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A seawater desalination scheme for global hydrological models

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Abstract

Abstract. Seawater desalination is a practical technology for providing fresh water to coastal arid regions. Indeed, the use of desalination is rapidly increasing due to growing water demand in these areas and decreases in production costs due to technological advances. In this study, we developed a model to estimate the areas where seawater desalination is likely to be used and the likely volume of production. The model was designed to be incorporated into modern global hydrological models (GHMs) that explicitly include human water usage. The model requires spatially detailed information on climate, income levels, and water use, which represent standard input/output data in modern GHMs. The model was applied to a specific historical period and showed fairly good reproduction of the present geographical distribution and national production of desalinated water in the world. The model was applied globally to two periods in the future (2011–2040 and 2041–2070) under three distinct socioeconomic conditions, i.e., SSP (Shared Socioeconomic Pathways) 1, SSP2, and SSP3. The results indicate that the usage of seawater desalination will have expanded considerably in geographical extent, and that production will have increased by 1.4–2.2-fold in 2011–2040 compared to the present (from 3.7 km^3 yr^{-1} in 2005 to 5.1–8.3 km^3 yr^{-1}), and 6.3–14.2-fold in 2041–2070 (23.4-52.7 km^3 yr^{-1}). The large spreads in these projections are primarily attributable to variations within the socioeconomic scenarios.

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1. Introduction

Water is vital to society. However, due to population increases, economic growth, and climate change, there is growing concern over sustainability of water use around the world. There have been a number of studies regarding present and future worldwide water availability and use. Initially, the mean annual runoff (i.e., river discharge) was regarded as the primary renewable water resource (Vörösmarty et al., 2000; Oki et al. 2001, 2003). With increasing sophistication of global hydrological models (GHMs), the sources of water have been subdivided into various categories, such as rivers, reservoirs, lakes, groundwater, and others (Hanasaki et al., 2008a,b; Wada et al. 2011, 2014; Döll et al., 2014).

In this study, we focused on desalinated water derived from seawater. Desalination is a technique for removing high concentrations of minerals and salts from saline and brackish water. Although it accounts for a marginal fraction at present, it may play a greater role in the future for several reasons. First, water demand is rapidly increasing in arid and semi-arid areas where precipitation is limited, and on some islands and cities with limited catchment areas. Desalination is a practical measure for providing freshwater to such areas because it is completely independent of the natural hydrological cycle. Second, due to rapid technological advances, the costs of production have dropped rapidly, making it competitive with traditional water resources (Bremere et al., 2001). These two factors have encouraged the rapid installation of desalination plants globally (see Figure S1). Indeed desalination is considered one of adaptation measures to climate change for the freshwater sector (Jimenz Cisneros et al., 2014).

Desalinated water has been included in some previous global water resource assessments based on simulations. Oki et al. (2001) presented a global water resource assessment incorporating reported national desalinated water production for various countries. Oki et al. (2003) conducted future global water projections assuming that the present volume of desalination production would remain unchanged. As production of desalinated water is increasing rapidly, however, this assumption underestimates the future contribution of desalination. Wada et al. (2011) incorporated desalinated water as water sources in their GHM called PCR-GLOBWB by spatially distributing national volume of usage for areas within 40 km of the seashore. They assumed that the volume would increase in proportion to the population. The above examples represent reasonable simplifications for GHMs, but further refinement is necessary because desalination is increasing rapidly and is strongly connected to climate and socioeconomic conditions. A few studies have projected future growth of desalination on a global scale. Bremere et al. (2001) projected the desalination capacity required for ten water-scarce countries in 2025 to meet their growing municipal water demands. They assumed that water use per person would remain constant and that growth in municipal water demand would be proportional to population increase. Ouda (2014) projected future water supply and demand in Saudi Arabia under three scenarios, taking into account desalinated water and treated wastewater. Further studies are needed to examine the effects of socioeconomic variables, such as growing water use per person, and to cover the whole globe because of the increase in areas where desalination is utilized.

In this study, we developed a model to infer the geographical distribution and production of seawater desalination. The model was designed to be incorporated into modern GHMs that are applicable for state-of-the art global long-term projections. There were two key questions. First, what are the common climatic and socioeconomic conditions associated with usage of seawater desalination around the world? Identification of such conditions would facilitate the development of a model to explain the present geographical distribution and production of seawater desalination. Second, what would be the production of desalinated water in the future under various socioeconomic scenarios? The model was developed and validated utilizing newly available global datasets. Future projections were conducted based on a comprehensive global water assessment (Hanasaki et al., 2013a,b). Both the distribution and production of seawater desalination were assessed for three socioeconomic scenarios.

This paper is structured as follows. Part 2 describes the data, model, and simulation settings. In Part 3, the results of the model and simulation are presented along with a discussion regarding its performance in reproducing the present distribution of desalination plants. The results of future projection are also shown. Part 4 concludes the paper.

2. Methods

2.1 Desalination data

To analyze the present installation of desalination plants, we mainly referenced DesalData (http://desaldata.com/). As of 2014, DesalData included data for more than 17,000 individual desalination plants around the world. The total capacity of desalination reached 46.9 $km^3\ yr^{-1}$ globally from all water sources. Individual records contain data such as plant status, source water type, user category, plant size, and geographical location (longitude and latitude).

Since the objective of this study was to develop a model that would be applicable to the global domain for long-term projections, to make the model robust, we focused on information regarding active Major Plants that use seawater as source water. Actually seawater is the primary source of desalination which amounts 29.3 $km^3\ yr^{-1}$, followed by brackish water, saline inland and river water, and others. We selected the year 2005 as the base year mainly due to the availability of socioeconomic data as discussed below. First, we selected the desalination plants (hereafter Major Plants) to be included in our analyses. Table S1 shows the detailed selection criteria. We selected 613 large plants using seawater as the water source. We examined the list of plants and amended the records if necessary. For example, DesalData contains some records indicating that plants in mountainous inland regions use seawater as the source, which is erroneous. In addition to plant-based information, we also collected municipality-based information for Saudi Arabia (KICP, 2011) and the United Arab Emirates (UAE) (RSB, 2013). To determine the distances between desalination plants and major cities of selected countries, the geographical data of major cities were collected. We referred to the GeoNames database (http://www.geonames.org), which reports the geographical locations and populations of major cities around the world. We selected cities with populations larger than 100,000 (hereafter Major Cities).

2.2 Hydrometeorological data

At present, Major Plants are located mostly in arid regions. To express aridity, the ratio of precipitation to potential evapotranspiration (hereafter Aridity Index, AI) was calculated globally. We used the WATCH Forcing Dataset (Weedon et al., 2011) as a global meteorological dataset for the historical period in question. This dataset covers the whole globe at a spatial resolution of 0.5° × 0.5° and includes basic meteorological variables at 6-hour intervals, i.e., precipitation, air temperature, specific humidity, wind speed, air pressure, and shortwave and longwave downward radiation. Using the data from 1971 to 2000, we calculated the mean annual precipitation and potential evapotranspiration globally. The latter was calculated using the H08 global hydrological model (Hanasaki et al., 2008a,b).

