A seawater desalination scheme for global hydrological models

Naota Hanasaki[1], Sayaka Yoshikawa[2], Kaoru Kakinuma[2], and Shinjiro Kanae[2]

[1]National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, 305-8506, Japan
[2]Graduate School of Science and Engineering, Tokyo Institute of Technology, 2-12-1-M1-6 O-okayama, Meguro-ku, Tokyo 152-8552, Japan

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

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 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 GHMs. The model was applied to a specific historical period (2005) 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 1.3–2.1-fold in 2011–2040 compared to the present (from 2,767×10^6m^3 yr^{-1} in 2005 to 3,669–5,847×10^6m^3 yr^{-1}), and 6.7–17.3-fold in 2041–2070 (18,452–47,930×10^6m^3 yr^{-1}). The estimated global cost for production for each period is 1,107-10,458×10^6 USD (0.002–0.019% of the global total GDP), 1,468–22,102×10^6 USD (0.001–0.019%), 7,381–181,176×10^6 USD (0.002–0.098%) respectively. The large spreads in these projections are primarily attributable to variations within the socioeconomic scenarios.

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. Kim et al. (2016) proposed an economic approach to project future desalination water production globally. They assumed that supply and demand of desalination is determined by the price mechasim, and reported that total desalination water would be reached 250km^3 yr^{-1} at the end of 21st century, 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 GHMs that are applicable for state-of-the art global long-term projections. There were two key questions. First, what are the climatic and socioeconomic conditions where seawater desalination is largely implemented 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. Section 2 describes the data, model, and simulation settings. In Section 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. Section4 concludes the paper.

2. Methods

2.1 Desalination data

To analyze the present installation of desalination plants, we mainly referenced DesalData (http://www.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 21.9 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 water scarcity 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 13.3 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. The detailed selection criteria and the rationale is shown in Table S1 and Supplemental Text. 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. The plants excluded from this study are listed in Table S2 with reasons.

We also collected country-based information for nine countries, i.e., UAE, Saudi Arabia, Kuwait, Spain, Qatar, Libya, Bahrain, Israel, and Oman, that produces largest desalination water in the world (hereafter Major Countries). In addition to above, we collected municipality-based information for Saudi Arabia (KICP, 2011) and the United Arab Emirates (UAE) (RSB, 2013). In spite of the authors' efforts, sub-national information for other countries were not found.

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 for each grid 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 and the methods of downscaling and bias correction were identical to those reported previously (Hanasaki et al. 2013a,b).

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, including desalinated water production, 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, 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 rapid 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 1. 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°.

SDM is a set of climatological, geographical, and socio-economic conditions to estimate the spatial extent where seawater desalination is likely used. By inputting gridded global maps, SDM extracts the grid cells that all conditions are met. We call these grid cells as the Area Utilizing Seawater Desalination (AUSD). In AUSD grid cells, seawater desalination is produced and used to meet local water demand under several assumptions. By combining the gridded map of AUSD and requirement of water withdrawal (i.e. potential water demand) which is a standard input/output data of latest global hydrological models, we can estimate the production of seawater desalination globally. An important point is that AUSD is not identical to the location of individual desalination plants. It is expected that the spatial extent of AUSD includes the locations of major seawater desalination plants, but it is not necessarily true that desalination plants are located at every AUSD grid cells because desalinated water can be transferred to surrounding grid cells through the pipe network.

The conditions and assumptions of SDM were determined based on the findings of the geographical distribution of desalination plants and national aggregated desalination water production as described in Section 3.1. Here for the readers' convenience, all the conditions and assumptions are shown. SDM extracts AUSD or the grid cells meeting the following three conditions:

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

Condition B) AI below 7.5%, and

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

In general, the desalination plants and regions using their production are located in arid coastal zones in relatively high-income countries. Conditions B, C, A correspond to each. As mentioned earlier, the globally uniform thresholds were determined by the analyses shown in Section 3.1. The thresholds are dependent on climatological data used and spatial resolution of interest, hence modified if SDM is applied in a different simulation settings. 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 30-80%.

Combining the assumptions, AUSD, and grid-based requirement of water withdrawal, the volume of desalinated water production can be estimated which is directly transferable with global hydrological models . 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 to determine the thresholds of SDM. Table 2 summarizes desalinated water capacity and production in Major Countries. They accounted for 85% of the seawater desalination plant capacity in 2005. 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 Major Plants 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 Major Plants in the Mediterranean and Middle East regions where majority of plants are concentrated. 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. We plotted the relationship between the AI and plant capacity at each grid cell. It shows remarkable difference in the distribution of capacity by AI. We applied the segmented regression method and estimated the break point at AI of 0.075 and set as the threshold of the Condition B of SDM.

