



Spatial assessment of site suitability for solar desalination plants: a case study of the coastal regions of Turkey

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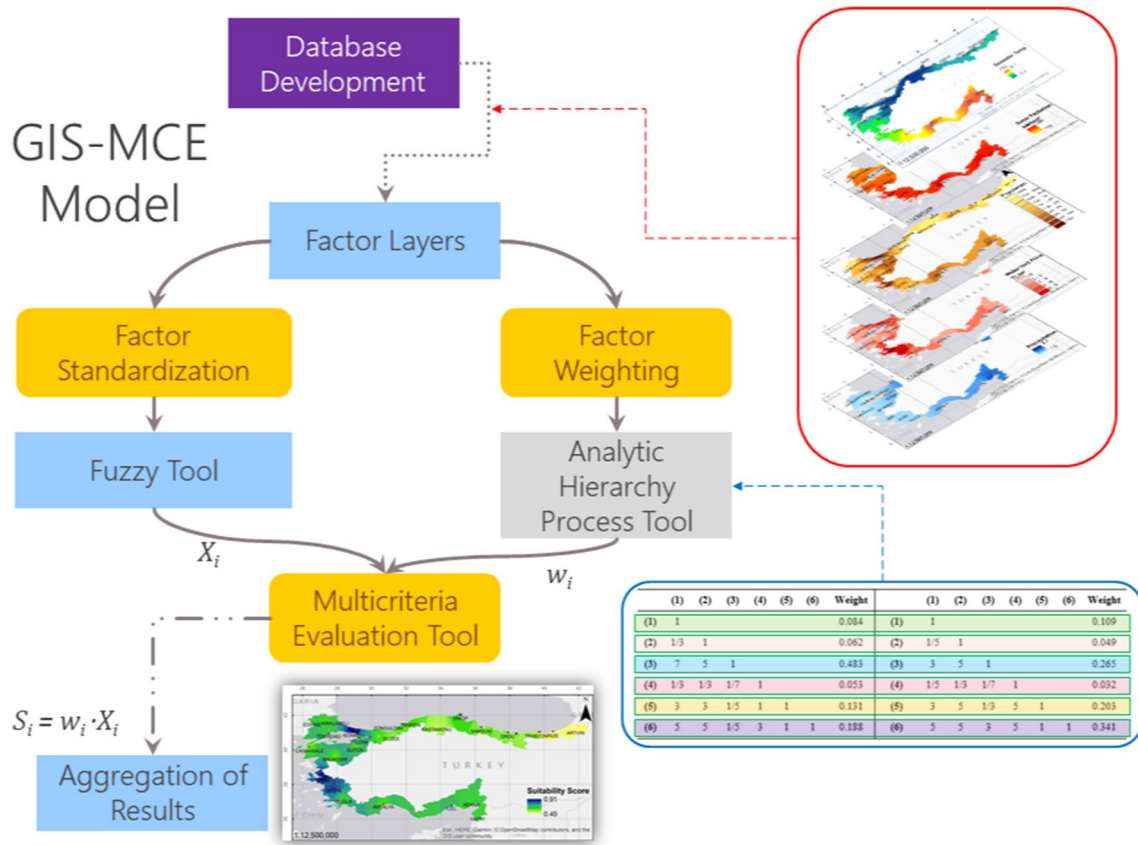
Abstract

Many countries, especially in arid and semiarid regions, suffer from water scarcity because of the decline in the existing freshwater reserves by consumption and pollution. Climate change also makes the problem even more difficult and costly. In order to resolve the increased water scarcity problem, seawater desalination powered by renewables such as solar and/or wind can be an opportunity to reduce future concerns of countries related to increased water demand. Site assessment for solar desalination plants is also essential in planning the establishment of these facilities, and many factors including environmental, economic, demographic, and climatic criteria should be taken into account. The study aims to develop a geographic information systems–multi-criteria evaluation (GIS-MCE) model divided into three sub-models including (1) fuzzy factor standardization, (2) analytic hierarchy process-based factor weighting, and (3) aggregation of sub-models in a logical manner. This study focuses on a model where environmental, demographic, and climatic factors are evaluated, but economic requirements, energy requirements, and uncertainties of desalination are not addressed. The developed GIS-MCE model assessed the site suitability of coastal regions of Turkey under the consideration of six criteria such as seawater temperature, seawater salinity, solar radiation, precipitation, population, and water unit price. As a result of the study, the most suitable sites for solar desalination were identified as İstanbul, İzmir, and Aydın in the Marmara and the Aegean regions, while the cities Artvin, Trabzon, and Rize in the Black Sea region have the lowest suitability.

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Graphic abstract



Keywords GIS · MCE · Renewable energy · Desalination · Water scarcity · Turkey

Introduction

Water scarcity today affects over 3 billion people on a global scale; nearly 2 billion people lack access to water, while 3.6 billion people live in potentially water-scarce areas (i.e., faced by water scarcity conditions at least 1 month of the year) (Bigas 2012; UNESCO 2015; WWAP/UN-Water 2018). Hence, a continuous supply of safe and reliable water is a leading issue in most of the urban areas, especially in arid and semiarid regions (Rosegrant et al. 2002; UN OCHA 2010). In urban water supply systems, the conventional short-term strategies to cope with water scarcity include long-distance water transport, the prevention of water losses and leakages or reduction of water use by public education and/or water reuse. The protection of water resources from point and non-point sources of pollution and enhancement of aquifers by artificial groundwater recharges are other preliminary strategies. In the long term, a potential solution is the utilization of alternative water supplies such as seawater and brackish

groundwater (Grubert et al. 2014). For this purpose, desalination designed to convert brackish or seawater to potable freshwater can be one of the promising methods to cope with water scarcity problems (Mahmoud et al. 2002; Ralay et al. 2004 Spang 2006; Salim 2011; Drouiche et al. 2011; Ghaffour et al. 2013; Dölgen et al. 2013; Salem 2013; Grubert et al. 2014; Ziolkowska 2015) and can fulfill some basic social requirements (Eltawil et al. 2009). Desalination has grown dramatically in the Middle East region (primarily Saudi Arabia, the United Arab Emirates and Kuwait), one of the most water-scarce regions of the world (Eltawil et al. 2009; Sharon and Reddy 2015). The process is also becoming an alternative method for water supply in North America, Asia, Europe, Africa (i.e., Oman) (Iglesias et al. 2007; Wheida and Verhoeven 2007; ESCWA 2009; Krysanova et al. 2010; IRENA 2012; Drouiche et al. 2011; Dölgen et al. 2013; Sharon and Reddy 2015) and Central America, South America and Australia to meet their freshwater demands (Sharon and Reddy 2015).

