Hydrol. Earth Syst. Sci. Discuss., 9, 13879–13932, 2012
www.hydrol-earth-syst-sci-discuss.net/9/13879/2012/
doi:10.5194/hessd-9-13879-2012

Hydrology and Earth System Sciences Discussions

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

A global water scarcity assessment under shared socio-economic pathways – Part 1: Water use

N. Hanasaki[1], S. Fujimori[1], T. Yamamoto[2], S. Yoshikawa[3], Y. Masaki[1], Y. Hijioka[1], M. Kainuma[1], Y. Kanamori[1], T. Masui[1], K. Takahashi[1], and S. Kanae[3]

[1]National Institute for Environmental Studies, Tsukuba, Japan
[2]Nagaoka National College of Technology, Nagaoka, Japan
[3]Tokyo Institute of Technology, Tokyo, Japan

Received: 28 November 2012 – Accepted: 7 December 2012 – Published: 18 December 2012

Correspondence to: N. Hanasaki (hanasaki@nies.go.jp)

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

Abstract

A novel global water scarcity assessment for the 21st century is presented in a two-part paper. In this first paper, water use scenarios are presented for the latest global hydrological models. The scenarios are compatible with the socio-economic scenarios of the Shared Socio-economic Pathways (SSPs), which are a part of the latest set of scenarios on global change developed by the integrated assessment, IAV (climate change impact, adaptation, and vulnerability assessment), and climate modeling community. The SSPs depict five global situations based on substantially different socio-economic conditions during the 21st century. Water use scenarios were developed to reflect the key concepts underpinning each situation. Each scenario consists of five factors: irrigation area, crop intensity, irrigation efficiency, industrial water withdrawal, and municipal water withdrawal. The first three factors are used to estimate agricultural water withdrawal. All factors were developed using simple models based on a literature review and analysis of historical records. The factors are grid-based at a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$ and cover the whole 21st century at 5-yr intervals. Each factor displays a wide variation among the different global situations depicted: the irrigation area in 2085 varies between 270 and 450 km^2, industrial water between 246 and 1714 $km^3\,yr^{-1}$, and domestic water withdrawal between 573 and 1280 $km^3\,yr^{-1}$. The water use scenarios can be used for global water scarcity assessments by identifying the regions vulnerable to water scarcity and analyzing the timing and magnitude of scarcity conditions.

1 Introduction

All societal and economic activities depend on water. The rapid and continuous growth of population and economic activity, mainly in developing countries, is increasing water use globally. Water availability is also changing because of human-induced climate change (Vörösmarty et al., 2000; Oki and Kanae, 2006; Kundzewicz et al., 2007). A number of studies have assessed the impact of global changes (i.e. socio-economic and climatic change) on water use and availability (Vörösmarty et al., 2000; Alcamo et al., 2003a, b, 2007; Arnell, 2004; Oki and Kanae, 2006). These studies have identified water-scarce regions in baseline periods by compiling statistical data for water use and availability and have projected future scarcity using numerical models. Hereafter we refer to such reports as global water scarcity assessments.

Although very successful, the earlier water scarcity assessments need to be updated and refined for three reasons. First, most were based on a conventional set of global change scenarios for the 21st century presented in the socio-economic scenarios of the Special Report on Emission Scenarios (SRES; Nakicenovic and Swart, 2000) and the climate scenarios of the Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007). A new set of global change scenarios is being released (Moss et al., 2010), consisting of the radiative forcing-based (i.e. greenhouse gas (GHG) emission) Representative Concentration Pathways (RCPs; van Vuuren et al., 2011), the climate scenarios of the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), and the socio-economic scenarios of the Shared Socio-economic Pathways (SSPs; Kriegler et al., 2012; O'Neill et al., 2012). To make use of the latest achievements of the integrated assessment, IAV (climate change impact, adaptation, and vulnerability assessment), and climate modeling community, global water scarcity assessments should utilize the new set of scenarios. Second, in most of the earlier water scarcity assessments, water use scenarios were weakly associated with socio-economic scenarios. The SSPs depict five substantially different future world situations (see Sect. 2 for detail), and water use scenarios are therefore required to reflect the key concepts underpinning each SSP. Third, most of the earlier studies assessed water availability and use over an annual time resolution. This resolution may overlook seasonal and inter-annual water scarcities caused by variations in water availability and use (Hanasaki et al., 2008b). This is particularly important in climate change impact assessment when analyzing whether increases in precipitation and runoff will alleviate local water scarcity.

HESSD
9, 13879–13932, 2012

Here we present a novel global water scarcity assessment using a global hydrological model called H08 (Hanasaki et al., 2008a, b). H08 simulates the natural water cycle (related to water availability) and major human activities (related to water use), such as water withdrawals and reservoir operation. It estimates water availability and use at daily time intervals, which enables the assessment of water scarcity at sub-annual time intervals. We ran H08 using the new set of scenarios (i.e. RCPs, CMIP5, and SSPs).

We faced two key challenges. First, because the SSPs include neither quantitative nor qualitative scenarios for water use, we had to develop them from scratch. Second, because there are neither clear guidelines nor relevant earlier studies, we had to establish an effective way to use the new set of scenarios.

The study is presented in two reports. This first report describes water use scenarios that are compatible with the SSPs. The second report (Hanasaki et al., 2012) describes the setup and results of water scarcity assessments taking into account sub-annual water scarcity. The structure of the first report is as follows. In Sect. 2, the latest socio-economic scenarios (SSPs) are introduced. In Sect. 3, water use scenarios in earlier reports are extensively reviewed. In Sect. 4, based on an understanding of SSPs and a literature review, new models for agricultural, industrial, and municipal water use are developed. An intermediate water use scenario is then developed, which is independent of the SSPs. Section 5 reports how water use scenarios compatible with the SSPs were developed by linking the intermediate water use scenario and the SSPs. In Sect. 6, the water use scenarios are discussed and compared with earlier studies. A water scarcity assessment using the water use scenarios is reported in the accompanying paper (Hanasaki et al., 2012).

We define the technical terms used to discuss water availability and use as follows. Water availability can be considered to refer to available water resources, constrained by the physical hydrological cycle and human activities (e.g. withdrawal and water regulation) in river basins. Water use is a general term for the utilization of water. Water consumption is water evaporated during use. Water withdrawal indicates the removal of water from a source, including water consumption, return flows, and evaporation

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

HESSD

9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

loss during delivery. Potential water demand is the estimated water use accompanying human activities regardless of water availability in terms of water withdrawal.

2 Shared Socioeconomic Pathways

The SSPs are new socio-economic scenarios for use in global climate change studies (Kriegler et al., 2012; O'Neill et al., 2012). The SSPs depict five different global situations (SSP1–5) with substantially different socio-economic situations. Each SSP contains a quantitative scenario and a narrative (qualitative) scenario. The narrative scenarios have been well documented by O'Neill et al. (2012), and thus only a brief summary is presented here. The five SSPs can be placed in a conceptual space of two dimensions (see Fig. 1a) where the horizontal axis represents socio-economic challenges for adaptation. Higher values indicate socio-economic factors that would make it more difficult to reduce emissions. The vertical axis represents socio-economic challenges for mitigation. Higher values indicate socio-economic factors that would make adaptation more difficult. SSP1 (Sustainability) represents a sustainable world where it is easy to mitigate and adapt to climate change because of the rapid development of low-income countries, reduced inequality, rapid technology development, and a high level of awareness regarding environmental degradation. Good yield-enhancing technologies for agricultural land are also incorporated. SSP2 (Middle of the Road) represents conditions where the socio-economic trends of recent decades continue. Reductions in resource use and energy intensity are achieved at historic rates, and there is intermediate success in addressing environmental problems such as air pollution. SSP3 (Fragmentation) represents conditions where it is difficult to mitigate and adapt to climate change because of extreme poverty and a rapidly growing population. There is serious degradation of the environment, and technological change in the energy sector is slow. Because of the limited coordination between regions, use of local energy resources is enhanced. SSP4 (Inequality) represents a highly unequal world both within and across countries. Mitigation can be achieved by a small rich global elite that

HESSD
9, 13879–13932, 2012

is responsible for much of the emissions, but it is difficult to adapt to climate change because of the large poor population that remains vulnerable. Crop yields would be high in industrial farming, but low for small-scale farming. SSP5 (Conventional Development) represents a situation where it is easy to adapt owing to robust economic growth, but difficult to mitigate the effects of climate change because the energy system is dominated by fossil fuels. Agro-ecosystems are highly managed, building on strong technological progress in the agricultural sector. Land use management is generally very resource intensive including the management of water systems. Table 1 summarizes the key details of each SSP as they relate to water use.

The quantitative scenarios of the SSPs cover the whole 21st century, including population, gross domestic product (GDP), and other relevant factors; however, the final products are currently (as of October 2012) under review. In this study, provisional quantitative SSPs developed by the Asia-Pacific Integrated Model (AIM; Kainuma et al., 2002) of the National Institute for Environmental Studies, Japan, were used (hereafter AIM-SSPs). The quantitative scenarios of the AIM-SSPs may vary from those that are finally settled, but it is unlikely that they will be totally different. The AIM-SSPs include eight socio-economic variables: GDP, population, primary energy, GHG emissions, electric production, and the value added for primary, secondary, and tertiary industries. The world is subdivided into 12 regions (Oceania, Japan, China, India, Rest of Asia, North America, Latin America, EU, Rest of Europe including Baltic countries, Former Soviet Union excluding Baltic countries, Middle East, and Africa). It covers the period from 2005 to 2100 at 5-yr intervals. Figure 2 shows population, GDP, and electricity production for each SSP.