Figure 3 shows the distances of the major desalination plants from the seashore and the primary cities of Major Countries. Desalination plants are typically located on seashore and supplying water to cities at close range. We calculated the distance 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 3 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 presume 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 30-80% 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 included the location of Major Plants in the Middle East (Figure 1), spreading along the seashore in Kuwait, Saudi Arabia, UAE, Bahrain, Qatar, and Oman. Yemen was not included because it fell below the income threshold, which agreed well with Table 2 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 high 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 AUSD in the region because AI was far above the threshold (Figure 2). 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 substantially low, which is close to the threshold of 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 2 includes the global and national volumes of desalinated water production for 2005. First, global total production and capacity of seawater desalination were estimated at $2{,}767\times10^6 \mathrm{m}^3\ \mathrm{yr}^{-1}$ and $3{,}459–9{,}223\times10^6 \mathrm{m}^3\ \mathrm{yr}^{-1}$, respectively. Note that the wide range in capacity reflects the production to capacity ratio included in Assumption C. The reported global total plant capacity in DesalData ($5{,}405\times10^6 \mathrm{m}^3\ \mathrm{yr}^{-1}$) was within the range of the latter. Next, the simulation results for national production agreed fairly well with AQUASTAT (Figure S2 shows a scatter plot of the data in Table 2). For Saudi Arabia, Kuwait, Qatar, Oman, the simulated and reported desalination water production agreed well. The simulation for UAE underestimated the data from AQUASTAT. 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.

So far, SDM was validated mainly from the view point of spatial extent of areas and total volume of desalinated water production in circa 2005. Although systematic validation of temporal dynamics of desalinated water was hampered mainly by the lack of access to long-term data on socio-economic conditions and water use, a simple validation for Assumption B was conducted and shown in Figure 5. The methods summary is shown in Supplemental Material. Conditions A-C and Assumptions A-C indicate that AUSD is temporary variable due to change in municipal and industrial water withdrawal because the other factors are unchanged in the time frame of a few decades. Figure 5 shows the relationship between national desalination capacity and municipal and industrial water withdrawal in AUSD for different periods between 1980–2005. In general the plots are located near the diagonal line. It supports Assumption B of SDM that the growth in the municipal and industrial water in AUSD is sustained by seawater desalination. Exceptions are the cases of Spain and UAE. As we discussed repeatedly, AUSD in Spain is not reproduced in this study. Although desalination capacity substantially increased in UAE during the period, AQUASTAT reports little increase in municipal and industrial water withdrawal. Taking marked economic growth in UAE during the period into account, the authors infered water withdrawal would have been grown larger than reported in AQUASTAT.

In summary, SDM was validated from three perspectives: geographical extent of AUSD (Figure 4), total desalination water production in 2005 (Table 2 and Figure S2), and temporal change in production (Figure 5). The simulated regions where desalination water is largely used are well reproduced compared to earlier studies introduced in Introduction Section. Although SDM advanced the modeling in global desalination, the results of SDM contain uncertainties mainly attributed to the limited data availability and simplicity of the model structure, the same with following future simulations.

3.3 Future simulation

Figure 6 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 Southern Africa and northern Chile (see Figure 6e and 6f). 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 PPP person^{-1} yr^{-1} for most countries in the world (Table 1 and Figure S3), AUSD is expected to expand into most of the arid areas in the world by 2055 (compare Figure 2 and Figure 6).

Using the model described here, the projected levels of desalinated water production in 2025 and 2055 are 1.3–2.1 and 6.7–17.3 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.

Further regional breakdown is shown in Table 5. Regional classification of SSP was adopted in this study, which subdivides the world into 11 regions (see Table S3 for the list of countries). In 2005, 85% of the production is concentrated in Middle East and Noth Africa (MENA)(including all the Major Countries). Second largest region is Northen America, which requires caution. 409 $\times 10^6$ m^3 yr^{-1} of seawater desalination in this region is for AUSD of seven grid cells in southern California, USA. In particular, two grid cells including the suburbs of Palm Springsand El Centro contribued mainly. In reality, no seawater desalination was used in these regions as of 2005, and SDM failed to reproduce the reality for these cases. It does not necessarily mean SDM is totally unusable, however, indeed several desalination plants are under plan in sorrounding areas (e.g. the Carlsbad Desalination Plant in San Diego). In 2025, MENA is projected to keep producing the largest volume of seawater desalination. Some new regions appear in tha table, markedly Latin America and the Caribbean. The emergence is mainly due to the per person GDP of Mexico, Chile, and Peru exceeded the threshold of 14000 USD PPP $person^{-1}$ yr^{-1}. In 2055, per person GDP exceeds the threshold in two densely populated countries Egypt and Pakistan (SSP1 only), which caused marked increase in seawater desalination of MENA and Southern Asia (ibid). Again, interpretation of these results require caution. The AUSD in Egypt and Pakistan includes the grid cells where the Nile and Indus River flows. For these gridcells, although located in extremely dry conditions, it is likely that water is supplied from rivers. The assumption B may not valid for these grid cells, hence the estimation may be overestimated. For better projections, availability of water resources should be evaluated by grid cells. Such simulation would be inplemented when SDM is fully integrated into global hydrological models with detailed water use sub-models such as the H08 model (Hanasaki et al., 2008a,b). The emergence of desalination is SSP dependent. For example, per person GDP of SSP1 grows faster than other scenarios, which explains why South Asia appears only in SSP1 and not in others.

The economic cost of seawater desalination was estimated for each case (Table 4 for globe, Tables S4 and S5 for regions). 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 $2,767\times 10^6 m^3 yr^{-1}$ with a cost of 1,107–10,458 10^6 USD, equivalent to 0.002%–0.019% of total global GDP. This number is much higher in the Middle East and North Africa (MENA), with values of 0.032%–0.302%. Among the scenarios, SSP3 in 2055 showed the highest numbers at 0.010%–0.098% globally and 0.120%–1.136% for MENA. This was mainly attributable to large water use and low GDP growth in SSP3.