Depending on the technology for fresh water production, the most common desalination processes can be grouped

as operated by (1) electricity as vapor compression (VC), reverse osmosis (RO) for seawater (SWRO) or for brackish water (BWRO) in which the fresh water is separated from dissolved salts by semipermeable membranes and electro-dialysis (ED) and by (2) heat as multistage flash (MSF), multi-effect distillation (MED) in which feedwater is heated under pressure and the vapor is condensed as pure water (Ali et al. 2011; Sharon and Reddy 2015; Zarzo and Prats 2018). The total electricity consumption of these conventional desalination processes varies between ~ 1.5 kWh/m³ for BWRO to ~ 27.25 kWh/m³ for MSF (Al-Karaghoul and Kazmerski 2013). The energy source typically is fossil fuels (Eltawil et al. 2009) but could also be renewables. Since the use of fossil fuels for desalination is debatable and environmental pollution would be a major concern, researchers have been in search of the alternate way of powering desalination systems by renewable energy (Eltawil et al. 2009; Subramani et al. 2011; Sharon and Reddy 2015). Renewable energy (RE)-driven desalination processes including wind, solar thermal, photovoltaic (PV), and geothermal (Eltawil et al. 2009; Sharon and Reddy 2015) are also grouped into two categories as (1) distillation processes operated by RE-produced heat and (2) membrane and distillation processes operated by RE-produced electricity or mechanical energy (Eltawil et al. 2009). As that RO process represents more than 88% of membrane processes production (Garcia-Rodriguez 2003; Eltawil et al. 2009), and PV is an increasingly developing technology with decreasing cost, PV-powered desalination as PV-RO can be considered one of the most promising forms of RE-driven desalination (Al-Karaghoul et al. 2010), especially in arid and semiarid regions faced with water scarcity (Bouchekima 2003; Gastli et al. 2010). According to Spang (2006); Al-Karaghoul and Kazmerski (2011) and Yılmaz and Söylemez (2012), PV-powered desalination might break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability, and the focus of this study is PV-powered desalination (PV-RO) process.

Turkey, located mainly in a semiarid region, will face with drought and water shortages or scarcity problems. While Turkey has been considered as a water-rich country in previous decades with lower populations (e.g., 63 million in 2000), now the country is categorized as the “water-stressed” country with a rising population (80.8 million in 2017). The water availability per capita in Turkey, which decreased from 1652 m³/ca y for 2000 to 1490 m³/ca y for 2017, has been predicted to decrease up to 1000 m³/ca y for 2030 with the estimated population of 100 million (GDShw 2009). Global warming also triggers water scarcity. According to the country profile report of OECD published in 2013, the observed changes and trends are increasing in summer temperature and reduction of winter temperatures and winter precipitation between 2007 and 2013. The projected impacts

are also prominent as (1) increase in summer temperature across the country, (2) reduction of winter precipitation, (3) more frequent arid seasons, (4) loss of surface waters, and (5) reduction of up to 200 mm of snow water equivalent over the high plains for the period 2071–2100. These impacts may cause major changes in the stream flow of river basins, soil degradation, and an increase in frequency and intensity of floods, all of which threat directly the freshwater resources (OECD 2013). Therefore, the use of desalinated water, as well as traditional water resources such as groundwater, rivers, and lakes, is necessary to prevent future water shortage problems in the country. In Turkey, one of the developing countries, problems relating to the use of fossil fuels for desalination should be resolved by taking account of the possible utilization of solar energy. High solar energy potential due to its geographic location (Uyan 2013) and the water-energy targets for 2023 development plans make Turkey perfect natural region for solar desalination plants (Uyan 2017).

Site assessment for solar desalination plants is one of the multi-criteria problems (Temiz and Tecim 2009; Perpina et al. 2013) as well as the site selection for hazardous wastes (Yesilnacar and Cetin 2005), healthcare facilities (Dell’Ovo et al. 2018), offshore renewable energy platforms (Cradden et al. 2016), aquaculture (FAO 1987), solid waste management (Sarptas et al. 2005), solar power plants (Akkas et al. 2017; Uyan 2017; Charabi and Gastli 2011), and dairy housing systems (Gay 2009). MCE-GIS methods are also increasingly useful for studies of site assessment relating to solar desalination plants. Grubert et al. (2014) developed GIS-MCE model with a quantitative *global* analysis that determines favorable sites for solar energy-based seawater reverse osmosis desalination (SWRO) under the consideration of specific criteria. Spatial data about solar radiation, seawater salinity, and seawater temperature were integrated and mapped with water stress, prevailing water unit prices, and population to determine regions where solar energy-based SWRO has the highest suitability. The study includes water-stressed tropical and subtropical cities that highlight the highest suitability for economically sustainable solar energy-based SWRO. Salim (2011) used GIS tools to select suitable sites in *Egypt* for groundwater solar desalination. Solar radiation, aquifer depth, aquifer salinity, distance from the Delta and the Nile Valley, the incidence of flash floods, dunes, rock faults, and seawater intrusion in the North Delta were taken into consideration as the criteria for the spatial analysis. A specific weight is given to each criterion according to its relative influence on the process of decision making. The results of the study show that groundwater solar desalination has a high potential in remote regions on the North-Western Coast, on the North Sinai Coast, and at the Southern Oasis. Gastli et al. (2010) assessed the suitable sites for the seawater desalination plants combined with

concentrated solar electric power by MCE-GIS method. The criteria of solar radiation, land slope, the proximity of seawater, and availability of sufficient land area were considered, and topography data (*digital elevation model*—DEM) were used to derivate these factors in ArcGIS software. The developed MCE-GIS model was applied to assess the land suitability of the study area *Duqum, Oman*, for combined concentrated solar power (CSP) and seawater desalination plants.

Turkey is one of the most populous developing countries. Just like the other countries, water is fundamental to economic survival like communication and transportation, with energy as the common denominator in the country. Desalination makes sense for mitigation of increasing water scarcity and sustainable life for the people. Hence, the present study was carried out with the following objectives:

- To apply an existing decision-making approach to Turkey's increasing water scarcity problem by using fundamental criteria affecting solar desalination site suitability in the country.
- To assess the suitability for coastal cities, where solar desalination is a priority or not to mitigate estimated water shortages and scarcity.