For the future period, we used the climate projections obtained with three global climate models (GCMs), i.e., MIROC4-ESM-CHEM, HadGEM2-ES, and GFDL-ESM2M. The selection and combination of GCMs and climate scenarios were identical to those reported previously (Figure 3 of Hanasaki et al., 2013a; Table 2 of Hanasaki et al., 2013b).

2.3 Socioeconomic data

For population and GDP, we referred to the Shared Socioeconomic Pathways (SSPs) Database provided by IIASA (https://secure.iiasa.ac.at/web-apps/ene/SspDb), which covers both the historical (1980–2005) and future periods (2005–2100) for 203 nations. The data for future periods came from model-based projections under five distinct socioeconomic views, i.e., SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Fragmentation), SSP4 (Inequality), and SSP5 (Conventional Development; O'Neill et al., 2014). GDP is shown in Purchasing Power Parity (PPP) in 2005 US Dollars (USD).

For nationwide water use data, we relied primarily on the AQUASTAT database (www.fao.org/nr/aquastat/) for the historical period in question. This database includes municipal and industrial water use data for 200 nations from 1960 to 2010 at 5-year intervals. Data are available for most countries in 2000 or 2005. For the future period, we used the projections of Hanasaki et al. (2013a). They estimated water withdrawal for irrigation, industrial, and municipal use over three periods (2011–2040, 2041–2070, and 2071–2100, centered on 2025, 2055, and 2085,

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

respectively). Projections of industrial and domestic water withdrawal were obtained with a semi-empirical model using electricity production and population as primary driving forces and scenario-based parameters on improvements in water use efficiency. The parameters were set to be compatible to the storyline of SSPs (e.g. slow improvements in SSP3 while raipd in SSP1). Consequently, as shown in Figures 12 and 14 of Hanasaki et al. (2013a), the projected future water withdrawal was largest in SSP3 and smallest in SSP1. The key socioeconomic factors are summarized in Table 3. In this study, we focused on three scenarios, i.e., SSP1, SSP2, and SSP3. Note that these projections are demand-side based without specifying water sources.

2.4 Desalination model

We developed the Seawater Desalination Model (SDM) that estimates the areas where desalinated water is used and the volume of desalinated water production. As the model is intended to be incorporated with the global water resources model H08 (Hanasaki et al., 2008a,b), for consistency, the model is grid-based with a spatial resolution of 0.5° × 0.5°.

Based on the findings of the geographical distribution of desalination plants as described in Section 3.1, SDM extracts the Area Utilizing Seawater Desalination (AUSD) or the grid cells meeting the following three conditions:

Condition A) nations with GDP exceeding 14,000 USD person^{-1} year^{-1}

Condition B) AI below 10%, and

Condition C) three consecutive grid cells (approximately 165 km of edge at the equator) of seashore.

Some important factors for the design of actual plants, such as the geographical suitability of seawater intake (Voutchkov, 2012), were excluded from this model because of the coarse resolution of the model and the lack of global data availability.

SDM estimates desalination water production under the following assumptions:

Assumption A) Seawater desalination is used for municipal and industrial purposes, not for irrigation.

Assumption B) All the municipal and industrial water withdrawal in AUSD is supplied by seawater desalination.

Assumption C) The production to capacity ratio, which shows the fraction of seawater desalination production of a country relative to the total plant capacity is 40-80%.

The rationale of Assumption A is that desalinated water is not considered to be affordable for irrigation (e.g. Bremere et al., 2001). Note the production cost is approximated as 0.86–3.21 USD m^{-3} (Lamei et al., 2008). The validity and limitations of these assumptions are examined in the next section. Assumption B is linked with Condition B: under such arid climatic condition, surface water is hardly available unless major rivers are flowing (e.g. the Nile in Egypt) and groundwater should not be abundant in a long-term perspective because natural recharge must be virtually zero. Consequently, it also implies certain economic advantage of seawater desalination, although we didn't explicitly include the cost for each water source into our model. Assumption C is based on the findings of data analyses shown in Sect. 3.1.

2.5 Simulation

Four simulations were conducted in this study using SDM. The first was a historical simulation for 2005 (hereafter HIS), which was used for model validation. The results were used to validate the locations and production volumes of desalinated water. The other simulations were the SSP1, SSP2, and SSP3 simulations for three periods (2011–2040, 2041–2070, and 2071–2100), which were consistent with the projection of Hanasaki et al. (2013a, b). The results were used to assess future desalinated water use.

3. Results and Discussion

3.1 Analyses of data collected

In this subsection, prior to discuss the simulation results, the collected data are analyzed. Table 1 summarizes desalinated water capacity and production in major countries. Nine countries, i.e., UAE, Saudi Arabia, Kuwait, Spain, Qatar, Libya, Bahrain, Israel, and Oman, accounted for 85% of the seawater desalination plant capacity in 2005 (hereafter Major Countries). UAE and Saudi Arabia produced the largest volumes of desalinated water, which accounted for more than half of the global total. The Major Countries share two characteristics. First, all are located in the Middle East or on the coast of the Mediterranean Sea and have arid or semi-arid climates. Second, their income is relatively high: per person GDP exceeds 14,000 USD PPP person^{-1} yr^{-1}. Condition A of SDM (see Subsection 2.4) reflects these findings.

Next, we focused on water use and desalination in Major Countries, as shown in Table 1. More than three times the volume of water was used by municipalities than by industry, except in Spain. Globally, 99% of seawater desalination plant capacity was installed for combined municipal and industrial use, with 90% for municipal water use. This confirms the validity of Assumption A of the SDM that seawater desalination is seldom used for agricultural water supply. The production to capacity ratio varied considerably among nations, ranging from 53% to 110%; the ratio sometimes exceeded 100%, probably due to inconsistencies in the data and the year of report.

Figure 1 shows the geographical distributions of 613 Major Plants around the world. Note that the plants were aggregated into gridded data with a spatial resolution of 0.5° × 0.5° for consistency with the final simulation. As clearly shown in the figure, the Major Plants were mainly located on the seashore and near large cities.

Figure 2 shows the AI of the present climate. Comparing Figures 1 and 2, the Major Plants are mainly distributed where the aridity index is less than 0.1. Condition B of the SDM reflects these findings.