The future projection is sensitive to Condition A (threshold of 14,000 USD PPP $person^{-1}$ yr^{-1}) and Condition B (aridity index of 0.075). Here, we conducted a sensitivity test on these thresholds. We examined thresholds of 0, 7,000, and 24,000 USD PPP $person^{-1}$ yr^{-1} for Condition A. A threshold of 7,000 USD PPP $person^{-1}$ yr^{-1} 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 PPP person^{-1} yr^{-1} was taken from the per person GDP of Israel, one of the non-oil-producing nations in Table 2. Present Condition A was taken from the per person 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 7. First, a higher threshold of per person GDP decreases the total desalination production due to reduction in AUSD. For the base year (2005), there is a gap between 0 and 7,000 USD PPP person^{-1} yr^{-1}. In contrast, there is no change in SSP1 between 0 and 14,000 USD PPP person^{-1} yr^{-1}, as per person 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 person GDP of 24,000 by 2055 (i.e., the growth in per person 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 7) 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 2.8 km^{3}yr^{-1} for these two purposes, accounting for 0.24% of the total. As shown in Table 1, 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 more than double and reach 2831 km^3 yr^{-1}. The estimated seawater desalination production levels are 18.5 and 47.9 km^3 yr^{-1} for these scenarios, accounting for 1.6% and 1.7% 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 11.7 million in 2005, but by 2055, is expected to increase to 147 in SSP1and 173 million in SSP3. The substantial increase in number is mainly attributed that AUSD spreads into densely populated northern Africa and a part of South Asia. 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. Indeed the estimated geographical extensions of present and future AUSD largely overlap with the regions where water resources are projected to decrease due to climate change typically in the Mediterranean (Jiménez Cisneros et al., 2014).

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. 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 rivers, 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. 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. Water use projections substantially differ among models and a systematic model inter-comparison is under way (Wada et al. 2016).

Finally, the limitations due to preconditions of SDM are summarized. First, SDM was designed to be incorporated into 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, 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. Third, partly in the consequence of the previous item, SDM is not able to analyze the effect of technology advances and subsequent cost reductions on the introduction of new desalination plants to regions with wetter climate and lower income. The results of sensitivity test of changing the threshold of Condition A (minimum per person GDP; Figure 7) and Condition B (maximum AI) provided us with some insights, but further investigations are needed for combined effect. Fourth, the availability of alternative water resources cannot be estimated by stand-alone SDM. Such analyses could be achievable if we combine SDM with the global hydrological model that explicitly simulate renewable/fossil groundwater. Fifth, overall, the performance of SDM largely owe to data availability. In this study, we mainly used the datasets that covers the globe (DesalData and AQUASTAT), and reports published by academic and governmental institutions written in English. Reports published by private sectors, written in local languages were not collected due to limitation of capability and resources. International collaboration would be needed for further systematic data collection.

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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Table 1. Global future scenarios in 2055 (extracted from Hanasaki et al., 2013a, b)

Item	2005	2025			2055		
		SSP1	SSP2	SSP3	SSP1	SSP2	SSP3
Radiative forcing	-	RCP2.6	RCP4.5	RCP6.0	RCP2.6	RCP4.5	RCP6.0
Global mean temperature rise [K]	0	1.7	1.5	1.4	2.4	2.9	2.9
Population [10^9person]	6.5	7.4	7.8	7.9	8.5	9.3	10.3
GDP [10^{12}USD]	56	88	84	79	319	255	186
Municipal water withdrawal [km^3/yr]	446	544	599	632	622	823	936
Industrial water withdrawal [km^3/yr]	724	853	1169	1436	520	1437	1895

Table 2. The major countries producing desalinated seawater in 2005.

	Country	GDP|PPP per person (SSP DB) [2005 USD person^{-1} yr^{-1}]	Water withdrawal (AQUASTAT) [10^6m^3 yr^{-1}]		Desalinated water production (AQUASTAT) [10^6m^3 yr^{-1}]		Desalination water plant capacity (DesalData) [10^6m^3 yr^{-1}]				Production to capacity ratio (A/B) [%]	Desalinated water production (simulated) [10^6m^3 yr^{-1}]			Desalination water plant capacity (simulated) [10^6m^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	858–2,287
2	Saudi Arabia	20,406	2,130	710	1,033	(2006)	1249	129	0	1,378	70	617	206	822	1028–2740
3	Kuwait	48,783	448	23	420	(2002)	448	0	0	448	94	448	23	472	590–1573
4	Spain	27,379	5,790	6,698	100	(2005)	280	0	35[1)]	315		0	0	0	0
5	Qatar	69,512	174	8	180	(2005)	171	0	0	171	105[4)]	174	8	182	228–607
6	Libya	14,015	610	132	NA[2)]	NA[2)]	104	37	0	142		26	6	32	40–107
7	Bahrain	28,068	178	20	102	(2003)	113	24	0	137	74	NA[3)]	NA[3)]	NA[3)]	NA
8	Israel	24,543	712	113	140	(2007)	135	0	0	135		10	2	12	15–40
9	Oman	21,047	134	19	109	(2006)	95	4	0	99	110	128	18	146	183–487
	Others						453	320	0	773		98	317	415	519–1,383
	Total				3034		4,809	561	35	5,405		2,020	649	2,767	3,459-9,223

1) Used for irrigation.