This study aims to develop GIS-MCE model divided into three sub-models including (1) fuzzy factor standardization, (2) AHP factor weighting, and (3) aggregation of sub-models into a logical manner. This study focuses on a model where environmental, demographic, and climatic factors are evaluated, but economic requirements, energy requirements,

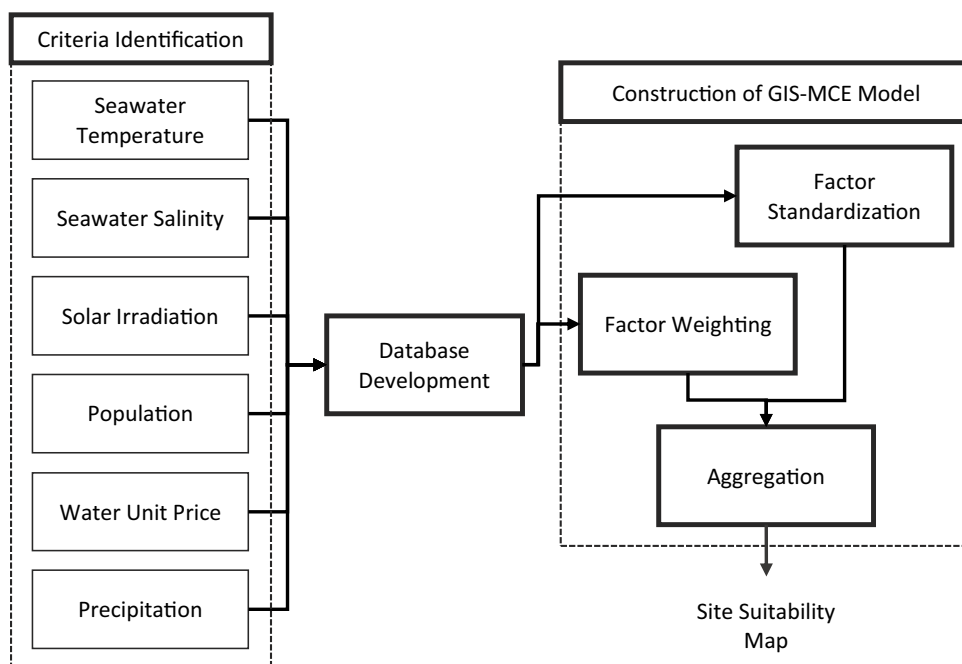
and uncertainties of desalination are not addressed. The solar desalination site suitability for *coastal regions of Turkey* was assessed for only technical purpose to support engineering works by the developed GIS-MCE model in which six criteria are considered.

Methodology

In this study, the concept of suitability assessment for solar desalination plants is demonstrated in Fig. 1. Here, the methodology is organized as follows:

1. *Identification of the multiple appropriate decision criteria* The important and effective factors in the suitability assessment for solar desalination plants were revealed based on the related literature (Alatiqi et al. 1999; Dore 2005; Tortajada 2006; Qiblawey and Banat 2008; Eltawil et al. 2009; GWI 2010; FAO 2012; Ouda 2013; 2014; Grubert et al. 2014; Rackam 2016; Aydin and Sarptas 2016).
2. *Spatial database development* The spatial data, that are required to analyze these factors, were also compiled from different databases (TSI 2015; Lancelot CMCC 2015; MODIS 2015; JRC 2015).
3. *Construction of the GIS-MCE model*
 - Factor standardization by the fuzzy tool (in Sect. 2.4.1),
 - Factor weighting by AHP tool (in Sect. 2.4.2) and

Fig. 1 The diagram of the applied methodology



- Aggregation of results in MCE tool (in Sects. 2.4.3 and 3.1).

Study area

The study area lies between the geographic coordinates from 36° to 42° N latitude and 26° to 43° E longitude, where it includes the coastal cities of Turkey as shown in Fig. 2.

The study area constitutes 54.69% of the country population and 28.35% of the country area, as shown in Fig. 3 in detail. The most populous city of the study area is İstanbul in the Marmara region constituting 18.5% of the country population with approximately 14 million inhabitants, while the less populous city is Artvin in the Black Sea region constituting 0.22% of the country population with 169,000 inhabitants.

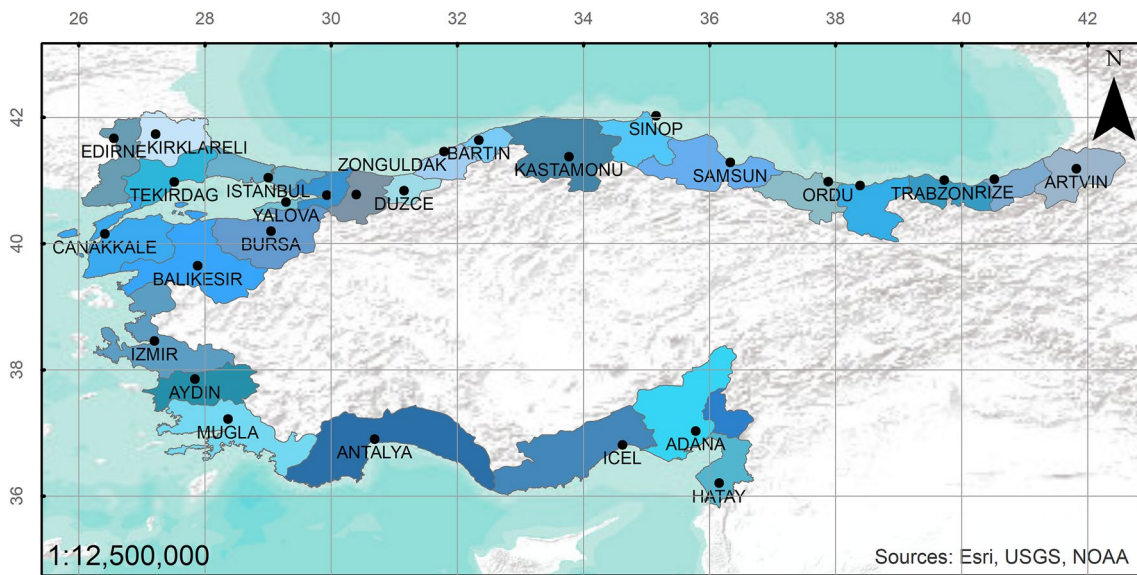
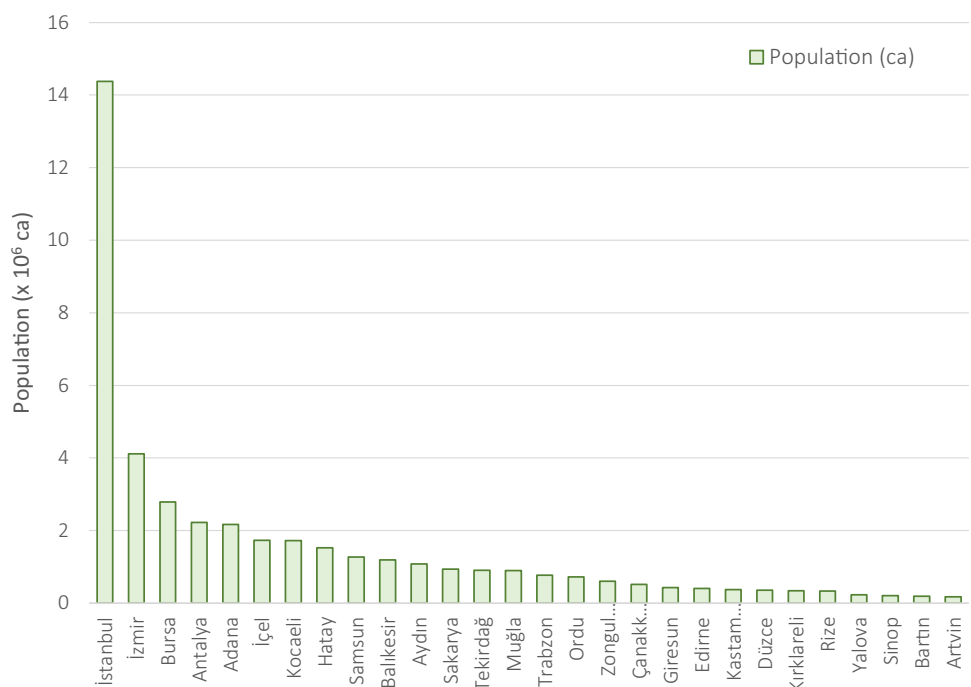


