45.3 %)		170 (100 %)

Table A1. Characteristics of the H08 model performance for total global net irrigation water requirements in 2000, with regard to field capacity, albedo, and double-cropping.

Variations	Conditions	IR ($km^3 yr^{-1}$)	Change rate (%)
Experimental design (this study)			
1. Field capacity (except paddy)	60 %		
2. Albedo	Seasonal change	1358	
3. Cropping option	Double		
Experimental design (sensitive test)			
1. Field capacity (except paddy)	75 %	1645	+21.1
2. Albedo	Fixed at 0.23	1263	−7.5
3. Cropping option	Single	1085	−20.1

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Table B1. Characteristics of the H08 model performance for MSR in 2000, with regard to a 90 %, 70 %, 50 %, 30 %, and 10 % storage capacity in medium-size reservoirs.

	Storage capacity of medium-size reservoirs	MSR ($km^3 yr^{-1}$)	Change rate (%)	Riv ($km^3 yr^{-1}$)	Change rate (%)	NNBW ($km^3 yr^{-1}$)	Change rate (%)
This study	100 %	472		345		510	
Sensitive test	90 %	462	−2.1	377	+9.3	519	+1.8
	70 %	434	−8.1	386	+11.9	539	+5.7
	50 %	393	−16.7	392	+13.6	574	+12.5
	30 %	334	−29.2	400	+15.9	624	+22.4
	10 %	236	−50.0	413	+19.7	709	+39.0

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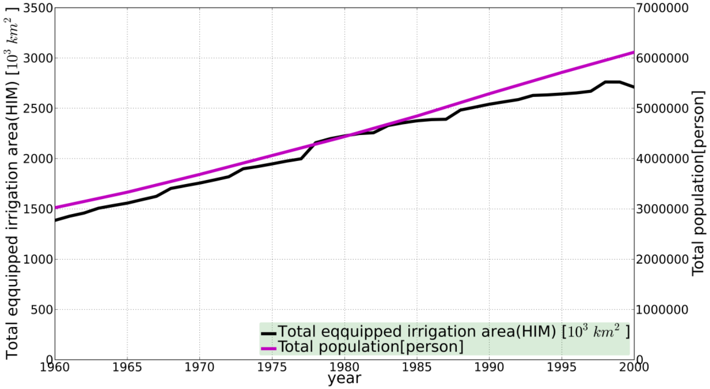
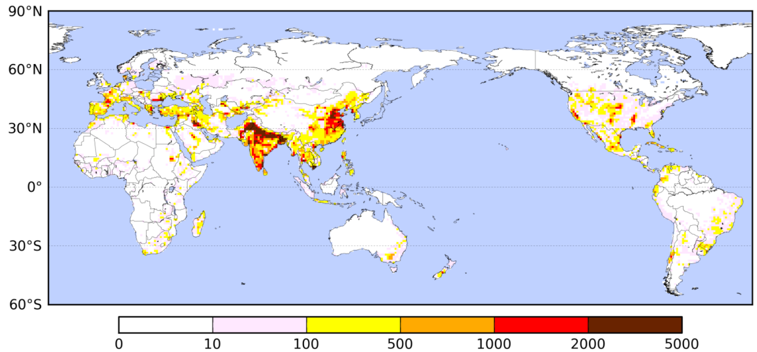


(a)



(b)

Fig. 1. Total irrigation equipped area under HIM (10^3 km^2 yr^{-2}) and total population during the period of 1960–2000 (**a**) and a distribution map showing the difference in irrigation area (km^2) between 1960 and 2000 (**b**).