2) Data only available for 1998 and earlier.

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

4) MDPS (2016) reports that desalination capacity and production in Qatar in 2012 are 1.42 ×10^6m^3 day^{-1}and 1.20 ×10^6m^3 day^{-1}respectively, consequently, the production to capacity ratio is 85% for this reference.

Table 3 Major cities that use desalinated water

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 4 Projected future production of desalinated water

	Period	Domain	Desalination production from seawater [$\times 10^6$ m^3 yr^{-1}]	Installed capacity for seawater [$\times 10^6$ m^3 yr^{-1}]	Installed capacity for all sources [$\times 10^6$ m^3 yr^{-1}]	Production cost [$\times 10^6$ USD]	Production cost to GDP [%]
Historical							
This study	2005	Globe	2,767	3,459-9,223 1)	–	1,107-10,458	0.002-0.019
AQUASTAT	2003 – 2007	Globe	5,405 (2)	–	–	–	
DesalData	2005	Globe	–	6,100	–	–	
Bremere et al. (2001)	2000	10 countries (3)	–	1,680 (4)	2660	–	
Lattemann et al. (2010)	2006	Globe	–	10,200	16,100	–	
Future (near term)							
This study (SSP1)	2025	Globe	3,669	4,586-12,230	–	1,468-13,868	0.001-0.011
This study (SSP2)	2025	Globe	4,884	6,105-16,280	–	1,953-18,460	0.002-0.019
This study (SSP3)	2025	Globe	5,847	7,309-19490	–	2,339-22,102	0.002-0.022
Bremere et al. (2001)	2025	10 countries (3)	–	5,080 (4)	8,070	–	
Lattemann et al. (2010)	2015	Globe	–	22,500 (4)	35,800	–	
Future (long term)							
This study (SSP1)	2055	Globe	18,452	23,065-61,507	–	7,381-69,750	0.002-0.022
This study (SSP2)	2055	Globe	39,851	49,814-132,837	–	15,940-150,636	0.006-0.060
This study (SSP3)	2055	Globe	47,930	59,913-159,767	–	19,172-181,176	0.010-0.098

(1) Assuming a rate of operation of 30%–80%.

(2) From all water 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).

Table 5 Production of desalinated water by regions [10^6 m^3 yr^{-1}]. See Table S3 for the classification of countries.

Region	2005	2025			2055		
		SSP1	SSP2	SSP3	SSP1	SSP2	SSP3
Sub-Saharan Africa	0	3	5	6	147	88	57
Centrally Planned Asia and China	0	0	0	0	0	0	0
Central and Eastern Europe	0	0	0	0	0	0	0
Former Soviet Union	0	9	11	28	10	31	40
Latin America and the Caribbean	0	1,072	1,395	1,654	953	1,763	2,730
Middle East and North Africa	2,352	2,422	3,284	3,576	15,131	37,336	44,449
North America	409	156	186	579	311	632	647
Pacific OECD	6	7	2	6	3	1	7
Other Pacific Asia	0	0	0	0	0	0	0
South Asia	0	0	0	0	1,898	0	0
Western Europe	0	0	0	0	0	0	0
World	2,767	3,669	4,884	5,847	18,452	39,851	47,930