Fig. 2 Study area

Fig. 3 The population of the coastal cities in Turkey



In the study, the coastal cities are located in the Black Sea, Mediterranean, Aegean, and Marmara regions. These regions have differences relating to both climate-precipitation pattern and the river volume potential. For example, the Black Sea region dominated by temperate oceanic climate with warm–wet winters and warm–humid summers just as the Marmara region, while the Mediterranean region has the climate pattern, where the summers are hot and arid, winters are warm and rainy as well as the Aegean region (Weather Online 2018).

The precipitation patterns of these regions are different. The coastal sites of the Black Sea region receive precipitation throughout the year averages 1114.3 mm, and thus, the region is known as the wettest place by annual rainfall in Turkey (Weather Online 2018). The annual rainfall averages 858 mm in the Mediterranean region, while it averages 828 mm in the Aegean region. (Kottek et al. 2006).

Identification of the criteria

Site assessment for solar desalination plants is also essential in planning the establishment of these facilities (Sanver and May 2010), and numerous factors including environmental, economic, demographic, and climatic criteria should be taken into account (Sephehr et al. 2017). This assessment involves geographically defined alternatives by the evaluation of multiple appropriate decision criteria. Although many parameters can be considered for site suitability assessment for solar desalination plants, in the study, the fundamental criteria were considered as the result of examined previous studies. So, these criteria were used to assess the site suitability for solar desalination plants.

Seawater temperature In desalination processes, high seawater temperatures as a process parameter for desalination plant are considered advantageous (especially seawater average temperature is higher than 25 °C) for several desalination methods such as seawater reverse osmosis desalination (SWRO) in terms of decreasing the operating cost of desalination systems (Grubert et al. 2014).

Solar radiation Higher radiation levels increase the energy potential and can be considered favorable for solar desalination systems (Qiblawey and Banat 2008; Grubert et al. 2014). Countries which are located in high solar insolation band and the high solar potential can be exploited to convert seawater to freshwater (Eltawil et al. 2009).

Seawater salinity This criterion can be evaluated as a process parameter just as seawater temperature because salinity levels of feed water are one of the most significant factors that have the largest effect on the cost of desalination (Alatqi et al. 1999; Dore 2005; Eltawil et al. 2009). Here, low seawater salinity is evaluated so suitably because low salinity causes a lower-energy requirement for SWRO and lower osmotic pressure difference between feedwater

and produced water. According to GWI (2010) and Grubert et al. (2014), the ocean salinity ranges from 5 to 40 practical salinity units (psu), with average as about 35 psu. Below this average value, the water salinity can be considered suitable for desalination; however, higher salinity values cause an increase in the osmotic pressure difference.

Population Population and its growth rate affect demand for services associated with water and changes in consumption forms of water, directly (FAO 2012). The demand for water will also grow to meet the needs of the growing population. However, growth in demand for water is higher than population growth. For example, in the last century, the world population has tripled, while the demand for water resources has increased sevenfold (WWF 2014). As a demographic parameter, population is so crucial as the indicator of water demand. Growing population causes hydric stress as overuse of freshwater resources (Rackam 2016) as a result of a steady increase in the living standards (Eltawil et al. 2009).

Water unit price In urban water supply systems, the unit prices of potable water become higher in cities where water can be produced and supplied in a difficult and costly manner (i.e., distant water supply sources, higher treatment needs). So, the water unit price can be considered as an indicator of water shortage or scarcity. Desalination is a feasible water supply option in regions with higher water prices because the costs for desalinated water are still twice or three times higher than those from traditional water treatment systems. Consequently, the water unit price is a substantial water demand management tool (Ouda 2013) as an indicator of the economic feasibility of the desalination system.

Precipitation As the indicator of water stress, the areas in arid or semiarid regions, where the rainfall is limited or scarce, have water stress, significantly (Tortajada 2006; Aydın and Sarptas 2016). Where the precipitation is high, the water resources can reach a sufficient amount. For this reason, desalination plants should be ideal in places where drought is severe. Especially, the countries such as Turkey, where the rainfall patterns and regional water cycles are highly variable and sensitive to climate change (increasing drought) effects (Eltawil et al. 2009; Future Directions 2016), and rain-fed rivers are one of the main sources of freshwater (Republic of the Turkey Ministry of Foreign Affairs, 2018). So, the amount of precipitation is very important to evaluate the site suitability analysis for solar desalination.

Database development

In order to analyze which coastal cities of Turkey are suitable for solar desalination; various data were compiled from different databases in this study. Most of the databases used

Table 1 Data and data sources

Data name	Database	Data name	Database
Seawater temperature	(1) MODIS data of AQUA mission (MODIS 2015) (2) LANCELOT—web tool (CMCC) (Lancelot CMCC 2015)	Water Price	Municipal water tariffs (TSI 2015)
Seawater salinity	LANCELOT—web tool (CMCC) (Lancelot CMCC 2015)	Solar Radiation	JRC EC PVGIS interactive maps (JRC 2015)
Precipitation	LANCELOT—web tool (CMCC) (Lancelot CMCC 2015)	Map of Cities	Ministry of environment and urban planning
Population	Turkish Statistical Institute (TSI 2015)		

in the study are free and open access. The databases and obtained data are given in detail in Table 1.

Seawater temperature data were obtained from both NASA's AQUA/MODIS as sea surface temperature (SST) raster layer and LANCELOT–Web Tool (CMCC) to use in the GIS environment directly. This product has 1-km resolution collected by MODIS instruments involving Terra and Aqua satellites. However, the resolution of MODIS data was 1 km (low resolution for the study); therefore, the data of LANCELOT were used. Here, the temperature values obtained from LANCELOT (LANCELOT CMCC 2015) are integrated into the multi-criteria decision-making process of the study in a raster format by using IDW tool of ArcGIS.