Hydrology and Earth System Sciences
Open Access
Discussions

Figure 3 shows the distances of the major desalination plants from the seashore and the primary cities. Distance was calculated using the Clark Lab's IDRISI Taiga Release 16.05 GIS platform software (Eastman, 2009). Note that due to technical limitations of the software, the individual plants were first aggregated into 5' × 5' grid cells, and then the distance was estimated at intervals of 1 km. We analyzed seven of the Major Countries including cities larger than 100,000 persons. The results indicated that 90% of the major desalination plants were located within 34 km from the seashore and 170 km from Major Cities. Taking the distance from the coastline and cities into account, the area using seawater desalination extended approximately 170–204 km (roughly corresponding to the edge (165 km) and diagonal (233 km) of 3 × 3 grid cells with a spatial resolution of 0.5° × 0.5°) from the seashore. Condition C reflects these findings.

For further geographical breakdown, Table 2 shows the water supply of the Major Cities in UAE and Saudi Arabia. The two largest cities in UAE, Abu Dhabi and Dubai, depend heavily on desalinated water. Municipal and industrial water for Abu Dhabi is supplied entirely by desalinated water (EAAD, 2012) and their plant capacity reaches 1.18×10^{6} m^{3} day^{-1}. Information on detailed water supply in Dubai was not available, but a news article suggested that 98.8% of Dubai's water is supplied by desalination (Hackley, 2013). These cases agreed well with Assumption B of the SDM. The total desalinated water production for the six cities in Saudi Arabia accounted for 80% of the national desalinated water supply. For these cities, desalinated water accounted for as much as 69% of the total supply. The sources of water varied between cities and regions. Jeddah, Makkah, Al Taif, and Al Madinah were largely dependent on desalinated water, which agreed well with Assumption B. On the other hand, about half of the water was obtained from groundwater for Riyadh, which is located 450 km from the seashore, and Dammam: the former case is contrary to Condition C (i.e., some cities distant from the sea may use seawater as the source for desalination) and the latter case is contrary to Assumption B (i.e., AUSD may use water other than desalinated water for municipal and domestic use). Although there are some exceptions, we believe that Assumption B is valid for long-term projection because the groundwater level is rapidly decreasing in these cities, implying poor sustainability (KICP, 2011). In addition, for example in Abu Dhabi in UAE, 98% of groundwater is saline or brackish, and therefore groundwater may require desalination treatment (EAAD, 2012). Finally, we found that the production to capacity ratio ranges 28% to 77% for these cities. We approximated it to 40-80% and set as Assumption C.

3.2 Historical simulation

HIS simulation was conducted to validate the SDM. Figure 4 shows the AUSD results of the HIS simulation. The AUSD largely agreed with the distribution of Major Plants in the Middle East (Figure 1), spreading along the seashore in Kuwait, Saudi Arabia, UAE, Bahrain, Qatar, Oman, and southwest Iran. Yemen was not included because it fell below the income threshold, which agreed well with Table 1 indicating that Yemen produces little desalinated water. Southern Oman was indicated as suitable for desalination, but this area currently has no desalination plants. This does not represent an overestimation of desalinated water production as the region is sparsely populated, and therefore water withdrawal is quite limited compared to the northeastern part of the country. The AUSD in the Mediterranean tends to be underestimated. In Libya, AUSD was only seen on the northeastern coastline of the country. Due to the low AI, there was no AUSD on the northwestern coastline, while there are actually Major Plants in this region (Figure 1). In Israel, the SDM estimated only one AUSD grid cell along the coastline of the Red Sea, while there are also actually plants along the coastline of the Mediterranean. In the case of southern Spain, although there are some Major Plants in this area (see Figure 1), the model failed to reproduce them because AI was far above the threshold (Figure 3). Similarly, desalination plants located on the islands of Italy failed to be reproduced by the SDM. Climate variations and hydrological characteristics may explain these discrepancies. Spain suffered from severe drought from 1991 to 1995, which triggered the rapid construction of major desalination plants in this country (March et al., 2014). Interestingly, March et al. (2014) reported that the plants are almost idle, which is consistent with our simulation results. Indeed, the AI of southeastern Spain in 1995 was close to the threshold of 0.1, which agreed with the SDM. Islands are hydrologically characterized by relatively small catchment areas, limited water storage capacities, and variable water demands if tourism is a major industry. These conditions may have enhanced the implementation of seawater desalination in such areas.

Table 1 includes the global and national volumes of desalinated water production for 2005. First, global total production and capacity of seawater desalination were estimated at 3716×10^6m^3 yr^{-1} and 4645–9290×10^6m^3 yr^{-1}, respectively. Note that the wide range in capacity reflects the production to capacity ratio included in Assumption C. The reported plant capacity in DesalData (5405×10^6m^3 yr^{-1}) was within the range of the latter. However, there were discrepancies in the breakdown, with the simulation tending to overestimate industrial water use, particularly for non-Major Countries. Next, the simulation results for national production agreed fairly well with AQUASTAT (Figure S2 shows a scatter plot of the data in Table 1). The simulation for UAE underestimated the data from AQUASAT. This was largely attributable to an inconsistency within AQUASTAT, in which desalination production exceeds the total of municipal and industrial water withdrawal. The severe underestimation in Spain and Israel was mainly due to failure of AUSD estimation, as mentioned above; there was no AUSD in Spain, and only one grid cell in Israel. Note that we could not perform the calculations for Bahrain because the area of land could not be resolved in our model.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
Open Access
Discussions

3.3 Future simulation

Figure 5 shows the estimated spread of AUSD at present and in 2055 under SSP1, SSP2, and SSP3 scenarios. For all cases in 2055, AUSD has expanded considerably compared to the present. The change in AUSD can be largely explained by growth in income: the change in AI due to climate change played a marginal role. In the case of SSP1, AUSD showed marked expansion of grid cells including Baja California in Mexico, northern Chile, the coastline of Northern Africa, and Southwest Africa. Interestingly, although present production is not significant, several desalination plants have actually been operational in Baja California and northern Chile since 1999 (DesalData). Note that the coastlines on the Caspian Sea in Central Asia became AUSD, as the inland lakes are categorized as sea. The expansions of SSP2 and SSP3 were somewhat limited compared to SSP1 because income levels in these scenarios were lower than in SSP1. As all SSP scenarios project considerable income growth with national income exceeding 14,000 USD for most countries in the world (Table 3 and Figure S3), AUSD is expected to expand into most of the arid areas in the world by 2055 (compare Figure 2 and Figure 5).

Using the model described here, the projected levels of desalinated water production in 2025 and 2055 are 1.4–2.2 and 6.3–14.2 times greater than present, respectively (Table 4). The earlier estimates show a considerable range, but our results are within the range of spread for the reported period of 2015–2025.