The SSPs do not include any climate policy and all adopt the business as usual (BAU) scenario in terms of GHG emission (Kriegler et al., 2012). The emission paths used in SSP1–5 roughly correspond to RCP6.0, RCP8.5 (strictly speaking, in between RCP6.0 and RCP8.5), RCP8.5, RCP6.0, and RCP8.5, respectively. Scenarios relating to climate policy for the SSPs, called the Shared Climate Policy Assumptions (SPA; Kriegler et al., 2012), have been proposed but remain under discussion. In this study,

HESSD
9, 13879–13932, 2012

we assumed SSP1–5 would correspond to RCP2.6, RCP4.5, RCP6.0, RCP2.6, and RCP6.0, respectively, when climate policy was included. This is a tentative assumption and may need to be revised once the theoretical background underpinning the SPA has been fully reviewed. The scenario matrix for the SSPs and RCPs is shown in Fig. 3.

As mentioned above, the SSPs do not include a water use scenario, but because each SSP depicts substantially different global situations, we can infer that agricultural, industrial, and municipal water use must vary among the scenarios. Although far from sufficient, the different narrative scenarios provide clues allowing for speculation regarding water use. On the basis of these clues, we developed the water use scenarios presented in this study.

3 Literature review and modeling strategy

The development of a global water use scenario (i.e. projection of future water demand) has been attempted for decades (e.g. earlier efforts published from 1967 to 1997 are summarized in Fig. 11.1 of Shiklomanov and Rodda, 2003). Here we review the existing literature regarding water use scenarios, which have been developed mainly for global hydrological models.

3.1 Agricultural water withdrawal

Agricultural water withdrawal accounts for 70 % of total global water withdrawal (FAO, 2011). Because irrigation accounts for most agricultural water withdrawal (Shiklomanov, 2000), we omitted other uses such as livestock drinking water.

In earlier reports, future agricultural potential water demand scenarios were developed using statistical models at a national or regional scale (e.g. Seckler et al., 1998; Shiklomanov, 2000; Oki et al., 2003). These models were simple regression models, with historical trends of national or regional agricultural water withdrawal being explained by basic socio-economic variables such as population and GDP.

HESSD
9, 13879–13932, 2012

Recently, global hydrological models (e.g. Alcamo et al., 2003a; Hanasaki et al., 2008a; Rost et al., 2008; Wisser et al., 2010; Wada et al., 2011) and macro-scale crop growth models (Liu et al., 2009; Liu and Yang, 2010) have been used to develop potential agricultural water demand scenarios. These models estimate potential irrigation water demand biophysically and have been heavily influenced by the work of Döll and Siebert (2002). Here we review their methodology in detail because it also plays a key role in this study. They first developed a digital map of the global area equipped for irrigation (A_{irg}) at a spatial resolution of 0.5° × 0.5° longitude and latitude (Döll and Siebert, 2000), and this map has been continuously updated (Siebert et al., 2005). They then established a methodology to estimate global crop water requirements by applying the concept of CROPWAT (Smith, 1992). CROPWAT is a numerical model that calculates irrigation water requirements from the following procedures. (1) An estimation of the crop-specific potential evapotranspiration (E_{pot}) during the cropping period. (2) An estimation of the effective precipitation (P_{eff}) taking into account meteorological conditions. (3) An estimation of the crop water requirements by calculating the difference between crop-specific potential evapotranspiration and effective precipitation. (4) An estimation of the net irrigation water (i.e. water evaporated from cropland) by multiplying by the irrigated harvested area (A_{hvs}). (5) An estimation of the gross irrigation water (i.e. water withdrawn from the water source for irrigation purposes, taking into account return flow and evaporation loss during delivery) by dividing by a factor called irrigation efficiency (e_{irg}). The planting of multiple crops is also taken into account. In this case, the total harvested irrigated area may exceed A_{irg}. The ratio of A_{hvs} to A_{irg} is called the irrigation intensity (i_{irg}).

The above review indicates that five factors are required to estimate irrigation water withdrawal: E_{pot}, P_{eff}, A_{irg}, i_{irg}, and e_{irg}. Döll (2002) projected global irrigation water withdrawal for the 2020s and 2070s under different climate scenarios using two global climate models and one GHG emission scenario in order to account for changes in E_{pot} and P_{eff}. However, A_{irg}, i_{irg}, and e_{irg} were fixed in that study. Alcamo et al. (2007) estimated water resource scarcity using the WaterGAP 2 model under multiple scenarios.

HESSD
9, 13879–13932, 2012

They set a single scenario of e_{irg} for both the SRES A2 and B2 scenarios, but A_{irg} and i_{irg} were fixed because the SRES did not include these parameters and there were diverse views regarding future trends. Because A_{irg}, i_{irg}, and e_{irg} directly influence irrigation water withdrawal, it is a challenge to establish scenarios based on these three terms.

We identified five comprehensive reports regarding agriculture and food, which included a quantitative projection of irrigation: Rosegrant et al. (2002, 2009), Bruinsma (2003), Alcamo et al. (2005), and de Fraiture et al. (2007). Details regarding the socio-economic scenarios used in these studies are highly variable, but all of them used the population scenario of the UN medium variant projection. Note that Alcamo et al. (2005) and de Fraiture et al. (2007) used the population scenario of the Techno Garden scenario of the Millennium Ecosystem Assessment (Alcamo et al., 2005), which is similar to the UN medium variant projection. In addition, Alcamo et al. (2005) proposed four irrigation scenarios in their study (Global Orchestration, Order from Strength, Adapting Mosaic, and Techno Garden), but we only referred to the Techno Garden irrigation scenario because its population scenario is similar to those of the other four reports.

Table 2 presents a summary of these five studies. Although the population scenarios are not very different, the projections of the global irrigated area vary widely. Among the five studies, the population growth rate used by Alcamo et al. (2005) was the smallest, and that of Bruinsma (2003) was the largest. All of the studies predicted the states of the food supply and agriculture for specific years (2025, 2030, and 2050); transient states were not described. Although climate change scenarios cover the whole 21st century, none of the studies described the world beyond 2050. Furthermore, except for Bruinsma (2003) and Rosegrant et al. (2007), the studies did not separate the growth of the irrigated area and crop intensity.

It was initially confusing why these studies have such a wide range of irrigation projections. All the studies present scenarios for the growth of crop yield and cropland to meet food demand. However, there is a limited explanation of how the growth in crop yields would be achieved and how much crop production would result from irrigated

HESSD
9, 13879–13932, 2012

agriculture. To answer these questions, region-specific information is required regarding the future trends of irrigation, fertilizer and pesticide applications, improvements in agricultural technology, and other related factors but these details are not specified and may be impossible to acquire. The results of our literature review imply that clear mechanisms linking the growth of irrigation and socio-economic factors are not yet fully developed. Thus, arbitrariness cannot be completely excluded when developing an irrigation scenario.

3.2 Industrial and municipal water withdrawal

Industrial and municipal water withdrawals account for 18 % and 12 % of the total global water withdrawal, respectively (FAO, 2011). Nevertheless their importance in the available global scenarios is limited.

Alcamo et al. (2003) developed a regression model for industrial water withdrawal. Their model is expressed as a multiple regression model using explanatory variables of electricity production and per capita GDP. Shen et al. (2008) developed a similar model but their model has no need for model parameters because of some strong assumptions. Their model explained industrial water withdrawal by electricity production, total primary energy, and GDP. Some recent studies have subdivided industrial water into manufacturing water and electricity production water. Vassolo and Döll (2005) developed separate global maps of thermoelectric power cooling water and manufacturing water use for the period around 1995. Voß et al. (2010) proposed a modeling framework to estimate the use of both nationwide manufacturing water and thermal cooling water, and Flörke and Eisner (2011) calculated this forward to 2050 under the SRES A2 and B1 scenarios. Hayashi et al. (2012) proposed a new type of model that accumulated sector-wise potential water demand. All of these earlier studies estimated model parameters from the historical record. The study of Flörke and Eisner (2011) was an exception in that two different parameters were used to contrast the concepts underpinning two scenarios. Table 3 summarizes earlier modeling studies of industrial water withdrawal.

HESSD
9, 13879–13932, 2012

In many cases, a municipal water withdrawal scenario has been developed together with an industrial scenario. Alcamo et al. (2003) developed a multiple regression model using explanatory variables of population and GDP. Shen et al. (2008), Voß et al. (2009), and Flörke and Eisner (2011) developed municipal water scenarios similar to the scenarios used in their industrial water model. Earlier attempts to model municipal water withdrawal are summarized in Table 4.

Alcamo et al. (2003) demonstrated that their models successfully reproduced historical time series of industrial and municipal water withdrawal. However such regression modeling has typically encountered two key problems. First, sufficient amounts of reliable data are essential for the estimation of model parameters, although published historical time series of water withdrawals are limited for many countries. Because the relevant parameters are highly variable among countries, transferring data from one country to another is not practical. Second, estimated model parameters represent historical relationships between industrial and municipal water withdrawals and socio-economic factors. It is not clear whether these parameters are valid under both the scenarios of the SRES and SSPs because they depict substantially different conditions. For example, two socio-economic scenarios are available for countries with a similar population and GDP, but with different underpinning concepts: one depicts a less resource-intensive future and the other depicts the opposite. If a common regression model is used for these scenarios, the resulting water use scenarios are similar. However, this seems incompatible with the different underpinning concepts of each scenario. Therefore, new types of models are required that better represent the different underpinning concepts of each scenario.