The solar radiation, population, water unit price, precipitation, and seawater salinity data were attained as the numeric format from the associated databases in Table 1. The water unit price map was created with numeric data based on the individual using of settlements the amount of water above 20 m³, that is the maximum charging of municipalities, for each city. Solar radiation map was also generated as kWh/m² based on the numeric data of European Commission PV-GIS database (JRC 2015) as if the solar desalination may be carried out with grid-connected PV-farms. These numerical data were integrated into the IDW tool in the ArcGIS environment, and the density maps of these criteria were created in spatial base. The data used in the study are given in Fig. 4.

In Fig. 4, the salinity range of the seawater is between 18.5 and 38.9 psu in Turkey. The seawater temperature also varies between 13.5 and 20.7 °C. The seawater temperature decreases from the south to the north in the country. In the Mediterranean region, seawater temperature is higher than the Black Sea region. Population variation from one city to another is sufficiently large as seen in Fig. 4.

Construction of GIS-MCE model

MCE is one of the most important decision-making processes (Jansen and Rietveld 1990; Burrough et al. 1992; Jankowski 1995; Jiang and Eastman 2000). GIS also

improves the capability of MCE in the spatial base (Carver 1991; Pereira and Duckstein 1993; Jiang and Eastman 2000).

MCE is applied to decision problems with multiple, sometimes competing objectives, resulting in tradeoffs between potential solutions. The principle of the method is to divide the decision problems into smaller understandable parts, analyze each part separately, and then integrate the parts in a logical manner (Malczewski 1997; Nas et al. 2010). Integrating GIS and MCE is a powerful tool to consider site assessment applications because GIS provides efficient handling and presentation of the data, and MCE supplies consistent ranking of the potential sites (Sener et al. 2006; Nas et al. 2010) for solar desalination based on various criteria. Recent developments in GIS have led to significant improvements in its capability for decision-making processes in land suitability assessment and environmental management, among which MCE is one of the most important procedures (Jansen and Rietveld 1990; Burrough et al. 1992; Jankowski 1995; Jiang and Eastman 2000). According to Uyan (2017), the main idea of MCE is to evaluate the degree to which a project fulfills a set of performance criteria, while GIS is a digital database management system used to store, process, manage, spatially analysis, query, and present large volumes of spatially distributed data collected from various sources. Therefore, MCE methods that integrated GIS tools are increasingly used for support by decision makers in many areas, such as the planning processes.

Site assessment of solar desalination plants needed to consider numerous technical and economic factors can be evaluated by multi-criteria decision making. Solar desalination can be economically feasible and technically applicable only under certain conditions. Regions faced with water shortage or scarcity because of dense populations, lack of freshwater resources, higher unit water prices, and challenged severe climatic impacts are more attractive areas for desalination plants. Therefore, regional installation of desalination plants requires an investigation related to suitable locations to build the facility for freshwater service. GIS-MCE methods can be practical and upgradable and allow consideration of complex spatial layers and topographic influences associated with the selection of suitable

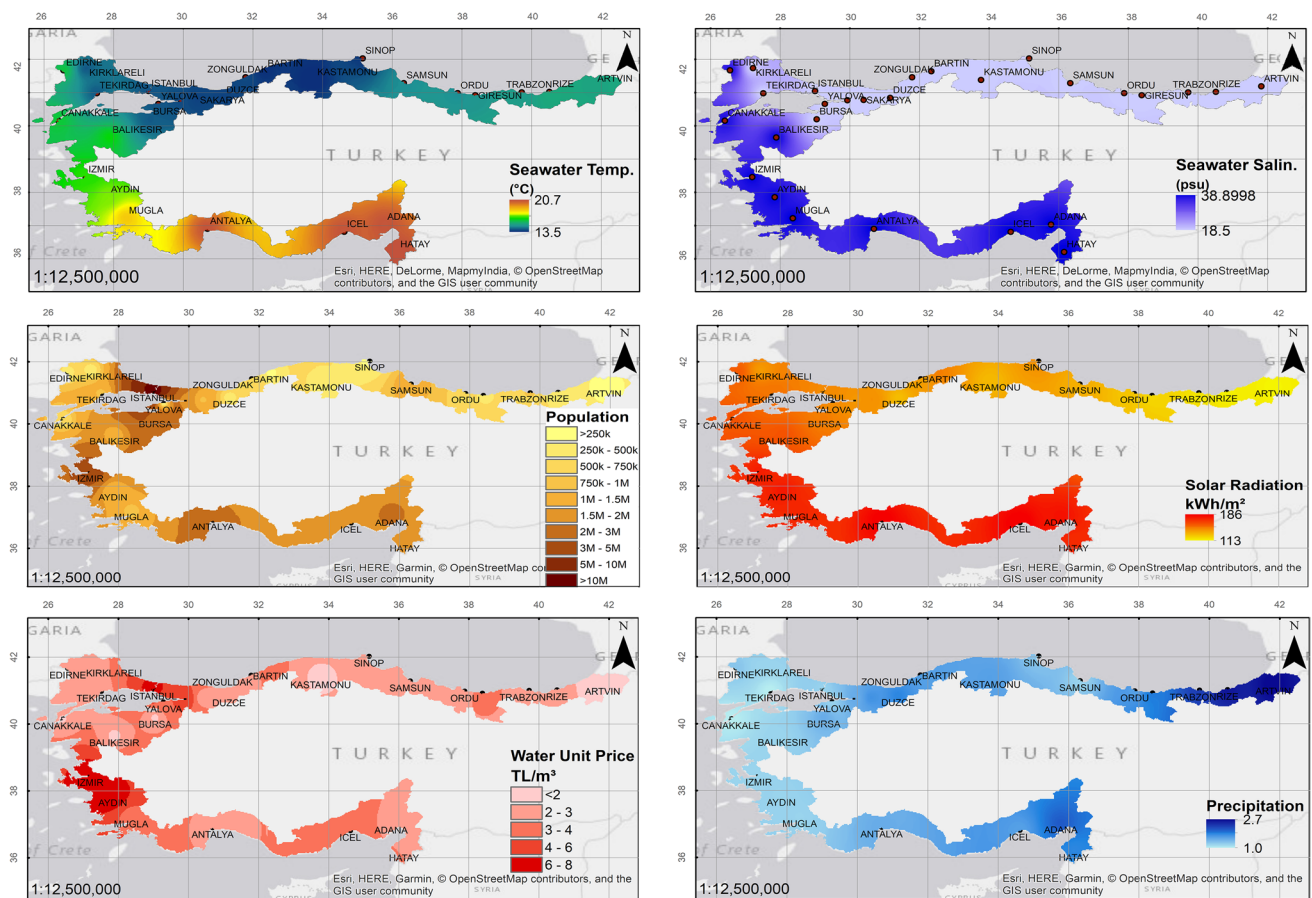


Fig. 4 The data used in the study

areas (Boggia et al. 2018) for desalination plants (Mahmoud et al. 2002; Sarptaş 2006; Uyan 2013; Aydın and Sarptaş 2014; Aydın 2015; Aydın and Sarptaş 2016).