The economic cost of seawater desalination was estimated for each case. Adopting the method of Lamei et al. (2008), we estimated the unit production costs at 0.40–3.78 USD m^{-3} based on the data available for 186 plants globally (see Supplemental Material for details). As shown in Table 4, the volume of seawater desalination was estimated at 3.7 $km^3 yr^{-1}$ with a cost of 1.5–14.0 10^9 USD, equivalent to 0.0025%–0.024% of total global GDP. This number is much higher in the Middle East and North Africa (MENA), with values of 0.033%–0.32%. Among the scenarios, SSP3 in 2055 showed the highest numbers at 0.011%–0.11% globally and 0.13%–1.2% for MENA. This was mainly attributable to large water use and low GDP growth in SSP3.

The future projection is sensitive to Condition A (per capita GDP threshold of 14,000 USD) and Condition B (aridity index of 0.1). Here, we conducted a sensitivity test on these thresholds. We examined thresholds of 0, 7,000, and 24,000 USD for Condition A. A threshold of 7,000 USD implies further reduction in cost due to technological change, while 0 implies that seawater desalination economically outperforms traditional water resource development in arid regions. The threshold of 24,000 USD was taken from the per capita GDP of Israel, one of the non-oil-producing nations in Table 1. Present Condition A was taken from the per capita GDP of Libya, which is an oil-producing nation. We considered that the threshold for oil-producing nations may be lower than for other countries due to massive consumption of fossil fuels for desalination. Similarly, we tested thresholds of 0.15 and 0.2 for Condition B, which expanded the potential area for AUSD (Figure 2).

The results of the sensitivity tests are shown in Figure 6. First, a higher threshold of per capita GDP decreases the

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

total desalination production due to reduction in AUSD. For the base year (2005), there is a gap between 0 and 7,000 USD. In contrast, there is no change in SSP1 between 0 and 14,000 USD, as per capita GDP exceeds 14,000 for most countries (see Figure S3b). The large drop between 14,000 and 24,000 USD for SSP3 indicates that in this scenario a large number of countries cannot exceed a per capita GDP of 24,000 by 2055 (i.e., the growth in per capita GDP in SSP3 is considerably slower than in the other scenarios). The discrepancies among SSPs are attributable to differences in water use. Hanasaki et al. (2013a) projected the lowest water use for SSP1 due to rapid decreases in municipal and industrial water use intensity, with the opposite being true for SSP3. The sensitivity test of AI showed a linear response (only the results of SSP1 are shown in Figure 6) due to gradual changes in AI (Figure 2).

3.4 Implications in the context of global water resource assessment

In 2005, the global total for industrial and domestic water withdrawal was reported to be 1,170 km^3 yr^{-1}(AQUASTAT). In this study, desalination production was estimated at 3.7 $km^3 yr^{-1}$ for these two purposes, accounting for 0.3% of the total. As shown in Table 3, water withdrawal will change considerably in the future. In the case of SSP1, which depicts a sustainable world, the projected water withdrawal is 1,142 km^3 yr^{-1} in 2055, showing almost no change from the present. However, in SSP3, which depicts a fragmented world, withdrawal will triple and reach 2831 km^3 yr^{-1}. The estimated seawater desalination production levels are 23.4 and 52.7 km^3 yr^{-1} for these scenarios, accounting for 2.0% and 1.9% of the global requirement, respectively. Although this portion appears small, desalinated water plays a critical role in AUSD. The population in the AUSD is estimated at 14.5 million in 2005, but by 2055, is expected to increase to 159.0 in SSP1and 184.3 million in SSP3. As the AUSD is extremely dry and vulnerable to water scarcity, it is crucial to secure municipal and industrial water for water security and human well being in AUSD regions.

3.5 Key uncertainties and limitations

The SDM model estimates AUSD and the volume of desalinated seawater based on three conditions and three assumptions. The results demonstrate that these conditions and assumptions allow us to successfully simulate seawater desalination in accordance with the purpose of this study. Here, each condition and assumption is revisited and key uncertainties are discussed.

Conditions A and B, which set thresholds on national average income and aridity, explain the present distribution of major desalination plants. It should be noted that countries meeting these conditions include major oil-producing countries. Seawater desalination has high energy consumption costs, even with the application of the latest technology. Hence, the price of energy is an important factor in the installation of desalination plants.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
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Published: 31 March 2016

Hydrology and Earth System Sciences
Discussions

Although we confirmed that non-oil-producing countries such as Spain and Israel had considerable desalination capacity, attention should be paid to the projected newly emerging AUSD in non-oil-producing countries, such as Chile, Namibia, etc. The income threshold may differ for these nations compared to major oil-producing countries because of differences in energy prices. Our modeling and validation can be never free from these regional biases, since majority of desalination plants have been constructed in the Middle East. It should be also noted that we fixed the thresholds for income and aridity according to Conditions A and B throughout the study period. This corresponds to the assumption that technology and costs of production are essentially fixed at present. Advances in technology would likely further lower the production costs, which would alter the threshold for plant installation.

Condition C, which sets the maximum distance from the seashore for AUSD, plays a crucial role in the simulated volume of desalinated water. Desalinated water can be used at large distances from the seashore if transportation costs are affordable. Assumption B, or 100% dependence on desalination in AUSD, is probably the largest uncertainty in the SDM. Although surface water is unreliable under super-arid conditions in AUSD, the dependence is influenced by the availability of other water sources, typically groundwater and sometimes long-distance water transfer (Lamei et al. 2008). Recycled water is another emerging source of freshwater in water-scarce regions. For example, Singapore has been strongly promoting recycled water usage, which is economically more efficient than seawater desalination due to Singapore's stringent waste water quality control and appropriate infrastructure (Tortajada, 2006). In contrast, desalination plants are occasionally implemented in relatively wet regions, e.g., on islands that are characterized by relatively small catchment areas, limited storage capacities, and large temporal variations in water demand. Such regional details are beyond the capability of present global hydrological models, but may substantially affect the results in some places.

In this study, we used the future water use projection of Hanasaki et al. (2013a) based on empirical relationships between water use and population and electricity production excluding regional details, and therefore projections for individual nations include substantial uncertainty. The spatial distribution of water use is another source of uncertainty. Historical and future water use are obtained first at the national scale, and then converted into grid cells under various assumptions. This study adopted the assumption that the spatial distribution of municipal and industrial water use is proportional to that of population. Third, we note that supply and demand are interconnected: seawater desalination relieves the availability of water constrained by hydrology. Increases in water availability may enhance water consumption. This may alter the future situation substantially from the historical past on which the water demand projections of Hanasaki et al. (2013a) were based.

Finally, the limitations of SDM are summarized. First, SDM was designed to be incorporated into modern GHMs typically simulated at the spatial resolution of 0.5°×0.5° (approximately 55km x 55km at the Equator). Resolving individual plants is impossible with this spatial scale, and planning and designing of individual plants are not the scope of this model. Second, SDM is intended to apply for long-term (30-100 years) global projection mainly driven by SSPs which only include basic and coarse socio-economic projection. Although the cost of desalination and its relative differences among alternative sources play crucial role in desalination projects in reality, the mechanism is not included in the present formulation of SDM.