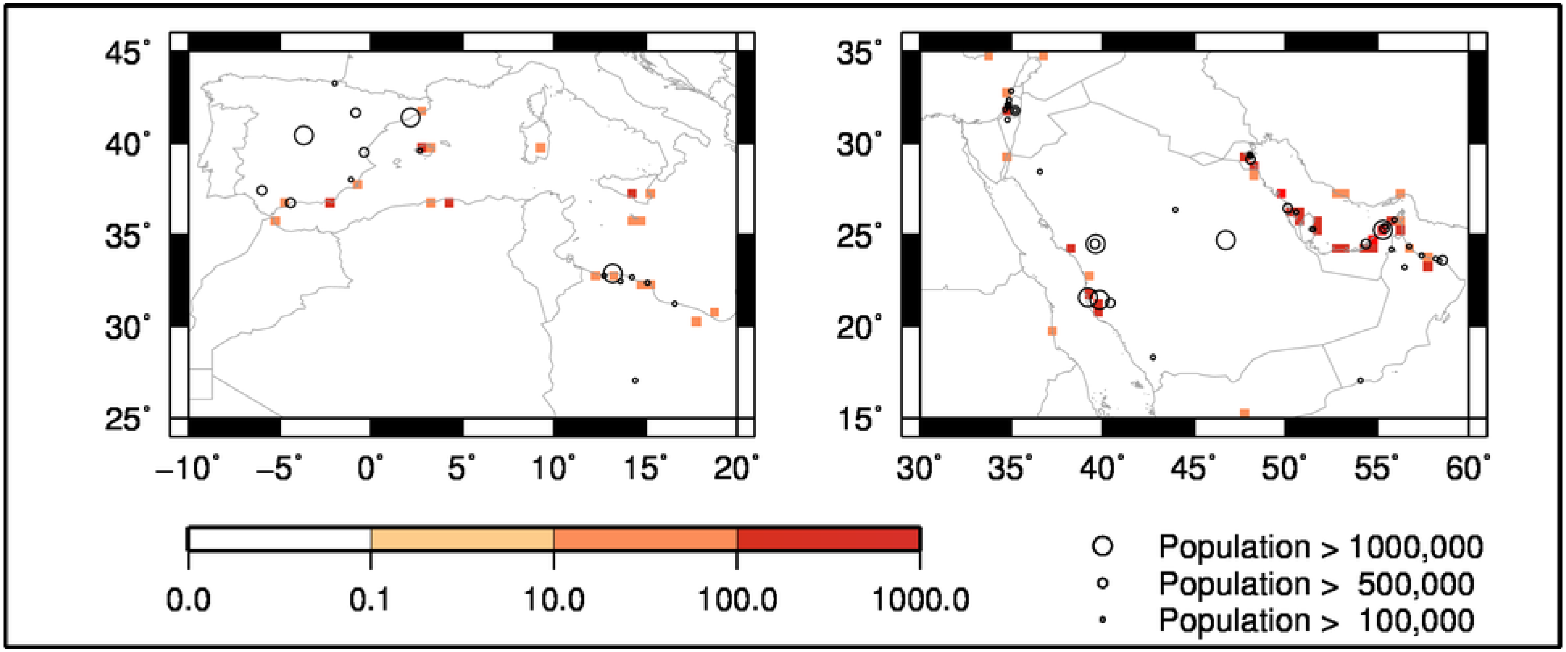

Figure 1 Actual locations of major desalination plants in the Mediterranean and Middle East in 2005. Boxes and circles represent plants (in 1000 m^3 day^{-1} of capacity; DesalData) and major cities (GeoNames), respectively.

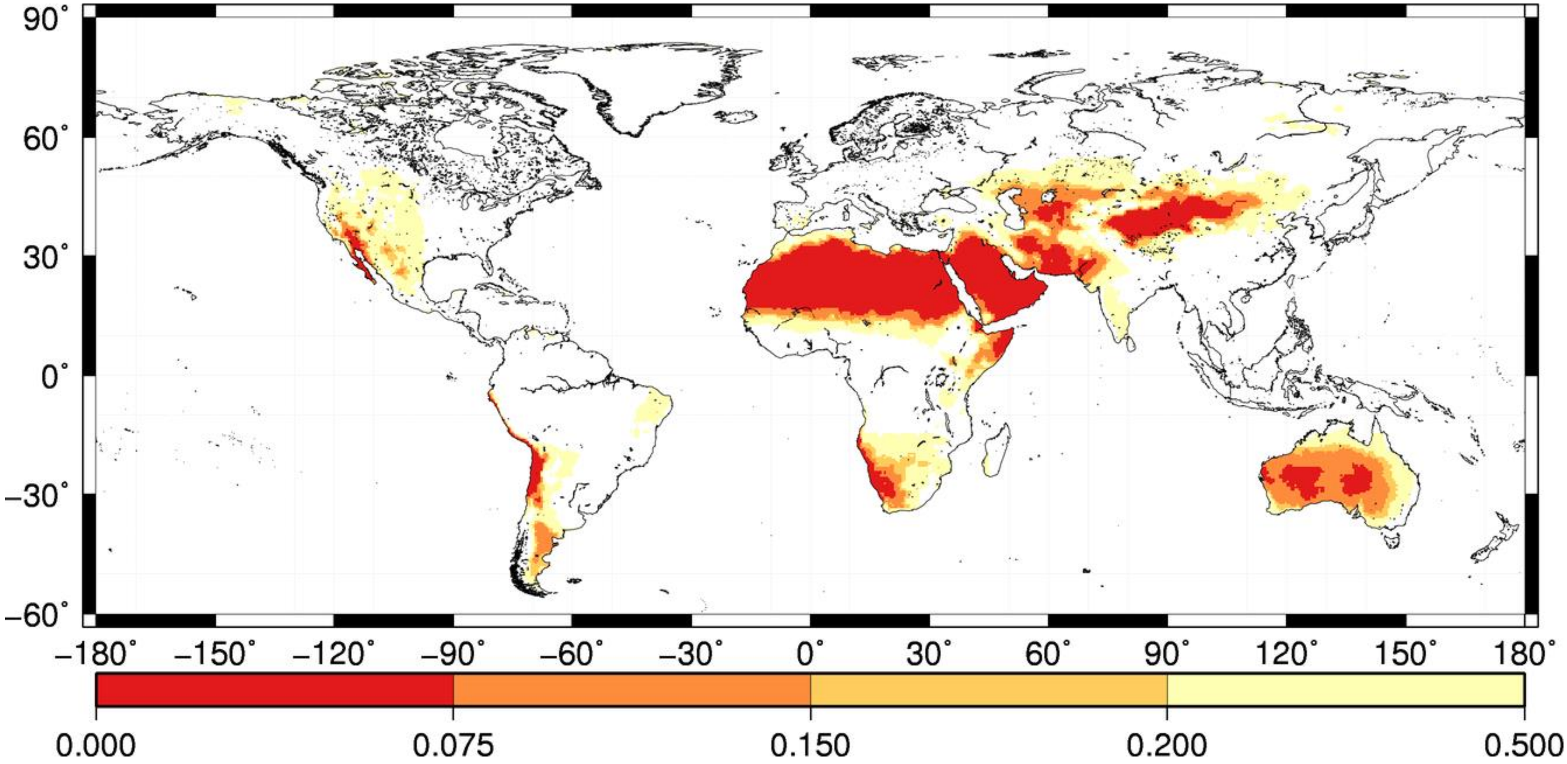

Figure 2. Simulated aridity index under the present climate (ratio of precipitation to potential evapotranspiration).