Factor standardization such as Boolean overlay or fuzzy overlay and factor weighting such as AHP constitute the structure of the GIS-MCE model. Here, the factors are standardized to a common numeric range and then overlaid by weighted averaging (Jiang and Eastman 2000). The result of the GIS-MCE model is the site suitability mapping of the decision-making process.

Factor standardization

In GIS-MCE assessments, the factors constitute the base of the spatial analysis; however, they cannot always be commensurable to assess them (Kao 2010). So, factors must be standardized to be able to compare with each other (Kao 2010). Several methods such as Boolean approach and Fuzzy logic approach can be used to standardize the factors. Since multiple factors are considered to assess the degree of suitability in most decision-making methods, suitability is commonly not Boolean but expresses varying

degrees of set membership, i.e., a fuzzy set (Zadeh 1965; Jiang and Eastman 2000). Each factor chosen by the analyst constitutes a direct or indirect indication based on which fuzzy set membership (or suitability) of an area can be assessed. In fuzzy standardization approach, fuzzy sets signify the factors (mentioned above) whose elements or values have degrees of membership valued in the real unit interval [0,1] (Aydın and Sarptaş 2014, 2016). The latter is a special case of the fuzzy sets as 0–1 membership of the normalization (Jiang and Eastman 2000). In the GIS context, land allocation and suitability assessment studies are considered as a fuzzy concept expressed as the fuzzy set membership in decision making (Burrough et al. 1992; Hall et al. 1992; Jiang and Eastman 2000). The fuzzy logic is applied for decision-making methods because it provides a very strong logic for the process of standardization (Jiang and Eastman 2000) that is recasting values into a statement of set membership, the degree of membership in the final decision set. Since the fuzzy logic allows each value of the factor to be assigned in different conformations between zero and one, it bridges a major gap between Boolean evaluation and continuous scaling in

the weighted linear overlay (Malczewski and Rinner 2015; Güngöroğlu 2017). An example shown by Hardy (1994) can be mentioned that it is about the set of old people, where *old* is a vague term. One might say, according to Boolean evaluation, that 60 is the dividing point between old and young. So, people over this age are old, and those less than 60 are young. In the fuzzy approach, however, someone with 55 years of age might be assigned a value of 0.6 to the set of old people, meaning that they are somewhat old. A 90-year-old person, on the other hand, would be considered very old and hence be assigned a value of 1 for their degree of membership in the set.

In the study, the suitability intervals for factors were developed based on the information about desalination that we found in the literature review discussed in Sect. 2.2. The standardization of these factors was applied by fuzzy tool of TerrSet software with the consideration of the suitability intervals for factors identified in the range of 0–1 (Table 2) as increasingly suitable from 0 to 1; decreasingly suitable from 1 to 0; not suitable (0) and suitable (1) as recasting values that assigned the factors (Fig. 5). For example, the suitability increases from 0 to 1 with increasing seawater temperature, but the suitability decreases

from 1 to 0 with an increasing amount of rainfall, controversially (Table 2).

Factor weighting

In decision-making processes, each factor in site suitability assessment studies does not have the same importance. For example, an investor may give more importance to the cost factor than environmental pollution. Therefore, the factors should be evaluated according to relative priorities (weights) because the priorities of attained factors are measured concerning each other (Bhushan and Rai 2004; Mu and Pereyra-Rojas 2017). As a multi-criteria decision-making approach, the *analytical hierarchy process (AHP)* (Saaty 1987) is also one of the methods which uses a specific input format for decision makers to express their preferences regarding multiple criteria and alternatives, namely pairwise comparisons (Benítez et al. 2012; Aydın and Sarptaş 2014, 2016; Mu and Pereyra-Rojas 2017). This format may be not perfect, but it expresses user preferences reasonably well in many practical situations as site selection assessments, suitability analysis and regional planning studies (Ayalew et al. 2005; Yalçın 2008).

Table 2 Criteria and suitability intervals

Criteria	Suitability intervals			
Seawater temp. (°C)	0–21 = (0,1)	21–30 = (1,0)		> 30 = 0
Seawater salinity (psu)	0–30 = (0,1)	30 = 1	30–40 = (1,0)	> 40 = 0
Solar radiation (kWh/m ²)	0–150 = (0,1)	> 150 = 1		
Population (million)	0–15 = (0,1)	> 15 = 1		
Water unit price (TL)	0–8.03 = (0,1)	> 8.03 = 1		
Precipitation (mm/day)	0–2 = (1,0)	> 2 = 0		

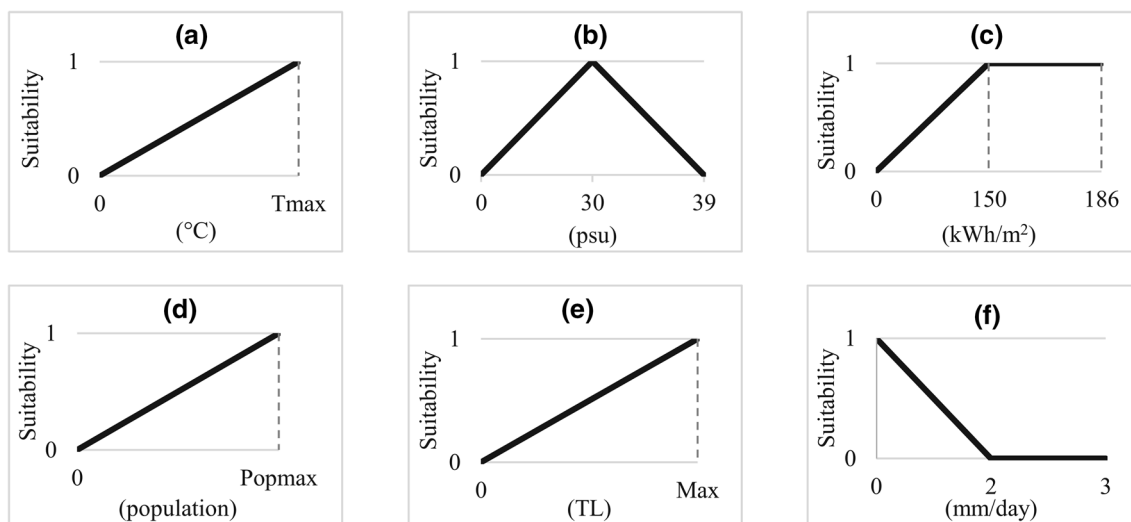


Fig. 5 Fuzzy graphs of **a** seawater temperature and **b** seawater salinity, **c** solar radiation, **d** population, **e** water unit price, and **f** precipitation