HESSD
9, 13879–13932, 2012

4 Model development

4.1 Agricultural water

4.1.1 Available information

In the previous section, we reviewed recent global hydrological models (including H08) and determined that five variables are required to estimate potential agricultural water demand: reference evaporation (E_{pot}), effective precipitation (P_{eff}), area equipped for irrigation (A_{irg}), crop intensity (i_{irg}), and irrigation efficiency (e_{irg}). Among these variables, E_{pot} and P_{eff} are calculated by the hydrological models using climate scenarios. The remaining three factors are basic boundary conditions of models and must be prepared. It is beyond the scope of this paper to develop a process-based model for A_{irg}, i_{irg}, and e_{irg} because it is difficult to even specify the key factors controlling the mechanisms of irrigation expansion. Therefore, we used the scenarios adopted in the five previous studies discussed in the previous section (Rosegrant et al., 2002, 2009; Bruinsma, 2003; Alcamo et al., 2005; de Fraiture et al., 2007).

4.1.2 Model

Here we take simplistic assumptions for developing scenarios for A_{irg}, i_{irg}, and e_{irg}. We assumed A_{irg}, i_{irg}, and e_{irg} are expressed as a power of time:

$$A_{irg,t} = (1 + r_{area})^{t-t_0} A_{irg,t_0} \quad (1)$$

$$i_{irg,t} = (1 + r_{int})^{t-t_0} i_{irg,t_0} \quad (2)$$

$$e_{irg,t} = (1 + r_{eff})^{t-t_0} e_{irg,t_0} \quad (3)$$

where r_{area}, r_{int}, and r_{eff} are the annual growth ratios of the irrigated area, crop intensity, and irrigation efficiency. The subscript t denotes time (year), and t_0 indicates the base year (2000).

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

4.1.3 Intermediate water use scenario

Here we propose an intermediate scenario of agricultural water use, which is independent of the SSPs. On the basis of Table 2, we set three options for r_{area} and r_{int}, (Table 5) and r_{eff} (Table 6). Two were taken from the highest and lowest values among the five reports we reviewed, and the remaining was an intermediate value. We used a global map of A_{irg} at the base year (2000) provided by Siebert et al. (2005) and i_{irg} and e_{irg} values were taken from Döll and Siebert (2002). All data were converted into a 0.5° × 0.5° grid, the standard spatial resolution of H08. Equations (1)–(3) were applied uniformly on a global basis for all three options of r_{area}, r_{int}, and r_{eff}, respectively. Note that some of the five reports expressed regional differences in r_{area}, but for consistency among scenarios, we assumed that the ratio is constant all over the world except for one special case that is described later. We also assumed that the ratio is constant throughout the century because neither transient projections nor projections beyond 2050 were available in the five reports.

4.2 Industrial water

4.2.1 Available data and historical trends

For modeling industrial water withdrawal, we revisited the historical records of AQUASTAT (FAO, 2011). AQUASTAT details the total industrial water withdrawals for 200 countries during the period of 1960–2010. Although data for the period around 2000 were available for most countries, other periods were often missing. We selected 16 nations for which a record for longer than 20 yr was available. We then collected electricity production data (World Bank, 2009) for these countries.

Figure 4 shows the relationship between time (year) and industrial water intensity ($m^3 yr^{-1} MWh^{-1}$) which is defined as industrial water withdrawal per unit of electric production. The nations were categorized into three categories: (A) intensity greater than $50 m^3 yr^{-1} MWh^{-1}$, namely, Belgium, Chile, China, India, Italy, Pakistan, Romania, and

HESSD
9, 13879–13932, 2012

Thailand; (B) intensity not greater than 50 but greater than 10 $m^3 yr^{-1} MWh^{-1}$, namely, Algeria, Japan, Jordan, Lebanon, Singapore, UAE, and Venezuela; and (C) intensity not greater than 10 ($m^3 yr^{-1} MWh^{-1}$), Israel only. Two characteristics are apparent from Fig. 4. First, there is a linear decreasing trend in industrial water intensity in all nations. Second, the range of slopes within each category is relatively small: from −5.8 to −0.7 for Category A countries, from −1.6 to +0.7 for Category B, and −0.2 for Category C ($m^3 yr^{-2} MWh^{-1}$). In contrast, there were substantial differences in industrial water intensity (see the vertical axes of Fig. 4).

4.2.2 Model

Because Fig. 4 clearly shows a linear decreasing trend in industrial water intensity, we assumed that industrial water withdrawal (I) ($m^3 yr^{-1}$) can be expressed as

$$I = \mathrm{ELC} \times \left(i_{\mathrm{ind,t0}} + s_{\mathrm{ind,cat}} \times (t - t_0)\right) \tag{4}$$

where ELC is electricity production (MWh), t_0 is the base year (2005), $i_{\mathrm{ind,t0}}$ is the industrial water intensity ($m^3 yr^{-1} MWh^{-1}$) at t_0, and $s_{\mathrm{ind,cat}}$ is the slope. The subscript cat indicates the three categories shown above.

To confirm the validity of Eq. (4), $i_{\mathrm{ind,t0}}$ and $s_{\mathrm{ind,cat}}$ were estimated for all 16 countries. $i_{\mathrm{ind,t0}}$ was estimated using the ELC and I for the base year. $s_{\mathrm{ind,cat}}$ was estimated using the least-square method because of the clear linear relationship as shown in Fig. 4. Figure 5 presents a historical projection of industrial water withdrawal. Even for a very simple model, historical trends are well captured.

4.2.3 Intermediate water use scenario

The model expressed in Eq. (4) needs one coefficient, $s_{\mathrm{ind,cat}}$. This could be calibrated for each nation if a historical time-series was available, and the model could be used for a future scenario analysis if we assume that the coefficient does not vary with time. However, for many countries of the world, suitable time-series records are lacking and

HESSD
9, 13879–13932, 2012

calibration is difficult; this causes problems when we apply Eq. (4) on a global basis. Moreover, as discussed in the previous section, each SSP represents very different conditions, which strongly implies that $s_{ind,cat}$ would also vary.

Here we propose an intermediate scenario of industrial water use. A schematic diagram is shown in Fig. 6a. We considered three sets of $s_{ind,cat}$ as shown in Table 7. The High Efficiency scenario (HE) assumes that all countries in the world can be represented by the median $s_{ind,cat}$ of the countries in each category. For example, the median $s_{ind,cat}$ for category A is close to the historical path of Thailand and China, the median $s_{ind,cat}$ for category B is close to Japan, and the median $s_{ind,cat}$ for category C is identical to Israel. We set the minimum i_{ind} at $2\,m^3\,yr^{-1}\,MWh^{-1}$. Our analyses indicated that there are nations displaying more rapid changes in $s_{ind,cat}$ but when this was applied globally including the major industrial countries, the results were unrealistic. We judged that the median of each category could be used in the HE because Thailand, China, Japan, and Israel can be considered to be representative of major industrial countries. In the Medium Efficiency scenario (ME), $s_{ind,cat}$ is half of that in the HE. In the ME scenario, we set the minimum i_{ind} at $10\,m^3\,yr^{-1}\,MWh^{-1}$. In the Low Efficiency scenario (LE), $s_{ind,cat}$ is a quarter of that in the HE. The minimum i_{ind} was set at $50\,m^3\,yr^{-1}\,MWh^{-1}$. If $i_{ind,t0}$ was already below the minimum i_{ind}, we assumed that the i_{ind} of the country in question would be unchanged throughout the century.

This model could be applied globally because $i_{ind,t0}$ and the category of the base year could be calculated from the national industrial water withdrawal data from AQUASTAT and the electricity production data of the World Bank (2009). Note that, as mentioned above, AQUASTAT does not include withdrawal data for the exact year of 2005. Data for the nearest year were used. Electricity production in the future was provided by the AIM-SSP for 12 regions. Because no further information was available, the rate of change was assumed to be uniform across the countries in a region. Equation (4) was applied for each nation. To make the results grid-based, we assumed that industrial water withdrawal is geographically distributed proportionally to the population. We used global population distribution data from the Center for International Earth Science

HESSD
9, 13879–13932, 2012

Information Network (CIESIN) and the Centro Internacional de Agricultura Tropical (CIAT) (2005).

4.3 Municipal water model

4.3.1 Available data and historical trends

Earlier studies have developed municipal water scenarios in a manner similar to that used here to develop industrial water scenarios and thus have faced similar problems to those discussed above. We also revisited the historical trends of municipal water withdrawal from AQUASTAT (FAO, 2011). Figure 7 shows the historical trend of municipal water withdrawal per person for 21 countries where a time series of longer than 20 yr was available. We then obtained population data (United Nations, 2011) and the GDP in 2000 USD (World Bank, 2009) for these countries. The countries were sorted into three categories, high-income nations (10 000 USD < per capita GDP, denoted H), medium-income nations (2000 USD < per capita GDP ≤ 10 000 USD, M), and low-income nations (per capita GDP ≤ 2000 USD, L).