4. Conclusions

We have developed a model to estimate the location and volume of desalinated water production. First, we identified climatic and socioeconomic conditions that are common to areas where seawater desalination is undertaken. Three typical conditions were found, i.e., relatively high income, aridity, and proximity to the seashore. We obtained common global parameters for each, and demonstrated that the present AUSD can be fairly well reproduced by the proposed model. Then, we assumed that municipal and industrial water in AUSD are fully supplied by seawater desalination, and estimated the production and plant capacity of seawater desalination. We achieved fairly strong agreement with independent data. Second, using the SDM and SSP socioeconomic scenarios, the future production of desalination water was projected globally. The results indicated that AUSD is expected to expand considerably in the 21st century. Income growth plays a primary role in the expansion of desalination plants.

Desalination is a practical engineering measure for meeting the growing water demand in arid regions and for adapting to climate change (Jiménez Cisneros et al., 2014). This study proposes one of the first models to express desalination in global water resource models supported by the available literature and technologies. Although further improvements are needed, the model provides a good starting point for dynamically incorporating information regarding desalination into global water resource assessment.

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Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
Discussions
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Table 1. The major countries producing desalinated seawater in 2005.

	Country	GDP|PPP per person (SSP DB) [2005 USD $person^{-1}$ yr^{-1}]	Water withdrawal (AQUASTAT) [$10^6 m^3 yr^{-1}$]		Desalinated water production (AQUASTAT) [$10^6 m^3 yr^{-1}$]		Desalination water plant capacity (DesalData) [$10^6 m^3 yr^{-1}$]				Production to capacity ratio (A/B) [%]	Desalinated water production (simulated) [$10^6 m^3 yr^{-1}$]			Desalination water plant capacity (simulated) [$10^6 m^3 yr^{-1}$]
			Mun.	Ind.	Total (A)		Mun.	Ind.	Others	Total (B)		Mun.	Ind.	Total	Total
1	UAE	66,855	617	69	950	(2005)	1,760	46	0	1,806	53	617	69	686	858–1,715
2	Saudi Arabia	20,406	2,130	710	1,033	(2006)	1249	129	0	1,378	70	718	239	957	1,197–2,393
3	Kuwait	48,783	448	23	420	(2002)	448	0	0	448	94	448	23	472	589–1178
4	Spain	27,379	5,790	6,698	100	(2005)	280	0	35	315		0	0	0	0
5	Qatar	69,512	174	8	180	(2005)	171	0	0	171	105	174	8	182	228–455
6	Libya	14,015	610	132	NA[1]	NA[1]	104	37	0	142		41	9	50	63–125
7	Bahrain	28,068	178	20	102	(2003)	113	24	0	137	74	NA[2]	NA[2]	NA[2]	NA
8	Israel	24,543	712	113	140	(2007)	135	0	0	135		10	2	12	15–30
9	Oman	21,047	134	19	109	(2006)	95	4	0	99	110	129	18	148	184–368
	Others						453	320	0	773		284	927	1,211	1,514–3,028
	Total						4,809	561	35	5,405		2,421	1,295	3,716	4,645–9,290

1) Data only available for 1998 and earlier.

2) Bahrain could not be resolved with the current spatial resolution of 0.5° × 0.5°.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences Discussions
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Table 2 Major cities that use desalinated water in the United Arab Emirates and Saudi Arabia

City	Water supply [m^3 day^{-1}] Total	Groundwater	Desalinated water (A)	(year)	Desalination water plant capacity (DesalData) (B) [m^3 day^{-1}]	Production to capacity ratio (A/B) [%]	Source
Riyadh (Saudi Arabia)	155,7000	745,000	812,000	(2009)	1,795,099	45	KICP, 2011
Jeddah (Saudi Arabia)	633,000	3,000	630,000	(2009)			KICP, 2011
Makkah (Saudi Arabia)	280,000	0	280,000	(2009)			KICP, 2011
Al Taif (Saudi Arabia)	137,000	23,000	114,000	(2009)			KICP, 2011
Total of above three cities	1,050,000	26,000	1,024,000	(2009)	2,557,833	40	
Al Madinah (Saudi Arabia)	327,000	55,000	272,000	(2009)	485,496	56	KICP, 2011
Dammam (Saudi Arabia)	345,000	190,000	155,000	(2009)	547,000	28	KICP, 2011
Total of above six cities	3,279,000	1,016,000	2,263,000	(2009)			
Abu Dhabi (UAE)			1,180,000	(2013)	1,520,000	77	RSB, 2013

Table 3 Global future scenarios in 2055 (extracted from Hanasaki et al., 2013a, b)

Item	SSP1	SSP2	SSP3
Radiative forcing	RCP2.6	RCP4.5	RCP6.0
Global mean temperature rise [K]	2.4	2.9	2.9
Population [10^{9}person]	8.5	9.3	10.3
GDP [10^{12}USD]	319	255	186
Municipal water withdrawal [km^3/yr]	622	823	936
Industrial water withdrawal [km^3/yr]	520	1437	1895

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
Open Access
Discussions

Table 4 Projected future production of desalinated water

	Period	Domain	Desalination production from seawater [$\times 10^6$ m^3 day^{-1}]	Installed capacity for seawater [$\times 10^6$ m^3 day^{-1}]	Installed capacity for all sources [$\times 10^6$ m^3 day^{-1}]	Production cost [$\times 10^6$ USD]
Historical						
This study	2005	Globe	10.2 (3.7 km^{3}yr^{-1})	12.7 – 25.4[(1)]	--	1,486 – 14,046
AQUASTAT	2003 – 2007	Globe	14.1[(2)]	--	--	--
DesalData	2005	Globe	–	16.7	--	–
Bremere et al. (2001)	2000	10 countries[(3)]	–	4.6[(4)]	7.3	–
Lattemann et al. (2010)	2006	Globe	–	27.9	44.1	–
Future (near term)						
This study (SSP1)	2025	Globe	13.9 (5.1 km^{3}yr^{-1})	17.4 – 34.8	--	2,032 – 19,202
This study (SSP2)	2025	Globe	17.7 (6.5 km^{3}yr^{-1})	22.1 – 44.3	--	2,585 – 24,433
This study (SSP3)	2025	Globe	22.7 (8.3 km^{3}yr^{-1})	28.3 – 56.7	--	3,308 – 31,264
Bremere et al. (2001)	2025	10 countries[(3)]	–	13.9[(4)]	22.1	–
Lattemann et al. (2010)	2015	Globe	–	61.7[(4)]	98	–
Future (long term)						
This study (SSP1)	2055	Globe	64.1 (23.4 km^{3}yr^{-1})	80.1 – 160.2	--	9,353 – 88,402
This study (SSP2)	2055	Globe	119.6 (43.7 km^{3}yr^{-1})	149.5 – 299.0	--	17,462 – 165,015
This study (SSP3)	2055	Globe	144.4 (52.7 km^{3}yr^{-1})	180.4 – 360.9	--	21,075 – 199,160

(1) Assuming a rate of operation of 40%–80%.