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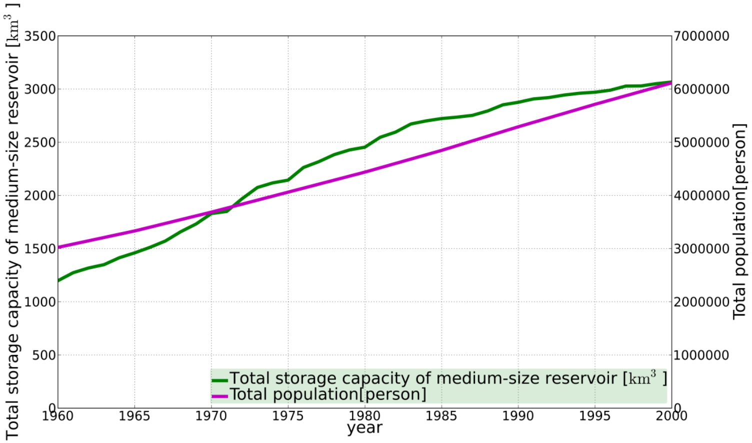
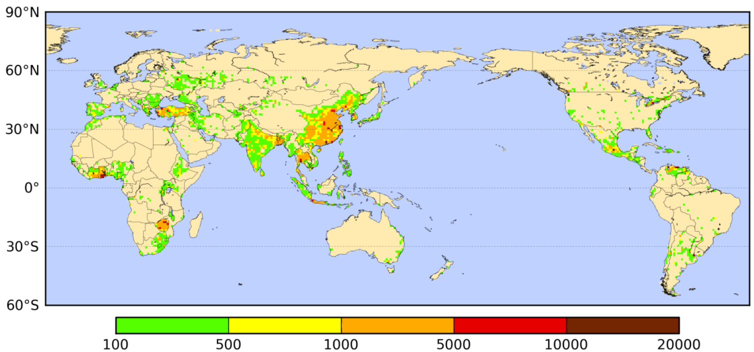


(a)



(b)

Fig. 2. Total storage capacity of medium-size reservoirs (km^3) and total population during the period of 1960–2000 (**a**) and a distribution map showing the difference in storage capacity (Mm^3) of medium-size reservoirs between 1960 and 2000 (**b**).

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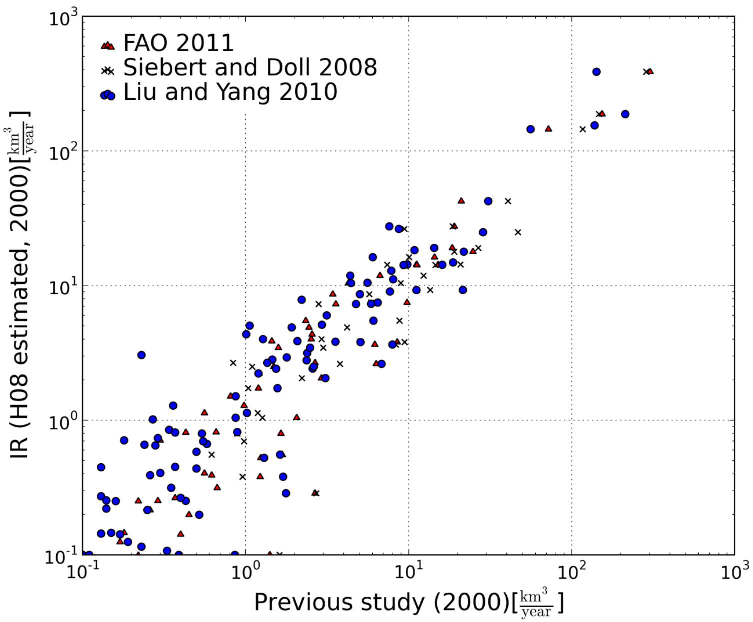

Fig. 3. Comparison between the IR ($km^3 yr^{-1}$) in previous studies (triangles: FAO, 2012; crosses: Siebert and Döll, 2008; circles: Liu and Yang, 2008) and that estimated by the H08 model in 2000.