We analyzed the trend of per capita water withdrawal for each nation. We found that per capita water withdrawal varied significantly, for example from 33.7 to 688.2 L day^{-1} person^{-1} in 2000. The range of values was slightly reduced to between 33.7 and 518.4 L day^{-1} person^{-1} when we excluded countries with a population of less than 10 million. This suggests that it is difficult to obtain general rules that are applicable to all countries in the world. In contrast, the range of slopes was much closer among nations being between −3.6 and 19.5 L day^{-1} person^{-1} yr^{-1} (Fig. 7). If nations with a population less than 10 million were excluded, the range of the slope was between −3.6 and 3.3 L day^{-1} person^{-1} yr^{-1}. Figure 7 reveals the central problem in municipal water modeling: there is no clear relationship between the volume of water withdrawal and per capita GDP, and its increasing or decreasing trend. For example, with the medium-income nations, an increasing trend can be observed for some countries (Mauritius and Venezuela), whereas for others stabilization and a decreasing trend are apparent

HESSD
9, 13879–13932, 2012

(Chile and Jordan). There are also nations using more than 400 L day^{-1} capita^{-1} (Mauritius and Venezuela) and less than 200 L day^{-1} capita^{-1} (Algeria, Thailand). Here we found two common characteristics among the 21 countries. First, in the nations with less than 2000 USD per capita GDP, municipal water withdrawal seems to be increasing (Mauritania and Vietnam are exceptions). Second, water withdrawal did not stabilize much below 200 L day^{-1} capita^{-1} in any nation.

4.3.2 Model

As with industrial water withdrawal, we modeled municipal water withdrawal (M; m^3 yr^{-1}) as

$$M = \mathrm{POP} \times \left(i_{\mathrm{mun,t0}} + s_{\mathrm{mun,cat}} \times (t - t_0)\right) \times 0.365 \quad (5)$$

where POP is the population (no of individuals), $i_{\mathrm{mun,t0}}$ is the municipal water intensity for the base year (L day^{-1} person^{-1}), $s_{\mathrm{mun,cat}}$ is slope, and the multiplier 0.365 is applied for unit conversion.

Historical trends of municipal water withdrawal were estimated using Eq. (5) and are shown in Fig. 8. This indicates that Eq. (5) reproduces the historical variation of municipal water well if the slope ($s_{\mathrm{mun,cat}}$) and interval ($i_{\mathrm{mun,t0}}$) are statistically estimated for each nation.

4.3.3 Intermediate water use scenario

Like for industrial water withdrawal, we developed an intermediate municipal water use scenario. Schematic diagrams are shown in Fig. 6b–c. We set three municipal water scenarios as shown in Table 8. In the HE scenario municipal water withdrawal decreases toward per capita municipal water use of 200 L day^{-1} globally. In the LE scenario municipal water withdrawal increases, and in the ME scenario it remains constant at the current level. Because we found the magnitude of slope to be between −3.6 and 3.3 L person^{-1} yr^{-1} for nations with a population of more than 10 million, we set $s_{\mathrm{dom,cat}}$

HESSD
9, 13879–13932, 2012

for HE and LE at −2 and 2 L person^{-1} day^{-1} yr^{-1}, respectively. For countries with a per capita GDP below 2000 USD, $s_{\text{dom,cat}}$ grows at the rate of 2 L person^{-1} day^{-1} yr^{-1} in all scenarios because we found that no country stabilized below this level. The increase in per capita water use continues until it reaches 200, 300, and 400 L person^{-1} day^{-1} for HE, ME, and LE, respectively. Note that 200 L person^{-1} day^{-1} is the same level as is currently withdrawn in nations such as Belgium and Chile and reducing this would be a challenging but realistic target. For example, Singapore is targeting domestic water use at 140 L person^{-1} day^{-1} (PUB Singapore's National Water Agency, 2012).

This model can be applied globally because $i_{\text{mun},t0}$ and the category of the base year can be calculated for all countries from the national municipal water withdrawal data of AQUASTAT, UN population data (2011), and GDP data from the World Bank (2009). As with industrial water, municipal water was geographically distributed at a 0.5° × 0.5° spatial resolution.

5 Linking water use scenarios and SSPs

We have developed models for agricultural, industrial, and municipal water withdrawal. Each model has one parameter. By setting three options for each parameter (Tables 5–8), we have developed three intermediate water use scenarios. In the next stage, we ensured their compatibility with the SSPs. We focused on the narrative scenarios of the SSPs (O'Neill et al., 2012), which are summarized in Table 1. The key items we focused on are technology change and environmental consciousness.

5.1 Interpretation of SSPs for irrigated areas and crop intensity

As mentioned earlier, the general relationships between the growth of irrigated areas and socio-economic factors have not been clearly established yet. It is known that undeveloped areas that are suitable for new irrigation projects are limited (Bruinsma, 2003). This implies that the rapid expansion of irrigated areas may be accompanied by

HESSD
9, 13879–13932, 2012

environmental degradation. An increase in the use of irrigation water imposes further alterations of river and groundwater systems, which are likely to impact ecosystems. Therefore, the general environmental consciousness of society is reflected in the possible future expansion of irrigation, with a possible restriction in expansion when environmental consciousness is high. Table 1 indicates that environmental consciousness is considered to be high for SSP1, medium for SSP2, and low for SSP3 and SSP5. The environmental consciousness for SSP4 is not clearly identified in its narrative scenario, but the pathway mentions low crop yields in small-scale farming, which implies less pressure toward irrigation for the majority of cropland. Therefore, SSP3 and SSP5 would be more likely to result in an expansion of the irrigated area, whereas SSP1 and SSP4 would be less likely. The situation for SSP2 would be intermediate between the two groups. Therefore, we assigned High Growth in Table 5 to SSP3 and SSP5, Medium Growth to SSP2, and Low Growth to SSP1 and SSP4. The combination is summarized in Table 9 and illustrated in Fig. 1b.

5.2 Interpretation of irrigation efficiency and changes in industrial and municipal water intensities

Irrigation efficiency and changes in industrial and municipal water intensities are considered to be dependent on the technology scenario of the SSPs in this study. Table 1 indicates that technology is high for SSP1 and SSP5, medium for SSP2, and low for SSP3. The narrative and quantitative scenarios of SSP4 indicate that technology is high in developed countries but low in developing countries. This implies that SSP1, SSP5, and SSP4 in developed countries would be more efficient, whereas SSP3 and SSP4 in developing countries would be less efficient. SSP2 would be intermediate between the two groups. Therefore, from Tables 6–8 we assigned High Efficiency to SSP1, SSP5, and SSP4 in developed countries, Medium Efficiency to SSP2, and Low Efficiency to SSP3 and SSP4 in developing countries. We defined developed countries as members of the Organization for Economic Co-operation and Development (OECD)

HESSD
9, 13879–13932, 2012

as of 2005 and developing countries as other countries. The combination is illustrated in Fig. 1c.

6 Results and discussion

6.1 Agricultural water scenarios

Figure 9 shows the irrigated area, crop intensity, and irrigation efficiency scenarios. Because these scenarios are expressed by a simple power law (Eqs. 1–3), they display simple relationships, but they highlight clear differences in the narrative scenarios of each SSP. Note that agricultural water withdrawal is reported in the accompanying paper (Hanasaki et al., 2012) because global hydrological simulations are required for its estimation. This study only sets up the boundary conditions of such simulations.

6.2 Uncertainties of agricultural water scenarios

Here we address the following points. First, in this study, we only considered the key differences in the narrative scenarios of the SSPs when determining a water use scenario. It is beyond the scope of this study to develop in-depth food and agricultural scenarios consistent with the SSPs. In reality, the growth of irrigation may reflect increases in food demand or price, investments in the agricultural sector, improved agricultural technology (e.g. yield increases), land use changes, and other factors (Faurès et al., 2007). The latest socio-economic scenarios sometimes include quantitative scenarios that cover total food production and the area under cropland (e.g. van Vuuren et al., 2011), but setting up irrigation scenarios from these scenarios is still difficult because allocating food production into rainfed and irrigated agriculture systems remains challenging. Further study is required for the development of more consistent scenarios. Second, all scenarios in this study assume that the irrigated area increases in the future, based on the five agriculture and food reports we reviewed (Rosegrant et al., 2002, 2009; Bruinsma, 2003; Alcamo et al., 2005; de Fraiture et al., 2007). However,

HESSD
9, 13879–13932, 2012

some earlier studies have assumed no change or a decrease in irrigation in the future. For example, Alcamo et al. (2007) assumed there would be no growth at all, and Hayashi et al. (2012) assumed a decrease of approximately 0.2 % yr^{-1} globally. The range of scenarios would be even larger if we adopted these assumptions. Third, the populations assumed in the SSPs and the five reports were different, but no population adjustment was performed in this study. Population would affect the growth of irrigation, although it is not the single dominant factor. Fourth, we extended the period beyond the original reports. For example, Bruinsma (2003) projected toward 2030, but we simply extended to 2100 because of the lack of further information. For SSP3 and SSP5, the total global irrigated area reaches 4.5×10^6 km^2, which slightly exceeds all the land with irrigation potential (4.03×10^6 km^2; Bruinsma, 2003). A continuous expansion of the area under irrigation throughout the century might be an unrealistic assumption because cropland suitable for irrigation is limited. An increase in crop intensity would be more realistic (i.e. multiple cropping is enhanced in the existing irrigated area). This suggests that the combined effect of area growth (r_{area}) and increase in crop intensity (r_{int}) would be more robust than two individual scenarios. Fifth, regional differences were not included. The only exception is SSP4, which uses different parameters for OECD countries and non-OECD ones. Moreover, we only considered changes in the currently irrigated area. Areas currently not irrigated continue to be un-irrigated throughout the century.