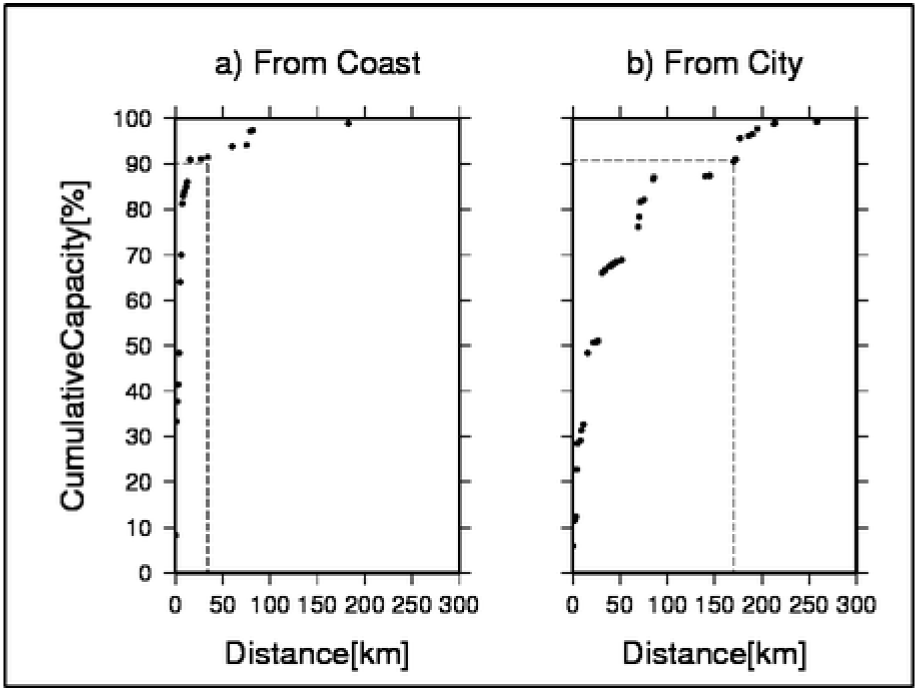

Figure 3 Cumulative capacity of desalination water and the distance of plants from the coastline (a) and major cities (b). The broken line shows the 90th percentile.

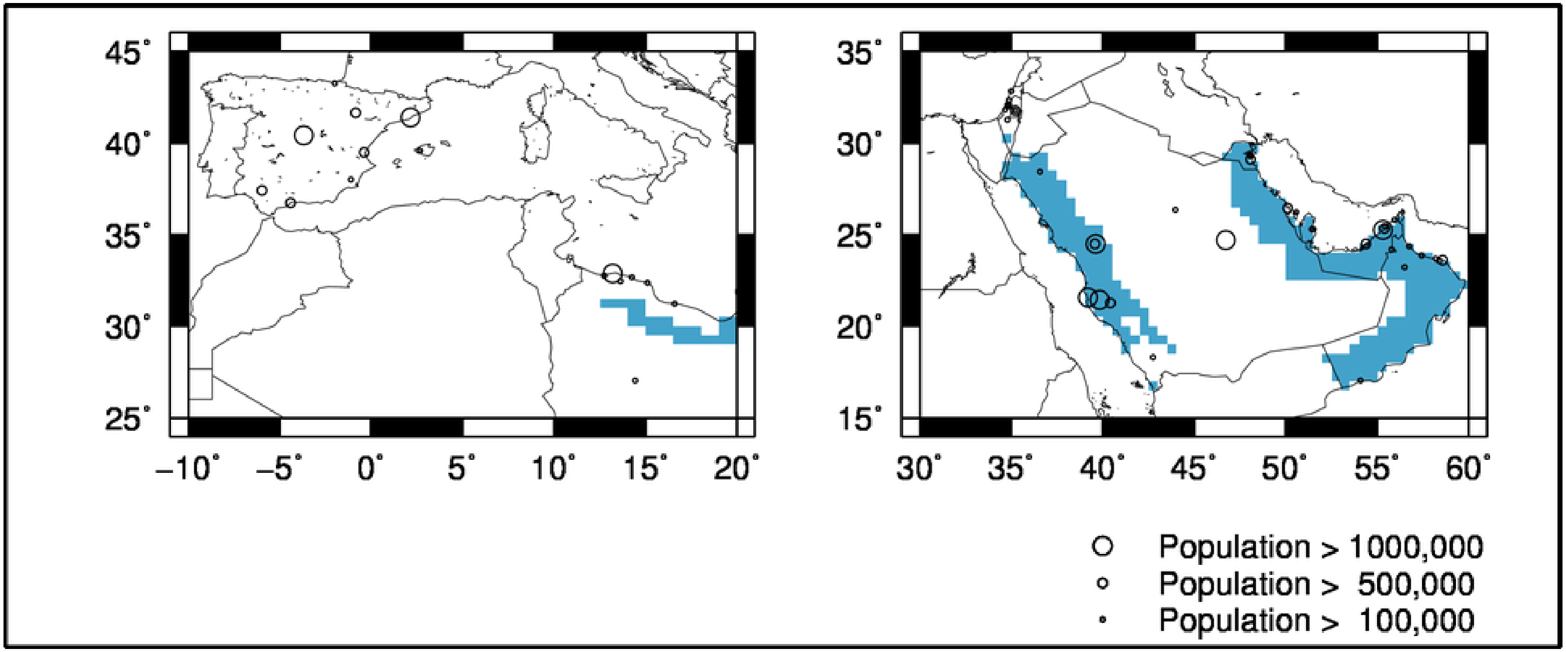

Figure 4 Simulated distribution of area utilizing seawater desalination (AUSD) in the Mediterranean and Middle East in 2005. Circles represent major cities (GeoNames).