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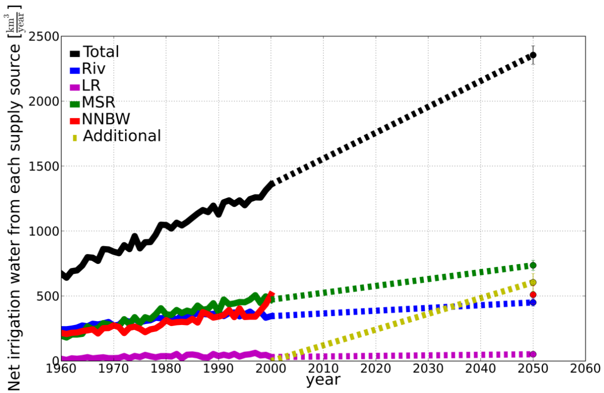
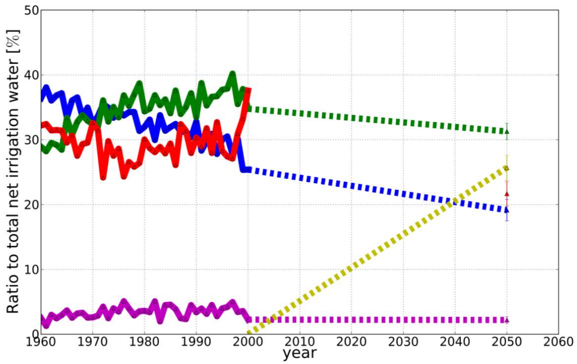


(a)



(b)

Fig. 4. Annual changes in global net irrigation water requirements ($km^3\,yr^{-1}$) from four water supply sources (Riv, LR, MSR, NNBW) during 1960–2000 and global net irrigation water requirements ($km^3\,yr^{-1}$) from five water supply sources (Riv_{2050}, LR_{2050}, MSR_{2050}, $NNBW_{2050}$, $Additional_{2050}$) in the year 2050 (**a**). The percentage contribution of the different water supply sources to the total IR (**b**).

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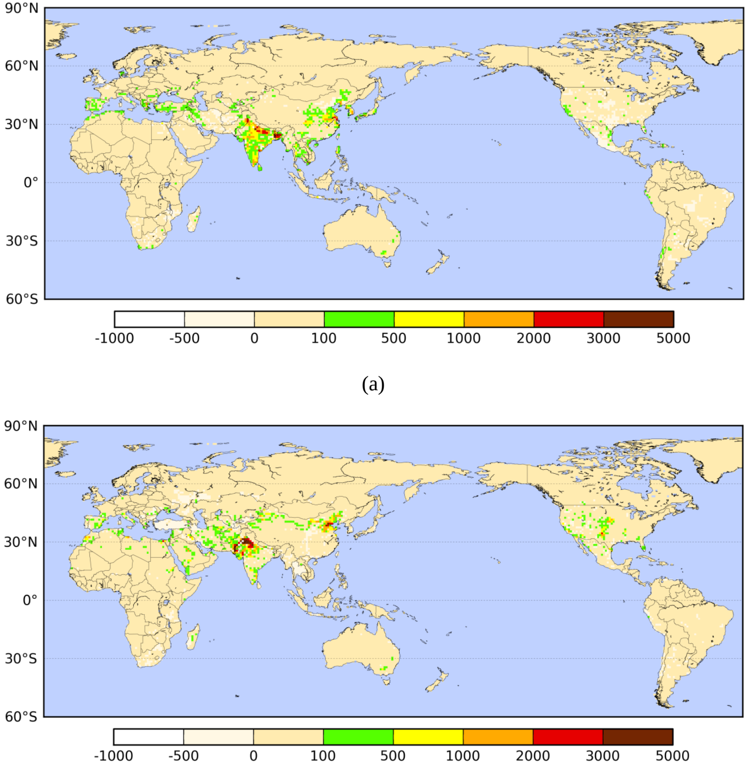

(b)

Fig. 5. Distribution of the differences in MSR (Mm^3) between 1960 and 2000 (**a**) and the differences in NNBW (Mm^3) between 1960 and 2000 (**b**).