6.3 Industrial water scenarios

Figure 10 shows the total global industrial water withdrawal. It highlights the differences in the narrative scenarios of the SSPs. For industrial water withdrawals, SSP1 and SSP5 indicate large decreases in the total volume of global water withdrawal. This is primarily explained by the rapid improvement in volume of industrial water withdrawn per unit electricity production (Table 7). Electricity production increases in the 21st century in both scenarios (Fig. 2c), but the effect of the improvement in efficiency is overwhelming. In SSP2, industrial water is relatively stable throughout the 21st century,

HESSD
9, 13879–13932, 2012

which indicates that improvements in efficiency and the growth of electricity production are compensating for each other. Although electricity production is almost stable after 2050, in SSP3 industrial water withdrawal increases, mainly because of the low efficiency.

Figure 11 shows the global distribution of changes in industrial water withdrawal. Note that the changes are shown for individual countries (i.e. the color changes at national boundaries). In SSP1 industrial water withdrawal decreases globally except for countries in Africa. The pattern is quite similar for SSP5, but owing to the larger electricity production, the amount withdrawn is larger than in SSP1. In SSP2 and SSP3 there are global increases. There is a significant contrast in SSP4, in which OECD industrial water withdrawal decreases in OECD countries due to rapid changes in technology. In contrast, there are only moderate increases in non-OECD countries because of the slower rate of technological change.

6.4 Comparisons with earlier studies

Figure 10 also shows the industrial water withdrawal scenarios of Alcamo et al. (2007), Shen et al. (2008), and Hayashi et al. (2012). Alcamo et al. (2007) developed a water use scenario for the SRES A2 and B2 scenarios, whereas Shen et al. (2008) used the SRES A1, A2, B1, and B2 scenarios, and Hayashi et al. (2012) used the ALPS-A scenario which is similar to SRES B2. Because the SRES, SSPs, and ALPS-A are different scenarios, direct comparisons do not make sense, but they do indicate the possible range of water withdrawal projections in the 21st century.

Industrial water withdrawal in SSP2 is close to the scenarios of Alcamo et al. (2007) and Hayashi et al. (2010). This is encouraging because both Alcamo et al. (2007) and Hayashi et al. (2010) estimated their model parameters from historical trends. This approach is compatible with the SSP2 assumption that the typical trends of recent decades will continue. SSP1 and SSP5 are very different, showing decreasing trends. Discussing model feasibility is quite difficult under the current regression modeling framework. Sector- and process-based models are required for better analyses.

HESSD
9, 13879–13932, 2012

6.5 Uncertainties in industrial water scenarios

The industrial water scenario was developed under the following assumptions. First, a linear decrease in electricity production per unit of water use ($s_{\mathrm{ind,cat}}$) was assumed during the study period. This was confirmed from available historic records (Fig. 5), but it is uncertain how far into the future the observed trend continues. Second, $s_{\mathrm{ind,cat}}$ was assumed to be uniform over the entire world. In reality, industrial water demand reflects the different activities of industrial sectors, method of electricity generation, and water use intensity. These terms have regional differences owing to differences in the stage of technology development. Ideally, a new type of model is needed that explicitly takes these individual factors into account. Hayashi et al. (2012) initiated the development of a sector-wise manufacturing water scenario. Vassolo and Döll (2005), Voß et al. (2011), and Flörke and Eisner (2011) initiated the development of technology-wise (power generation method and cooling type) electricity-production water scenarios. These approaches are promising, but also challenging because they require very detailed global inventories of manufacturing and power generation from the present to the future, including geographical information.

6.6 Municipal water scenarios

Figure 12 shows the total global municipal water withdrawal. In SSP1, withdrawal is projected to be almost constant throughout the 21st century because population growth is low and this scenario assumes that all countries move toward a water use level of 200 $\mathrm{L\,day^{-1}\,person^{-1}}$. The other four scenarios show an increase in water use. SSP3 has the largest increase because it has the highest population growth and the largest increase in per capita water use (Table 8). SSP2, SSP4, and SSP5 are intermediates between SSP1 and SSP3, reflecting their population and per capita water use scenarios.

Figure 13 shows the global distribution of changes in municipal water withdrawal. Basically, all scenarios have a similar pattern: water withdrawal increases in developing

HESSD
9, 13879–13932, 2012

countries, particularly in Africa. This is easily explained because many of these countries currently fall below the water use level of 200 L day^{-1} $person^{-1}$, and therefore, under all scenarios, per capita water withdrawal will increase. Moreover, population increases are expected in these countries.

6.7 Comparison to earlier studies

The range of the total global municipal water withdrawals in the five scenarios for three periods is within the range reported by Alcamo et al. (2007), Shen et al. (2008), and Hayashi et al. (2010). The range of withdrawal values in SSP1–5 is relatively narrow, and the general pattern and magnitude is close to that of Shen et al. (2008). Alcamo et al. (2007) reported a range much larger than any of our scenarios. Alcamo et al. (2007) assumed that the per capita water use in developing countries increases to the current mid-range levels of the USA and Europe. This corresponds to more than 400 L day^{-1} $person^{-1}$, which is close to our assumption for SSP3. Moreover, because of the formulation used by Alcamo et al. (2007), per capita water withdrawal increases much more rapidly than in our model. These two factors explain the differences between our results and theirs. Shen et al. (2008) assumed more conservative growth, and eventually, their scenarios and ours approach each other.

6.8 Uncertainties in municipal water scenarios

Municipal water scenarios are characterized by the following assumptions. All nations are sorted into two GDP categories by adopting a threshold of 2000 USD. For countries where per capita GDP is less than 2000 USD, per capita water use increases at the rate of 2 L day^{-1} $person^{-1}$ yr^{-1} until it reaches 200, 300, and 400 L day^{-1} $person^{-1}$ for the High, Medium, and Low Efficiency scenarios, respectively. For other countries, per capita water use decreases at a rate of 2 L day^{-1} $person^{-1}$ yr^{-1} until it declines to 200 L day^{-1} $person^{-1}$, remains constant, and then increases at a rate of 2 L day^{-1} $person^{-1}$ yr^{-1}, respectively. All of the above assumptions are based on

HESSD
9, 13879–13932, 2012
A global water scarcity assessment – Part 1
N. Hanasaki et al.

historical time-series (Figs. 7 and 8), but the limitations should be carefully noted. First, we applied these assumptions uniformly across the globe. This eventually leads to a very homogeneous global water use (i.e. all nations withdraw 200 L day^{-1} $person^{-1}$ of municipal water), which might be unrealistic. In reality, municipal water use reflects the customs and climate of each region. Current water use is quite diverse across various nations as shown in Figs. 7 and 8. Second, in some cases, domestic and municipal water is not strictly separated in global reports; hence care must be taken with comparisons. Following the categorization of AQUASTAT, we separated water use into agricultural, industrial, and municipal water, but some earlier studies have also reported domestic water, which primarily indicates the water use of households. We simply judged that a strict separation is impractical because of the limitations of data availability.

7 Summary

This study developed a global water use scenario that is compatible with the Shared Socio-economic Pathways (SSPs), which are a part of a new set of scenarios for global climate change. The water use scenario was developed to reflect both the quantitative and qualitative descriptions of each SSP. The scenarios include the five factors of irrigation area, crop intensity, irrigation efficiency for estimation of agricultural water withdrawal, and industrial and municipal water withdrawal, which are required to run modern global hydrological models. All of these scenarios are grid-based operating at a spatial resolution of $0.5^\circ \times 0.5^\circ$ and cover the entire 21st century. The accompanying paper (Hanasaki et al., 2012) analyzes global water availability and scarcity in the 21st century by utilizing the water use scenarios developed here.

Acknowledgements. The authors are grateful to Keigo Noda andTaikan Oki for their useful comments. This research was supported by the Environment Research and Technology Development Fund (S-10 and A1103) of the Ministry of the Environment, Japan, CREST of the

HESSD
9, 13879–13932, 2012

Japan Science and Technology Agency, and the National Institute for Environmental Studies Special Research Fund.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S.: Development and testing of the WaterGAP 2 global model of water use and availability, Hydrolog. Sci. J., 48, 317–337, 2003a.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S.: Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions, Hydrolog. Sci. J., 48, 339–348, 2003b.

Alcamo, J., van Vuuren, D., Cramer, W., Alder, J., Bennett, E., Carpenter, S., Christensen, V., Foley, J., Märker, M., Masui, T., Morita, T., O'Neill, B., G. Peterson, G., Ringler, C., Rosegrant, M., and Schulze, K.: Changes in ecosystem services and their drivers across the scenarios, in: Ecosystems and Human Well-being: Scenarios, edited by: Hassan, R., Scholes, R., and Ash, N., Island Press, Washington, DC, 299–373, 2005.

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

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

Bruinsma, J.: World agriculture: towards 2015/2030 An FAO perspective, EarthScan, 2003.

Center for International Earth Science Information Network (CIESIN) Columbia University, and Centro Internacional de Agricultura Tropical (CIAT): Gridded Population of the World Version 3 (GPWv3): Population Grids, Socioeconomic Data and Applications Center (SEDAC) Columbia University, Palisades, NY, 2005.

Döll, P.: Impact of climate change and variability on irrigation requirements: A global perspective, Climatic Change, 54, 269–293, 2002.

Döll, P. and Siebert, S.: A digital global map of irrigated areas, ICID J., 49, 55–66, 2000.