In this study, the criteria for site suitability assessment are qualitative and often can be represented only by a subjective judgment in a linguistic format. So, the AHP method was used (Saaty 1980, 1987), which is one of the decision-making methods such as ELECTRE and PROMETHEE (Konstantinos et al. 2019). According to Konstantinos et al. (2019), there are several advantages to use AHP in decision-making processes: This method is easier to use by the pairwise comparisons to weight criteria and compare alternatives. It is scalable to allow the insertion or removal of criteria. Additionally, the scenarios can be created easily by recalculation of weight coefficient. Also, the results of AHP can be combined with GIS to visualize the results from the decision-making analysis in the form of maps (Konstantinos et al. 2019). In this method, perceptions and judgments associated with the criteria were organized in a hierarchy and were compared in pairwise comparison matrices to determine the relative magnitudes of the criteria that influence decision results. AHP method was divided into two phases: (1) aggregation of individual preferences/weights in pairwise comparison matrices and (2) calculation of the collective preference/weights by the geometrical mean formula (Table 3) as given in Eq. 1:

$$\left(\prod_{i=1}^n x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 \cdot x_2 \cdot \dots \cdot x_n} \tag{1}$$

In Eq. 1, the values of x_1 , x_2 , and x_n are the priority weights of the factors. The result of this equation gives the collective weights of the factors, separately. In the AHP method, the pairwise comparison matrices were constructed with a rating of criterion against every other criterion by assigning a relative value between 1 and 1/9 to the intersecting cell (Table 3). The fundamental scale for pairwise comparison was defined as equal (1), moderate (3), strong

(5), very strong (7), and extreme (9) importance according to Goepel (2017). When the criterion on the vertical axis is more important than the criterion on the horizontal axis, the values vary between 1 and 1/9 (Yalçın 2008). The pairwise matrices were integrated into the AHP tool of TerrSet software to calculate priority weights. The collective weights were also estimated by the averaging of the priority weights through Eq. 1 (Table 3).

In Table 3, the survey mechanism providing opinions of two experts in environmental engineering are given by two pairwise comparison matrices. The experts have given the values (i.e., 1/3, 1/7, or 5) into the matrices, and the priority weights of factors were calculated by us for two sub-tables in the GIS environment. For example, seawater temperature factor (item 1) is considered moderately important (1/3) than precipitation (item 4) for expert 1 in the sub-table on the left, while it is considered strongly important (1/5) for expert 2 in the sub-table on the right. The other pairwise comparisons can be assessed in light of these sub-tables. The judgment of ranks was based on the opinions of the experts, and the collective (overall) weights were calculated by the average of the priority weights of two pairwise matrices by the geometrical mean formula. Results of the collective weights indicate that the solar radiation is in the first rank since it can be evaluated as energy input of solar desalination systems. The water unit price is in the second rank because it can be considered as an indicator of water shortage or scarcity, while precipitation is in the sixth rank that can be thought to be moderately significant for the technical assessment of site suitability for solar desalination.

Aggregation of results: performing of GIS-MCE model

In the study, the GIS-MCE model with standardized and weighted factors was performed by MCE tool in the TerrSet environment to generate the site suitability

Table 3 The pairwise comparison matrices, priority weights, and collective weights

Ex.1	(1)	(2)	(3)	(4)	(5)	(6)	PW	Ex.2	(1)	(2)	(3)	(4)	(5)	(6)	PW	CW
(1)	1						0.084	(1)	1						0.109	0.097
(2)	1/3	1					0.062	(2)	1/5	1					0.049	0.055
(3)	7	5	1				0.483	(3)	3	5	1				0.265	0.374
(4)	1/3	1/3	1/7	1			0.053	(4)	1/5	1/3	1/7	1			0.032	0.042
(5)	3	3	1/5	1	1		0.131	(5)	3	5	1/3	5	1		0.203	0.167
(6)	5	5	1/5	3	1	1	0.188	(6)	5	5	3	5	1	1	0.341	0.264

PW priority weights (for two matrices), *CW* collective weights (overall score)

- (1) Seawater temperature
- (2) Seawater salinity
- (3) Solar radiation
- (4) Precipitation
- (5) Population
- (6) Water unit price

map for solar desalination plants in the coastal cities of Turkey. In TerrSet, the weighted linear (WL) combination approach was used to obtain the result. According to Malczewski (2000), WL combination model is one of the most widely used GIS-based decision approaches. For land suitability and site selection analysis, this method is frequently used because of ease to implement the method within GIS environment using map algebra operations and cartographic modeling. There are two critical elements of WL combination: (1) the weights assigned to the factors and (2) the procedures for deriving commensurate input layers of factors (Malczewski 2000).

The weighted linear approach used in the study includes these two elements as follows:

Procedure: Fuzzy standardization (commensurate raster layers of factors) and

Weighting: AHP approach (collective weights for each factor).

WL combination method combines the commensurate factor layers and weights using the multiplication and addition overlay operations to obtain the overall score for each pixel (Malczewski 2000). Here, the pixel with the highest score is the best. For example, each pixel of fuzzy standardized raster layer of solar radiation was multiplied by the AHP result as 0.374. The water unit price was also multiplied by 0.264, while the population by 0.167. These multiplications are used in a composite ranking to have a result for the technical assessment of solar desalination site suitability.

Results and discussions

Result of the GIS-MCE model

As a result of the model implementation, the suitability map for solar desalination plants was generated with the suitability score between 0.91 (best suitable) and 0.45 (low suitable). The resulting map with the suitability scores of each