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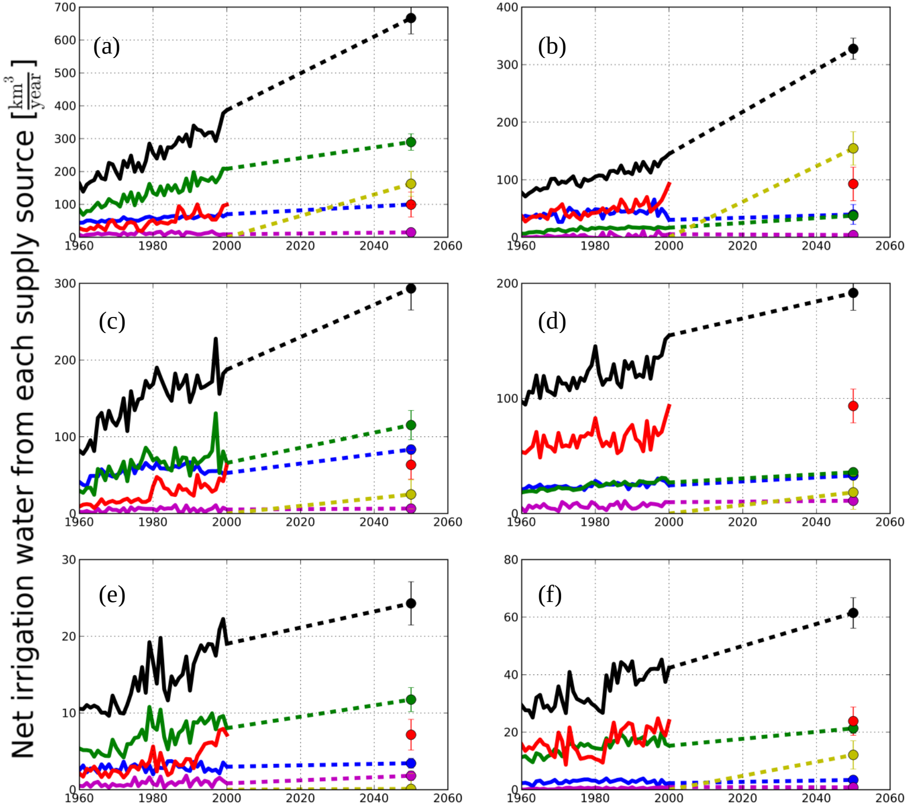

Fig. 6. Annual changes in net irrigation water requirements from four water supply sources (Riv, LR, MSR, NNBW) during 1960–2000 and global net irrigation water requirements from five water supply sources (Riv_{2050}, LR_{2050}, MSR_{2050}, NNBW_{2000}, Additional_{2050}) in the year 2050 in **(a)** India, **(b)** Pakistan, **(c)** China, **(d)** the United States, **(e)** Mexico, and **(f)** Iran.

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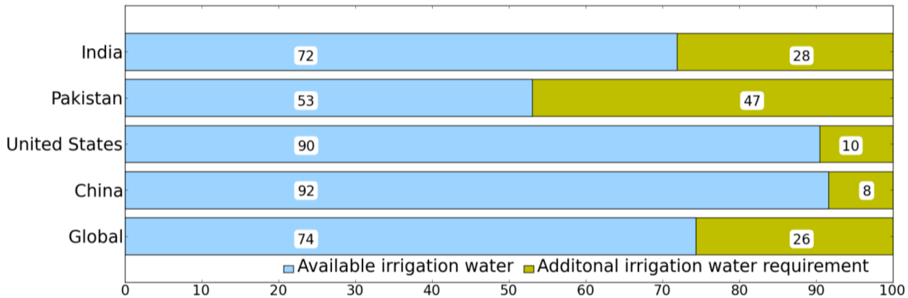

Fig. 7. Additional net irrigation water requirements beyond the total amount from Riv_{2050}, LR_{2050}, MSR_{2050}, and $NNBW_{2000}$, for the irrigation area in the year 2050, if met by horizontal expansion of irrigation area. Values given in percentage of the total IR for the four countries.

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