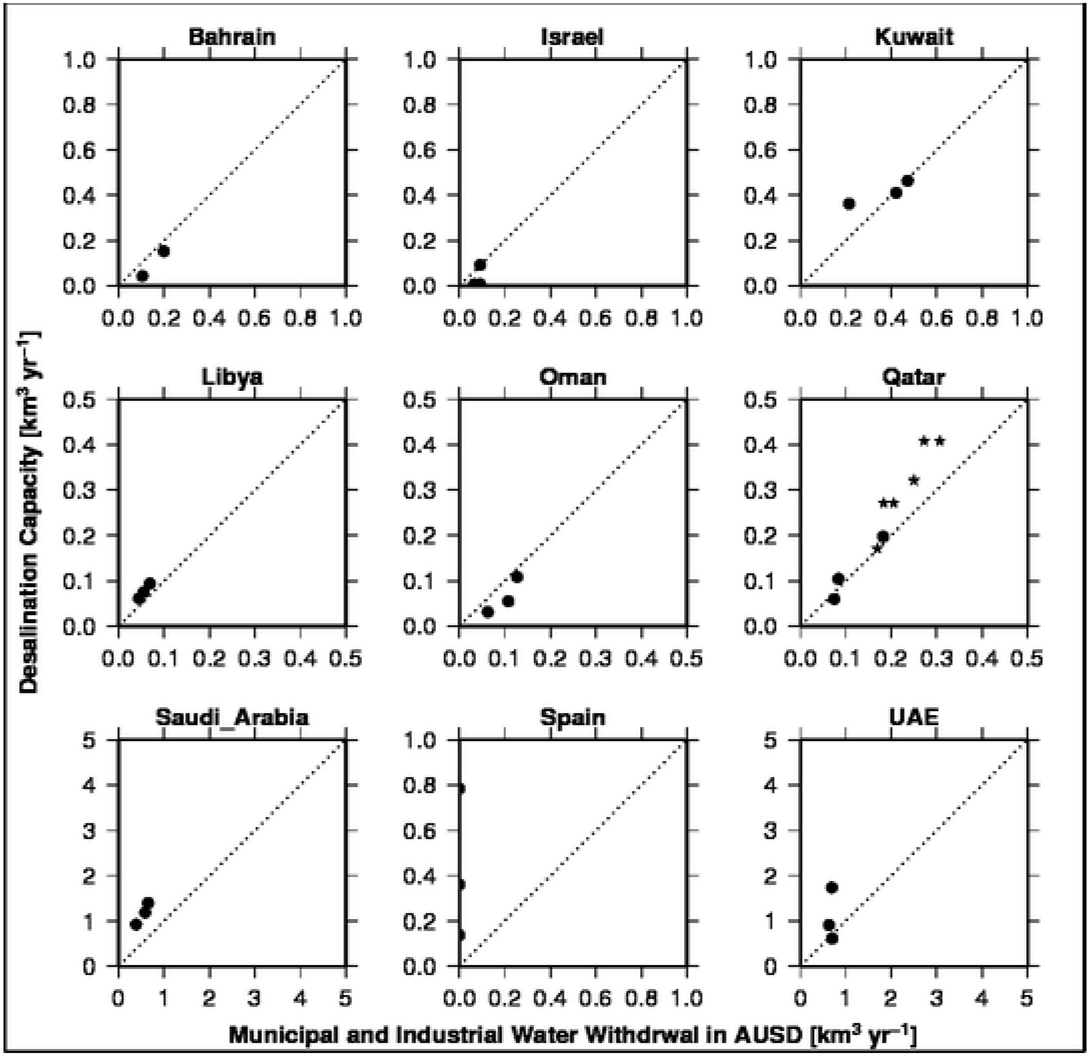

Figure 5 Comparison between national desalination capacity and municipal and industrial water withdrawal in AUSD. Each plot indicates one specific year. The shape of symbols indicate the data source of municipal and industrial water withdrawal in AUSD: circles for AQUASTAT and stars for MDPS (2016).