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

Flörke, M. and Eisner, S.: Development of spatially detailed global estimates of 20th and 21st century sectoral water requirements, WATCH Technical Report Number 46, CESR, University of Kassel, Kassel, Germany, 25, 2011.
Food and Agriculture Organization (FAO): AQUASTAT, available at: http://www.fao.org/nr/water/aquastat/main/index.stm, last access: 25 October 2012, 2011.
Faurès, J.-M., Svendsen, M., and Turral, H.: Reinventing irrigation, in: Water for Food, Water for Life, edited by: Molden, D., Earthscan, London, UK, 353–394, 2007.
de Fraiture, C., Wichelns, D., Rockström, J., and Kemp-Benedict, E.: Looking ahead to 2050: scenarios of alternative investment approaches, in: Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture, edited by: Molden, D., Earthscan, London, 2007.
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., 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. Discuss., 9, 13933–13994, doi:10.5194/hessd-9-13933-2012, 2012.
Hayashi, A., Akimoto, K., Tomoda, T., and Kii, M.: Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population, Mitig. Adapt. Strateg. Glob. Change., 1–28, doi:10.1007/s11027-012-9377-3, 2012.
Kainuma, M., Matsuoka, Y., and Morita, T.: Climate policy assessment: Asia-Pacific Integrated Modeling, Springer, Tokyo, Japan and New York, USA, 2002.
Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., and Wilbanks, T.: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways, Global Environ. Chang., 22, 807–822, doi:10.1016/j.gloenvcha.2012.05.005, 2012.

HESSD
9, 13879–13932, 2012

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.

Liu, J. and Yang, H.: Spatially explicit assessment of global consumptive water uses in cropland: green and blue water, J. Hydrol., 384, 187–197, 2010.

Liu, J., Zehnder, 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.

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: The WCRP CMIP3 multimodel dataset: a new era in climate change research, B. Am. Meteorol. Soc., 88, 1383–1394, 2007.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, doi:10.1038/nature08823, 2010.

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, 612 pp., 2000.

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

Oki, T., Agata, Y., Kanae, S., Saruhashi, T., and Musiake, K.: Global water resources assessment under climatic change in 2050 using TRIP, IAHS Publication, 280, 124–133, 2003.

O'Neill, B. C., Carter, T. R., Ebi, K. L., Edmonds, J., Hallegatte, S., Kemp-Benedict, E., Kriegler, E., Mearns, L., Moss, R., Riahi, K., van Ruijven, B., and van Vuuren, D.: Meeting Report of the Workshop on the Nature and Use of New Socioeconomic Pathways for Climate Change Research, National Center for Atmospheric Research, Boulder, CO, 2012.

PUB Singapore's National Water Agency: Water Conservation Awareness Programme, avaiable at: http://www.pub.gov.sg/conserve/households/wacprogramme/pages/default.aspx, last access: 30 September, 2012.

Rosegrant, M. W., Cai, X., and Cline, S. A.: World Water and Food to 2025: Dealing with Scarcity, International Food Policy Research Institute, Washington DC, 2002.
Rosegrant, M., Fernandez, M., and Shinha, A.: Looking into the future for agriculture and AKST, in: Agriculture at a Crossroads, edited by: McIntyre, B. D., Herren, H. R., Wakhungu, J., and Watson, R. T., Island Press, Washington DC, 2009.
Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., 44, W09405, doi:10.1029/2007WR006331, 2008.
Seckler, D., Amarasinghe, U., Molden, D., de Silva, R., and Barker, R.: World Water Demand and Supply, 1990 to 2025: Scenarios and Issues, International Water Management Institute, Colombo, Sri Lanka, 1998.
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., 11–33, doi:10.1623/hysj.53.1.11, 2008.
Shiklomanov, I. A.: Appraisal and assessment of world water resources, Water Int., 25, 11–32, 2000.
Shiklomanov, I. A. and Rodda, J. C.: World Water Resources at the Beginning of the Twenty-First Century, Cambridge University Press, 2003.
Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K., and Feick, S.: Development and validation of the global map of irrigation areas, Hydrol. Earth Syst. Sci., 9, 535–547, doi:10.5194/hess-9-535-2005, 2005.
Smith, M.: CROPWAT – A computer program for irrigation planning and management, FAO, Rome, 1992.
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.
United Nations: World Population Prospects: The 2010 Revision, vol. I: Comprehensive Tables ST/ESA/SE R.A/313, 481, 2011.
Vassolo, S. and Döll, P.: Global-scale gridded estimates of thermoelectric power and manufacturing water use, Water Resour. Res., 41, W04010, doi:10.1029/2004WR003360, 2005.
Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: vulnerability from climate change and population growth, Science, 289, 284–288, 2000.

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

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

Voß, F. and Flörke, M.: Spatially explicit estimates of past and present manufacturing and energy water use, WATCH Technical Report Number 17, CESR, University of Kassel, Kassel, Germany, 16, 2010.
Voß, F., Flörke, M., and Alcamo, J.: Preliminary spatially explicit estimates of past and present domestic water use, WATCH Technical Report Number 23, CESR, University of Kassel, Kassel, Germany, 17, 2009.
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.
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.
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.
World Bank: World Development Indicators 2009, World Bank, Washington DC, USA, 2009.

HESSD
9, 13879–13932, 2012

Table 1. Summary of the narrative scenarios of the SSPs.

	SSP1	SSP2	SSP3	SSP4	SSP5
Technology development	High	Medium	Low	High in developed countries but low in others	High
Environmental consciousness	High	Medium	Low	High in developed countries, but low in others	Low[a]
Crop yields	–	–	–	High in industrial farming, but low for small-scale farming	–

[a] O'Neill et al. (2012) described a "highly engineered environment, highly managed land use and water intensive world."

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

Table 2. Projection of irrigated area, crop intensity, and irrigation efficiency in earlier reports.

Reference	Scenario	Population	GDP	Irrigated area reported in the literature (10^6 ha)	Irrigation equipped area ($\% yr^{-1}$)	Cropping intensity ($\% yr^{-1}$)	Irrigation efficiency ($\% yr^{-1}$)
Rosegrant et al. (2002)		UN 1998 med	original	375 (1995)[b], 441 (2025)[b]			–
Bruinsma (2003)		UN 2001 med	WB 2001	202 (2000)[c], 242 (2030)[c]	0.6	0.4	0.3
Alcamo et al. (2005)	MA-TG	MA-TG	MA-TG	239 (2000)[c], 252 (2050)[c]	0.11		–
de Fraiture et al. (2007)	CA-Irrigated area expansion	MA-TG	MA-TG	340 (2000)[a], 450 (2050)[a]	0.6		–
de Fraiture et al. (2007)	CA-Comprehensive	MA-TG	MA-TG	340 (2000)[a], 394 (2050)[a]	0.3		–
de Fraiture et al. (2007)	CA-Irrigated yield improve	MA-TG	MA-TG	340 (2000)[a], 370 (2050)[a]	0.15		–
de Fraiture et al. (2007)	CA-Rainfed area expansion	MA-TG	MA-TG	340 (2000)[a], 340 (2050)[a]	0		–
de Fraiture et al. (2007)	CA-Rainfed yield improve	MA-TG	MA-TG	340 (2000)[a], 340 (2050)[a]	0		–
de Fraiture et al. (2007)	CA-Trade	MA-TG	MA-TG	340 (2000)[a], 340 (2050)[a]	0		–
Rosegrant et al. (2009)		UN 2005 med	MA-TG	433 (2000)[b], 473 (2050)[b]	0.06	0.15	0

[a] Harvested area.
[b] Potential irrigated area.
[c] Area equipped irrigation.
MA: Millennium Ecosystem Assessment, CA: Comprehensive Assessment, UN: United Nation population prospects, WB: World Bank, TG: Techno Garden, med for medium variant projection.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
9, 13879–13932, 2012
A global water scarcity assessment – Part 1
N. Hanasaki et al.

Table 3. Summary of industrial water withdrawal estimation models in earlier studies.

References	Drivers	Technological change	Structural change
Alcamo et al. (2003a, 2007)	Electricity production	Parameter	Per capita GDP
Shen et al. (2008)	Electricity production		Primary energy, GDP
Voß et al. (2010), manufacturing water	Manufacturing output expressed in gross value added	Parameter	GDP
Voß et al. (2010), thermal cooling water	Electricity production	Parameter	Fraction of cooling type
Hayashi et al. (2012)	Sector-wise production of manufacturing sectors		

HESSD
9, 13879–13932, 2012

Table 4. Summary of municipal water withdrawal estimation models in earlier studies.

References	Drivers	Technological change
Alcamo et al. (2003a, 2007)	Population	Parameter
Shen et al. (2008)	Population, GDP	
Voß et al. (2009)	Population	Parameter
Hayashi et al. (2012)	Population, GDP	

HESSD
9, 13879–13932, 2012

Table 5. Scenarios for irrigated area growth and crop intensity change.

	Low growth (LG)	Medium growth (MG)	High growth (HG)
Irrigated area growth ($\%\,yr^{-1}$)	0.06	0.30	0.60
Crop intensity change ($\%\,yr^{-1}$)	0.15	0.20	0.40

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

Table 6. Scenarios for irrigation efficiency change.

	High efficiency (HE)	Medium efficiency (ME)	Low efficiency (LE)
Irrigation efficiency change ($\%\,yr^{-1}$)	0.30	0.15	0.0

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

HESSD

9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

Table 7. Scenarios for industrial water intensity change ($m^3 yr^{-2} MWh^{-1}$).

	High efficiency (HE)	Medium efficiency (ME)	Low efficiency (LE)
$50 \leq i_{ind}$	−2.5	−1.2	−0.6
$10 \leq i_{ind} < 50$	−0.7	−0.35	0
$i_{ind} < 10$	−0.2	0	0

HESSD
9, 13879–13932, 2012

Table 8. Scenarios for municipal water intensity change (L person^{-1} day^{-1} yr^{-1}).