(2) From all sources.

(3) Malta, Barbados, Singapore, Jordan, Yemen, Bahrain, Kuwait, Qatar, Saudi Arabia, Libya.

(4) Values for seawater were not reported. We assumed 63% of the source was seawater, taken from the estimate for 2006 by Lattemann et al. (2010).

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
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Discussions

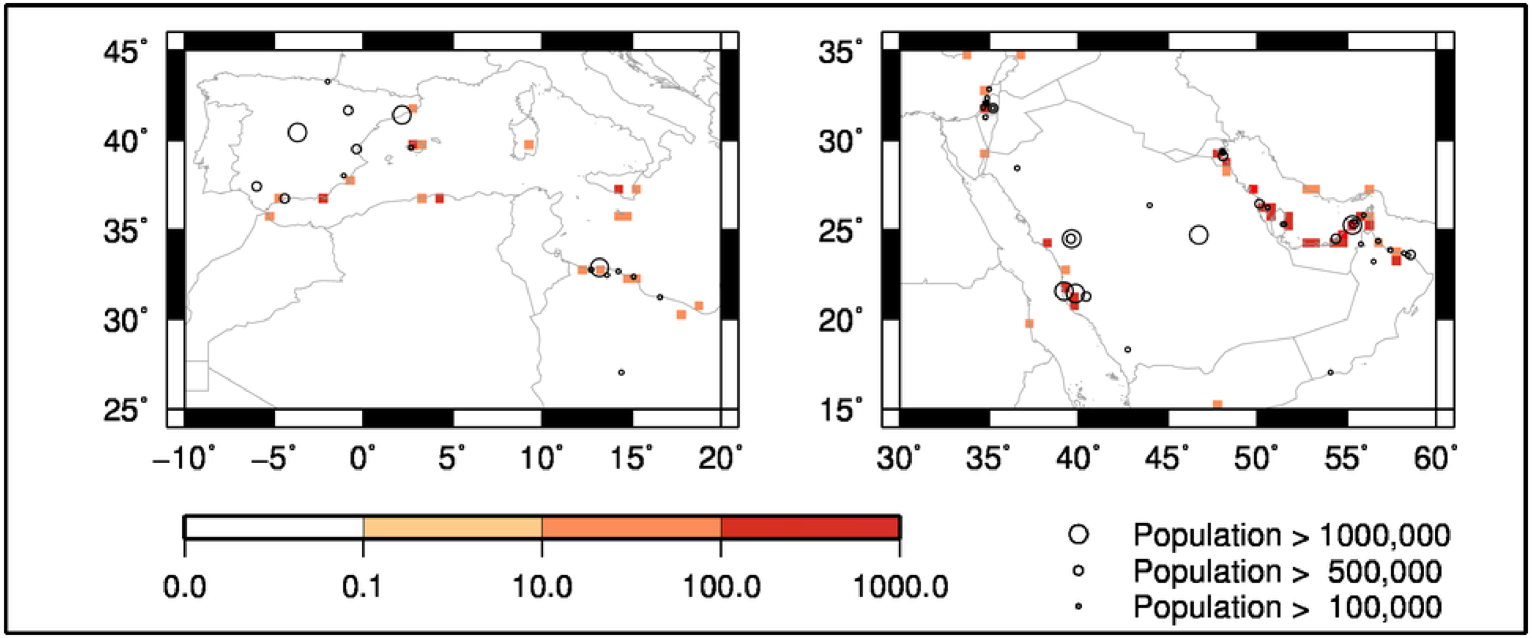

Figure 1 Actual locations of major desalination plants in the Mediterranean and Middle East in 2005 (boxes: 1000 m^3 day^{-1}; DesalData). Circles represent major cities (GeoNames).