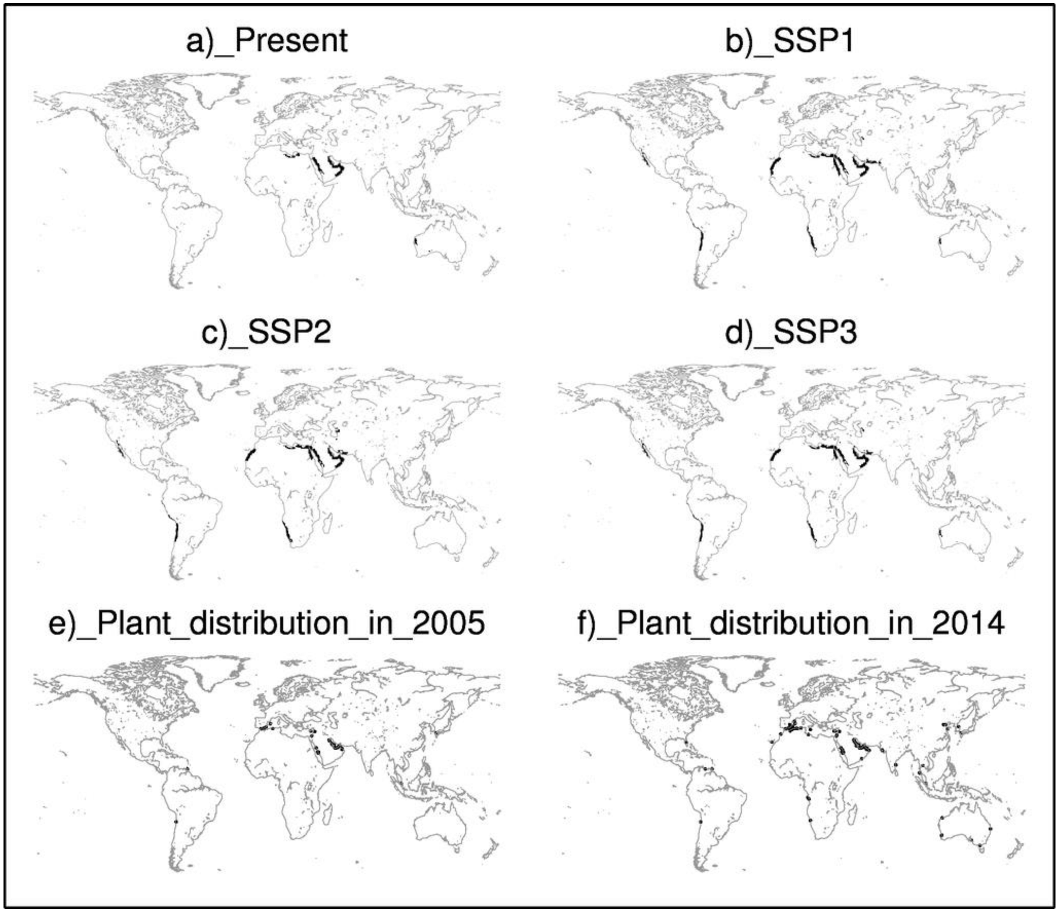

Figure 6 Global distributions of area utilizing seawater desalination (AUSD) in (a) 2005, (b) SSP1 in 2055, (c) SSP2 in 2055, and (d) SSP3 in 2055. Locations of seawater desalination plants (only larger than 50,000 m^3 day^{-1} in capacity) in (e) 2005 and (f) 2014.

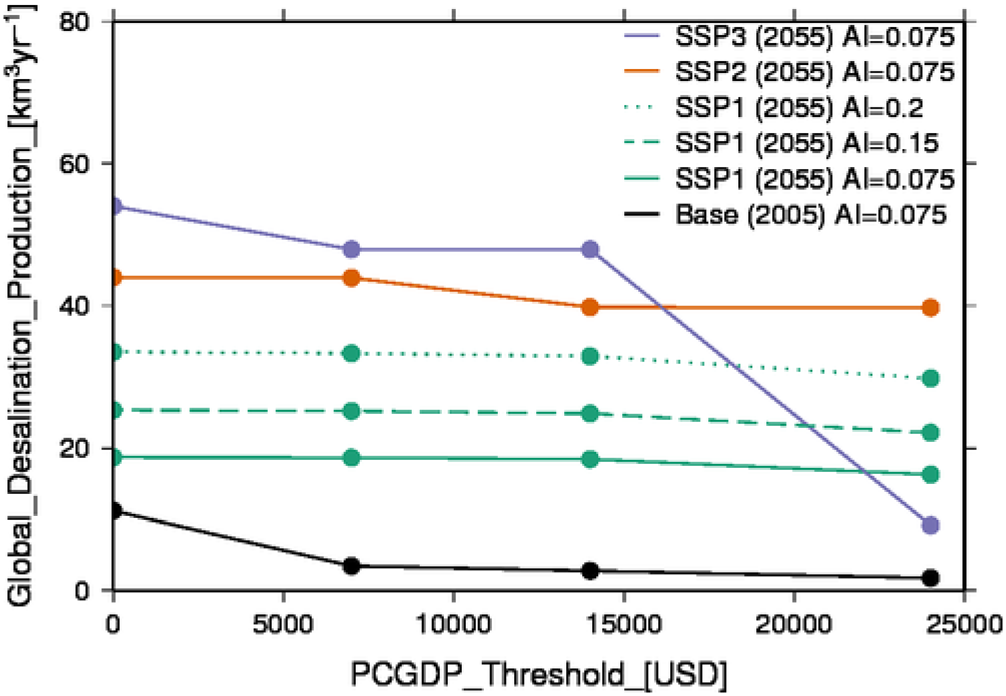

Figure 7 Sensitivity of per person GDP (PCGDP; Condition A) and the aridity index (AI, Condition B) with respect to global total production of seawater desalination. Black, blue, green, and red lines for base year (2005), SSP1, SSP2, and SSP3 in 2055, respectively. Solid, broken, and dotted lines for AI = 0.075, AI = 0.15, and AI = 0.2, respectively. The sensitivity of AI is only shown for SSP1 in 2055.