		High efficiency (HE)	Medium efficiency (ME)	Low efficiency (LE)
per capita GDP < 2000 USD	$200 \leq i_{dom}$	-2 ($200 \leq i_{dom}$)	0	2
	$i_{dom} < 200$	2 ($i_{dom} < 200$)	2 ($i_{dom} < 300$)	2 ($i_{dom} < 400$)
2000 USD ≤ per capita GDP		-2 ($200 \leq i_{dom}$)	0	2

HESSD

9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

Table 9. Parameters for Eqs. (1)–(5).

	SSP1	SSP2	SSP3	SSP4	SSP5
Irrigated area growth (% yr^{-1})	0.06	0.30	0.60	0.06	0.60
Crop intensity change (% yr^{-1})	0.15	0.20	0.40	0.15	0.40
Improvement in irrigation water efficiency (% yr^{-1})	0.30	0.15	0.00	0.00	0.30
Improvement in industrial water efficiency (Table 7)	HE	ME	LE	MIX	HE
Improvement in municipal water efficiency (Table 8)	HE	ME	LE	MIX	HE

MIX indicates HE in OECD countries and LE in non-OECD countries.

HESSD
9, 13879–13932, 2012

Table 10. Total global potential demand for industrial water withdrawal ($km^3 yr^{-1}$).

	SSP1	SSP2	SSP3	SSP4	SSP5
2025	853	1169	1435	1087	1000
2055	519	1437	1895	1116	808
2085	246	1259	1714	851	521

HESSD
9, 13879–13932, 2012

Table 11. Total global potential demand for municipal water withdrawal ($km^3 yr^{-1}$).

	SSP1	SSP2	SSP3	SSP4	SSP5
2025	544	598	631	583	549
2055	622	822	935	780	645
2085	573	973	1280	967	619

HESSD
9, 13879–13932, 2012

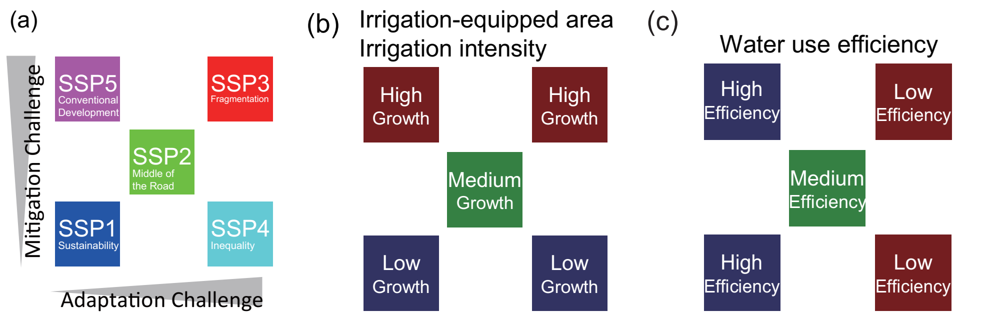

Fig. 1. (a) The five SSPs in a conceptual space of adaptation challenge and mitigation challenge. **(b)** Scenarios for irrigation-equipped area and irrigation intensity. **(c)** Scenarios for water use efficiency.

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

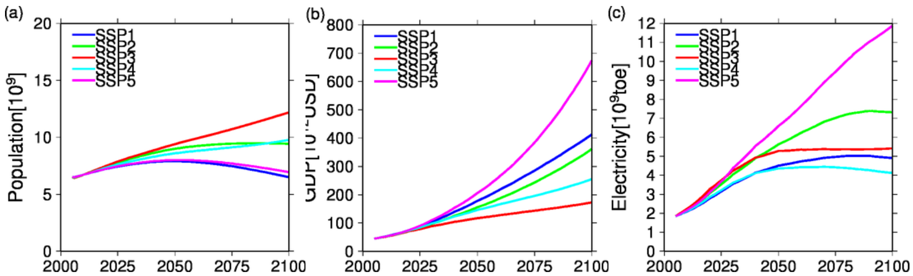

Fig. 2. Socio-economic factors of AIM-SSP. **(a)** Population, **(b)** GDP, and **(c)** electricity production of each SSP.

HESSD
9, 13879–13932, 2012

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
SSP1	SSP1 policy		SSP1 BAU	
SSP2		SSP2 policy		SSP2 BAU
SSP3			SSP3 policy	SSP3 BAU
SSP4	SSP4 policy		SSP4 BAU	
SSP5			SSP5 policy	SSP5 BAU

Fig. 3. Scenario matrix of SSPs and RCPs.

HESSD
9, 13879–13932, 2012

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

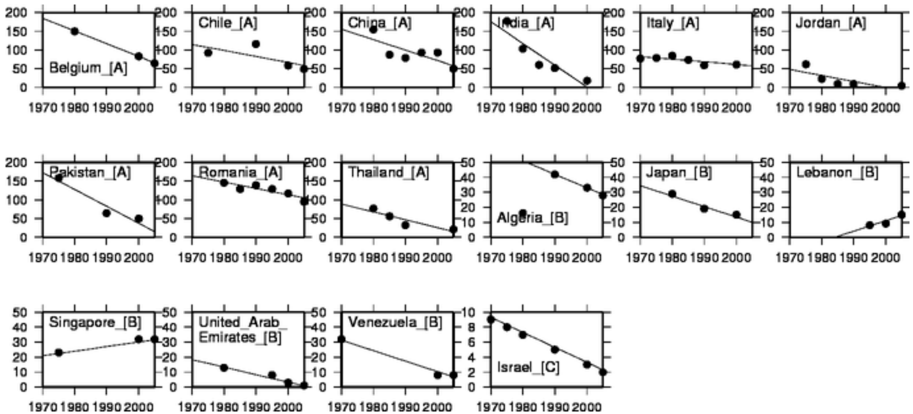

Fig. 4. Historical records of national industrial water intensity (plot) and regressions (line) ($m^3 yr^{-1} MWh^{-1}$).

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

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

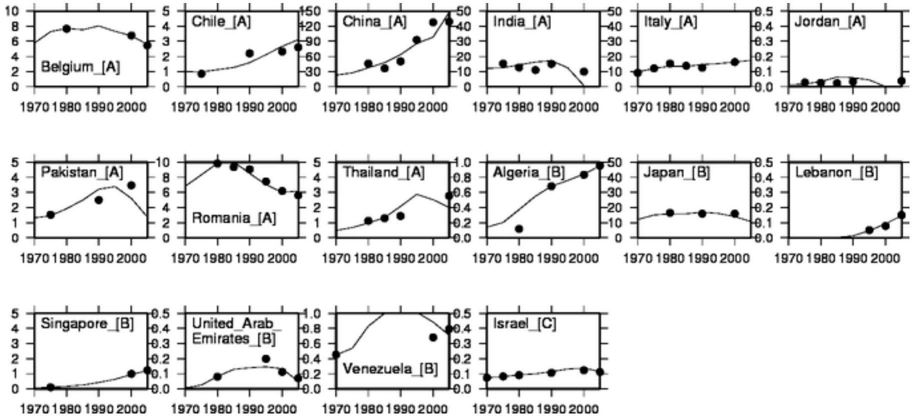

Fig. 5. Historical records of national industrial water withdrawal (plot) and estimations with Eq. (4) (line) ($km^3 yr^{-1}$).

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

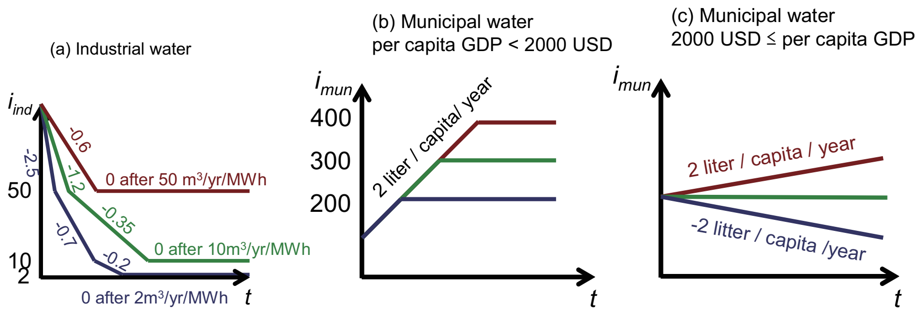

Fig. 6. Schematic diagram of intermediate water use scenarios for **(a)** industrial water withdrawal, **(b)** municipal water withdrawal for countries with per capita GDP < 2000 USD, and **(c)** for countries with 2000 USD ≤ per capita GDP.