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
Open Access
Discussions

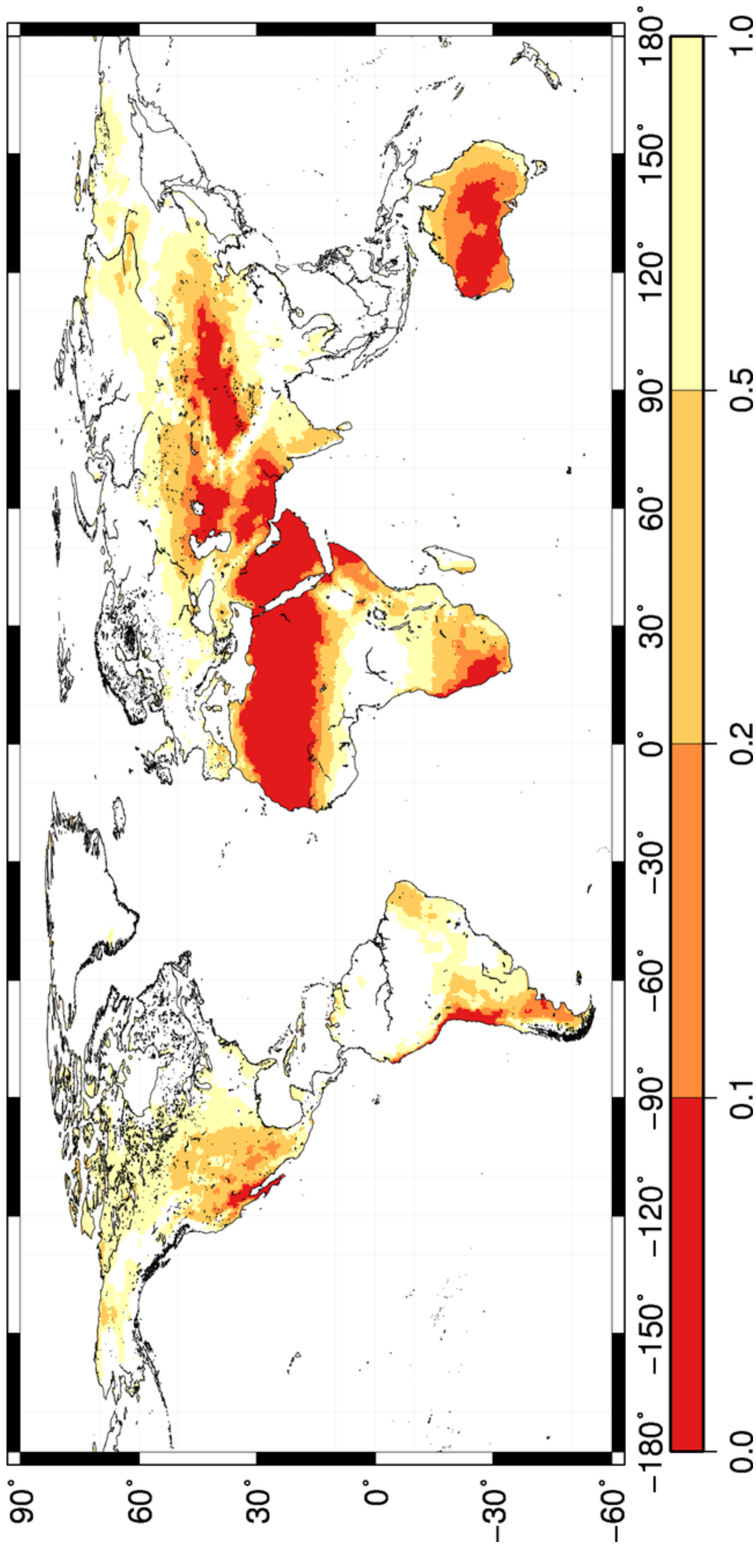

Figure 2. Simulated aridity index under the present climate (ratio of precipitation to potential evapotranspiration).

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
Open Access
Discussions

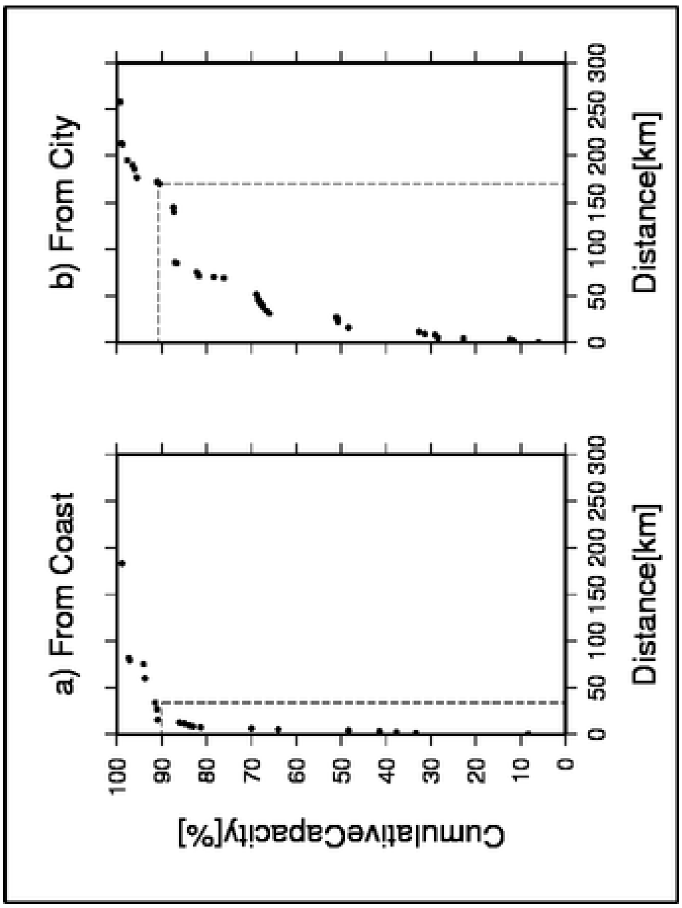

Figure 3 Cumulative capacity of desalination water and the distance of plants from the coastline (a) and major cities (b). The broken line shows the 90th percentile.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

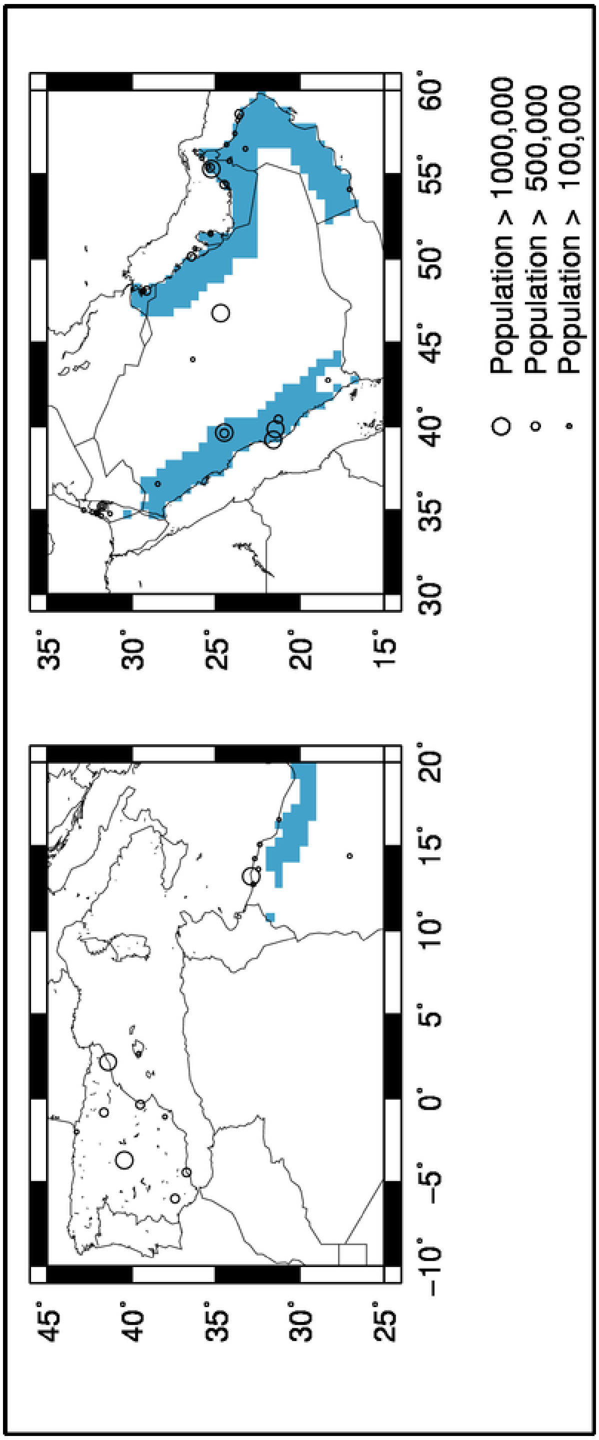

Figure 4 Simulated distribution of area utilizing seawater desalination (AUSD) in the Mediterranean and Middle East in 2005. Circles represent major cities (GeoNames).