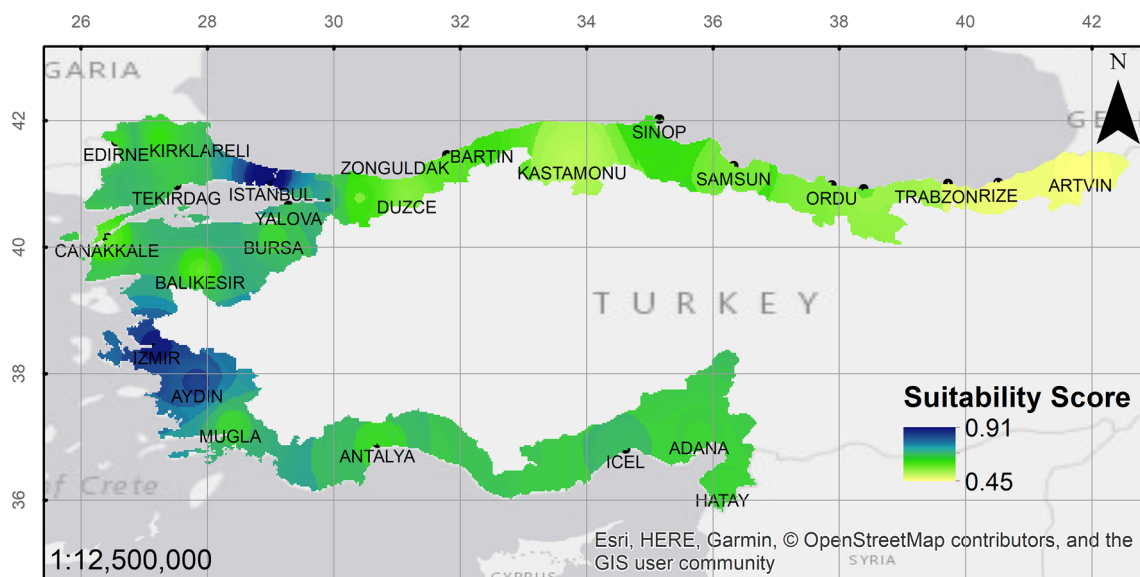


Fig. 6 Site suitability map for solar desalination plants in coastal cities

Table 4 The site suitability qualification of the cities

Suitability	Suitability Range	Area ($\times 10^3$ km ²)	% of the study area	Cities
Lowest	0.45–0.6	55	24.2	Trabzon, Rize, Ordu, Kastamonu, Giresun, Düzce, Artvin, Sinop, Samsun
Low	0.6–0.7	125	55.3	Zonguldak, Yalova, Tekirdağ, Sakarya, Kırklareli, İçel, Hatay, Edirne, Çanakkale, Bartın, Antalya, Adana
Moderate	0.7–0.8	35	15.5	Muğla, Bursa, Balıkesir, Kocaeli
High	0.8–0.9	10	4.6	İzmir, Aydın
Highest	0.9–1.0	1	0.5	İstanbul

city is shown in Fig. 6. Here, the suitability scale of the map is continuous; however, the cities are evaluated in several suitability classes as lowest (suitability score between 0.45 and 0.6), low (0.6–0.7), moderate (0.7–0.8), high (0.8–0.9), and highest (0.9–1) in Table 4. In this study, the areas where the solar desalination can be performed are evaluated from a technical point of view. The classes of suitability specified in Table 4 are important for suggesting cities where solar desalination is a priority or not. For example, cities with the lowest suitability are not completely eliminated in the study. These cities are not recommended as regions where solar desalination should be performed primarily in terms of the technical criteria discussed.

The developed GIS-MCE model was applied for all coastal cities of Turkey (227,173 km²), and it was found that especially İzmir, Aydın, and İstanbul have the highest suitability scores between 0.8 and 1.0. The fact that the site suitability value of highly populated cities such as İstanbul and İzmir is higher than in other cities. Here, the population dominates the overall suitability despite being in the third rank, because the variation of city populations is significantly large (e.g., 14 million inhabitants for İstanbul and 169,000 inhabitants for Artvin). In Aydın, the site suitability value was higher just as İstanbul and İzmir. As the water unit price was in second place in the factor weighting, this criterion becomes the major indicator of site suitability for this city.

Apart from highest suitable areas, the cities such as Muğla, Bursa, Balıkesir, and Kocaeli also have the moderate suitability, because the factors were similarly and moderately influential even though the weighting of the factors can be distinct. Since the criteria in these cities do not have major differences, the cities such as Zonguldak, Yalova, Tekirdağ, Sakarya, Kırklareli, İçel, Hatay, Edirne, Çanakkale, Bartın, Antalya, and Adana have the low suitability for solar desalination.

The lowest suitability scores (decreasing to 0.5) for solar desalination were found in the Black Sea region, especially for the eastern cities of Rize and Artvin. It is mainly caused by higher water availability in the region due to high precipitation pattern and inexpensiveness of water supply.

Conclusions

Solar desalination is a promising future water supply source for coastal cities in arid and semiarid regions. However, the feasibility of solar desalination plants cannot be determined only by considering the availability of solar radiation and the lack of water supply for potable use. Planning of solar desalination plants, including several technical and economic factors, requires a comprehensive site assessment. The primary factors that must be

considered in a solar desalination site assessment were identified as seawater temperature, solar radiation, seawater salinity, population, water unit price, and precipitation. Population was considered as the indicator of water demand, while precipitation and water unit price criteria were evaluated as the indicator of water availability/scarcity.

This study underlines that GIS-based analysis provides more practical, upgradable, and time/cost-efficient solution to determine areas where the solar desalination is technically suitable and economically feasible.

The results of the case study for coastal cities of Turkey show that İstanbul, İzmir, and Aydın have the highest suitability (0.8–1.0) for future solar desalination implementations. While Antalya and Adana, southern cities of Turkey, have higher solar radiation than İstanbul, and even İzmir and Aydın, the suitability scores for these cities are lower (0.6–0.7) due to higher precipitation and lower water unit prices as compared with İstanbul, İzmir, and Aydın. While Aydın and Muğla, two neighboring cities of the Aegean Region, have similar solar radiation, precipitation levels, and population, Aydın has higher suitability score for solar desalination than Muğla due to its higher water unit price. With lower seawater temperature, population, water unit prices, and higher precipitation levels cities in the Black Sea Region, the northern region of Turkey has the lowest suitability for future solar desalination implementations.

The correlation analysis of the criteria with the site suitability values also indicates that the water unit price (the indicator of economic feasibility of desalination) and population (the indicator of the water need) criteria have the highest effects on resulting site suitability for the solar desalination plants.

The GIS-based analysis, applied in this study, was a large-scale site assessment for solar desalination plants. In the case of an actual implementation project for a solar desalination plant, a city-specific detailed site selection analysis must be carried out with comprehensive criteria and enhanced data. In future studies, site assessment and site selection studies for desalination plants can be carried out under different energy sources.

This study has not intended to evaluate the environmental suitability of seawater desalination systems. Nevertheless, it must be noted that despite the many benefits of desalination, with currently implemented technologies, severe concerns rise over potential negative impacts on the environment. Key issues include the concentrate (saline brine) and chemical discharges to the marine environment, the emissions of air pollutants, and the energy demand of the processes. In the case of solar desalination, high energy demand and energy-related air emissions are not in question; however, the sustainability of these systems must be examined in terms of solar energy generation.

As an alternative source of potable water, desalination is also characterized by high capital and operational and maintenance (O&M) costs—mainly caused by the high energy demand of the desalination processes. For this reason, Arabian Gulf countries such as Saudi Arabia, Kuwait, and UAE, with high total GDP, have been and are still the hot spot of intense desalination activity. While solar desalination systems decrease the energy demand of the desalination processes and their related operational costs, the economic feasibility of the systems should be evaluated for each project.

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