HESSD

9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

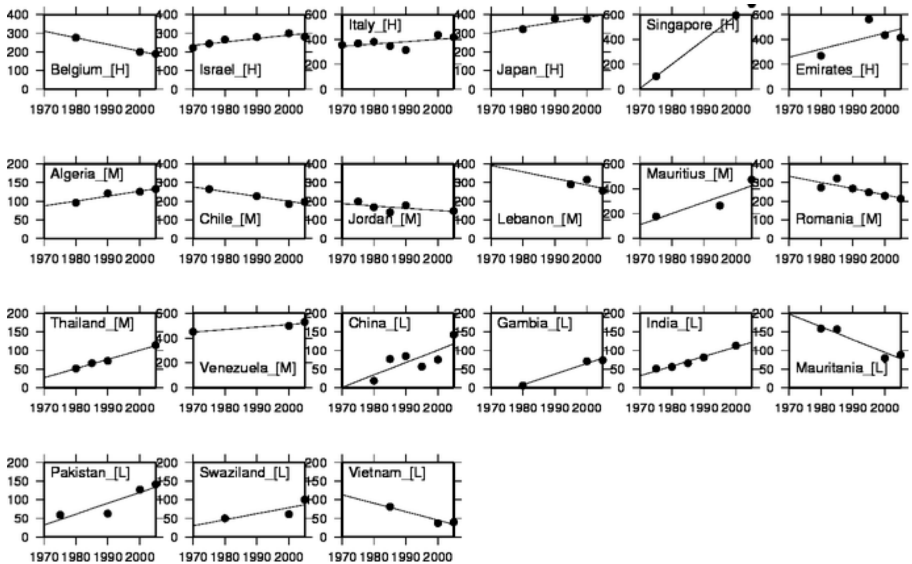

Fig. 7. Historical records of national municipal water intensity (plot) and regressions (line) ($\mathrm{L\,day^{-1}\,person^{-1}}$).

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

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

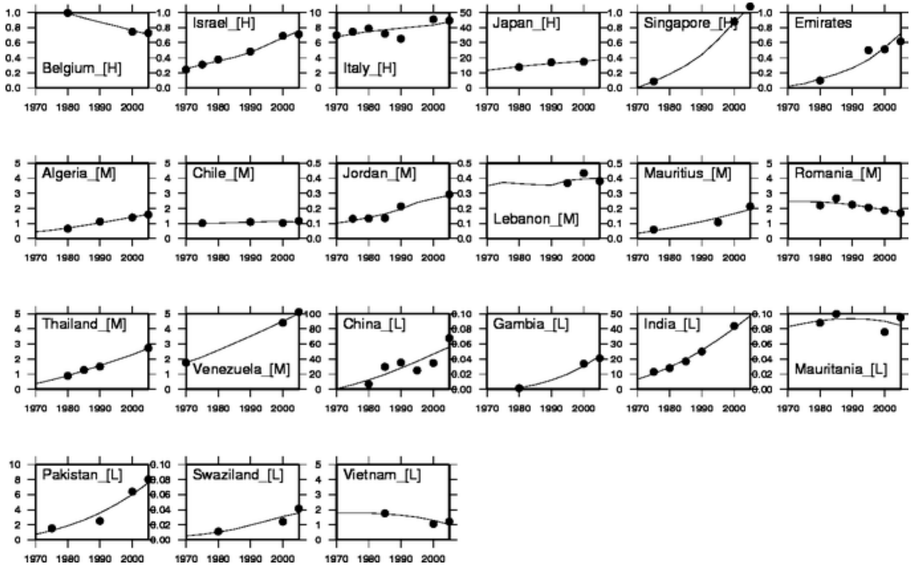

Fig. 8. Historical records of national municipal water withdrawal (plot) and estimations with Eq. (5) (line) ($km^3 yr^{-1}$).

HESSD
9, 13879–13932, 2012

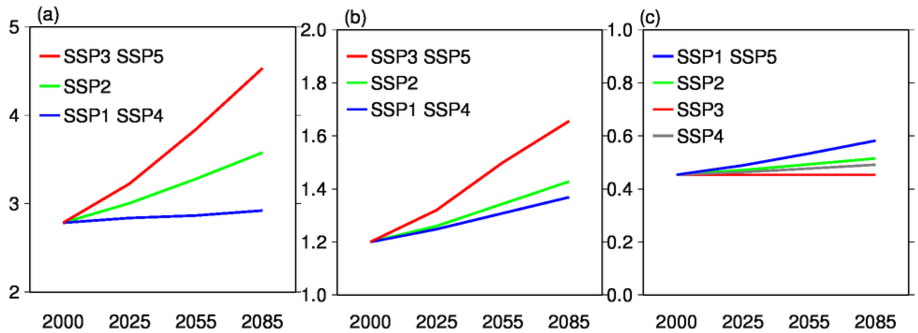

Fig. 9. Scenarios for agricultural water withdrawal. **(a)** Global total irrigated area (10^6 km^2), **(b)** global mean crop intensity (crops yr^{-1}), **(c)** global mean irrigation efficiency (–).

HESSD
9, 13879–13932, 2012

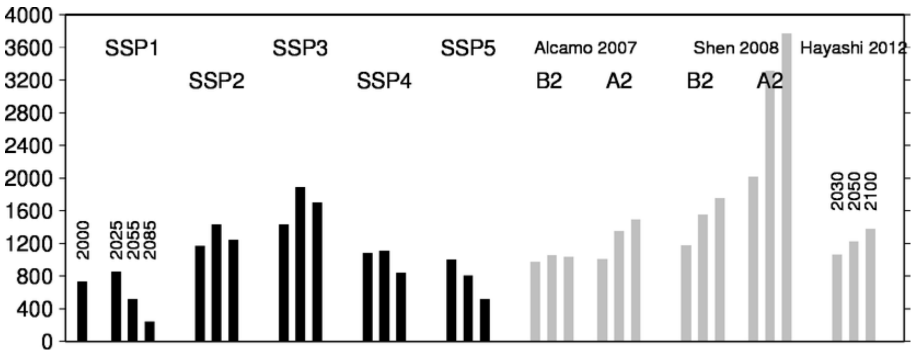

Fig. 10. Scenarios for total global industrial water withdrawal ($km^3 yr^{-1}$).

HESSD
9, 13879–13932, 2012
A global water scarcity assessment – Part 1
N. Hanasaki et al.

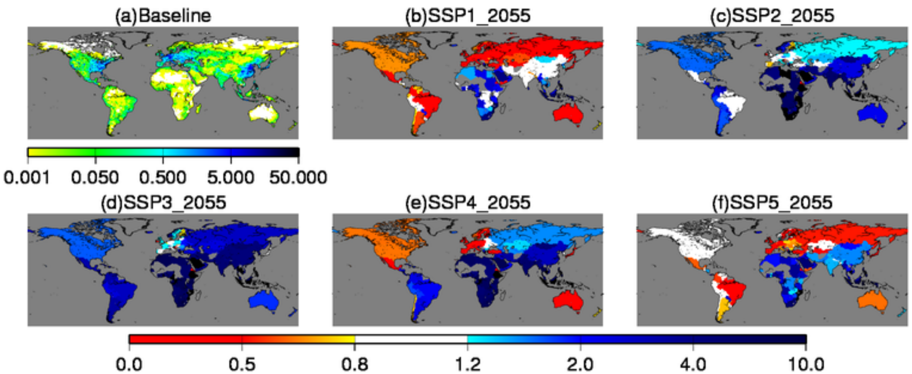

Fig. 11. Global distribution of industrial water withdrawal. **(a)** Baseline year (circa 2000) ($m^3\,s^{-1}$), **(b–f)** Change (ratio) from the baseline year for SSP1–5 in 2055.

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

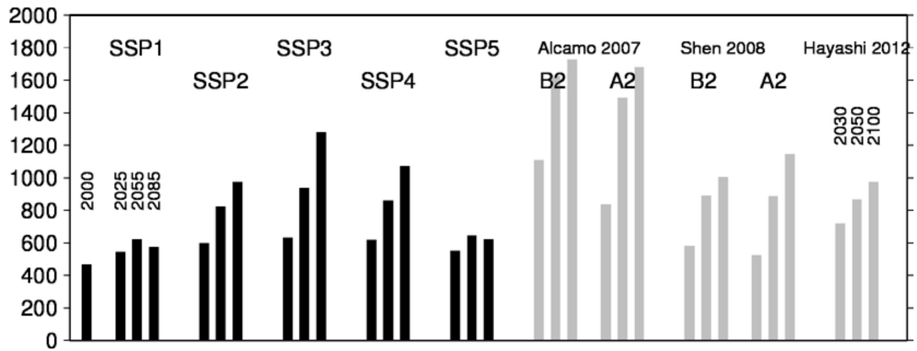

Fig. 12. Scenarios of total global municipal water withdrawal ($km^3 yr^{-1}$).

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

HESSD
9, 13879–13932, 2012

A global water scarcity assessment – Part 1

N. Hanasaki et al.

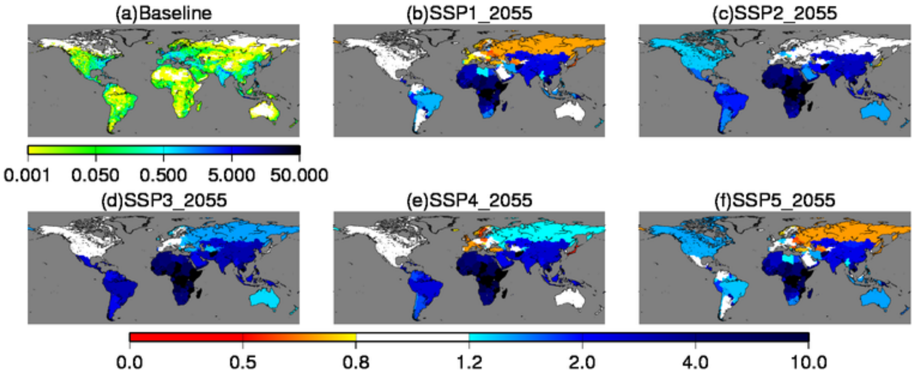

Fig. 13. Global distribution of municipal water withdrawal. **(a)** Baseline year (circa 2000) ($m^3 s^{-1}$), **(b–f)** Change (ratio) from the baseline year for SSP1–5 in 2055.