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

Hydrology and Earth System Sciences
Discussions
Open Access

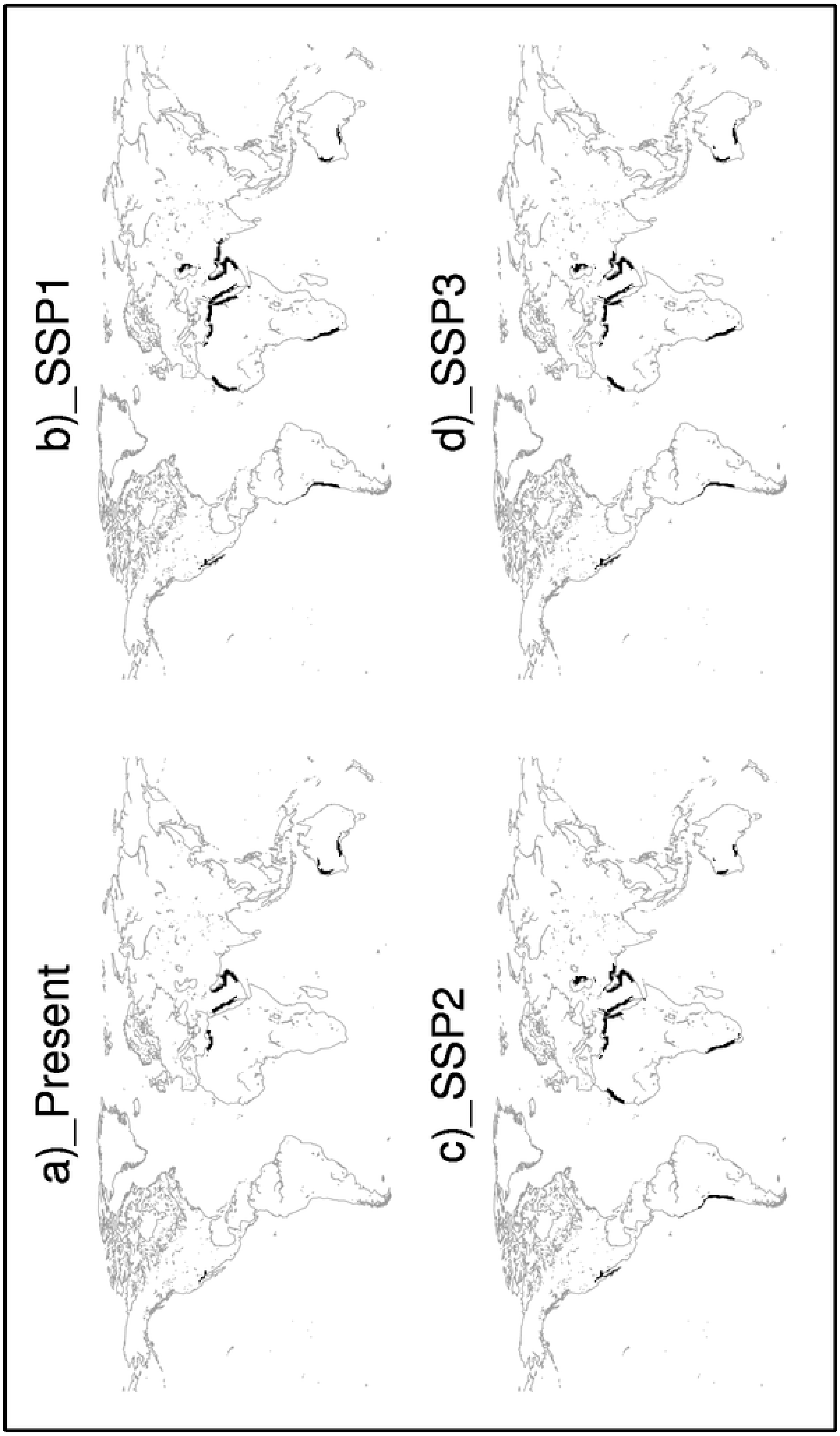

Figure 5 Global distributions of area utilizing seawater desalination (AUSD) in (a) 2005, (b) SSP1 in 2055, (c) SSP2 in 2055, and (d) SSP3 in 2055.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-119, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 31 March 2016

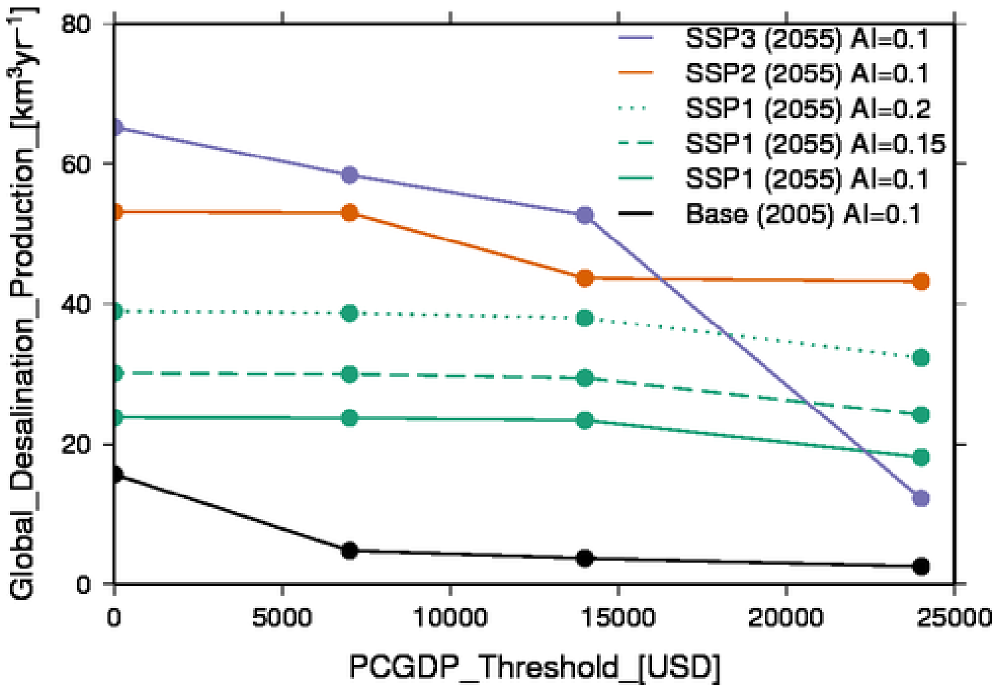

Figure 6 Sensitivity of per capita GDP (PCGDP; Condition A) and the aridity index (AI, Condition B) with respect to global total production of seawater desalination. Black, blue, green, and red lines for base year (2005), SSP1, SSP2, and SSP3 in 2055, respectively. Solid, broken, and dotted lines for AI = 0.1, AI = 0.15, and AI = 0.2, respectively. The sensitivity of AI is only shown for SSP1 in 2055.