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Where does solar-aided seawater desalination make sense? A method for identifying sustainable sites

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HIGHLIGHTS

- GIS-multicriteria decision analysis is applied to desalination site selection.
- GIS-MCDA is a flexible framework for decision makers and applicable to desalination.
- Global sites are screened for favorable natural and economic conditions.
- Selected feedwater characteristics can enable lower process energy intensity.
- Available solar energy can enable on-site clean energy production.

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ABSTRACT

Global water planners are increasingly considering seawater desalination as an alternative to traditional freshwater supplies. Since desalination is both expensive and energy intensive, taking advantage of favorable natural and societal conditions while siting desalination facilities can provide significant financial and environmental returns. Currently, policy makers do not use a location-specific integrated analytical framework to determine where natural and societal conditions are conducive to desalination. This analysis seeks to fill that gap by demonstrating a multi-criteria, geographically-resolved methodology for identifying suitable regions for desalination infrastructure where 1) available renewable resources can offset part of the fossil energy load; 2) feedwater characteristics reduce the total energy needed for desalination; and 3) human populations have capacity and willingness to pay for desalinated water. This work demonstrates the method with a quantitative global analysis that identifies favorable sites for solar-aided seawater reverse osmosis desalination (SWRO) based on specific target criteria. Location-based data about natural conditions (solar insolation, ocean salinity, and ocean temperature) are integrated and mapped with social indicators (water stress, prevailing water prices, and population) to identify regions where solar-aided SWRO has the highest potential. This work concludes that water-stressed tropical and subtropical cities show the highest potential for economically sustainable solar-aided SWRO.

1. Introduction

Water stress in some form confronts nearly 80% of the human population, and about 65% of continental discharge feeds habitats that face moderate to high biodiversity threats [1]. Even regions traditionally considered water-rich have difficulty providing sufficient water for direct human use, agriculture, industry, the environment, and other users [2]. Pollution and rising costs associated with treating and distributing new sources of water are among the largest issues facing water planners [3]. Such challenges are often entwined in positive feedback loops that exacerbate the declining availability of high-quality water. For example, municipal and industrial wastewater discharges steadily load waterways and aquifers with pollutants, and rising population and economic growth raise the rate of these discharges. In addition, climate change has the potential to disrupt patterns of water availability [4,5] that have motivated human decisions with long-term implications, such as city locations, urban structure, reservoir placement, and water system design. Despite already stressed water supplies, a large portion of the global population does not yet have access to affordable, safe, sufficient water [6], and providing water while protecting other species and the environment could be even more challenging in the future.

Consequently, policy makers are considering alternative water supplies that meet demand while proving resilient against these challenges.

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Desalination is one potential solution to the problem of supplying humans with clean drinking water. Access to desalination can reduce dependence on precipitation cycles and enable the use of traditionally unusable water, but it dramatically increases costs and the water supply's reliance on energy (see e.g. [7,8]). Desalination is generally capital intensive with significant maintenance needs, and its high energy requirements do not end at the plant site. Coastal desalination facilities virtually require that the water supply be sited at low elevation, which means that costs and energy use for water distribution will be higher for areas that would otherwise use higher elevation sources (note, however, that the opposite could be true if deep groundwater is the alternative).

Humans have long practiced some form of desalination [9], typically by evaporation or intensive filtration. Despite technological advances, these two techniques remain dominant in the form of thermal desalination and electrically-driven membrane desalination, which is primarily done by reverse osmosis (RO) [9]. Descriptions of the major technologies and their status, including overviews of global desalination capacity, including information about location, source water, fuel, and plant size, are outside the scope of this work but can be found in the literature (e.g. [7,9,10]). Also outside the scope of this work are the environmental challenges associated with disposing the salts removed from product water. While desalinated water can displace fresh water that would otherwise be taken from environmentally sensitive sources, thereby reducing ecological stressors [1], it can also create new ecological stress in ocean habitats, particularly when saline brines are discharged to ocean waters (see e.g. [10] for further discussion).

Desalination is more energy intensive than most other sources of fresh water (Table 1; [11,12]), which in turn means that desalinated water is often more expensive and environmentally impactful than other forms of water supply — particularly because most existing and planned desalination facilities rely on fossil fuels. Waste streams associated with energy, such as water-borne contamination from fuel extraction and air-borne emissions from fuel combustion (e.g. carbon dioxide, acid deposition, and particulates), could actually worsen water problems in some areas (see e.g. [13,14]). While abundant energy can be used to create abundant water supplies, the type of energy used can have side effects worthy of additional consideration. Such side effects, including pollution, cost, and fuel security have inspired the construction of a number of desalination facilities powered with renewable sources, descriptions of which can be found in the literature (e.g. [15,16]). Thus, it is worthwhile to consider ways to both reduce the fossil intensity of desalination, for example by augmenting with renewable energy, and to reduce the total energy intensity of desalination, for example by seeking lower salinity feedwater sources.

Desalination is unlikely to become a major source of freshwater without major reductions in cost and energy intensity. However, site-specific conditions like extreme water stress, high water costs, and natural characteristics that are favorable for desalination can contribute to desalination's viability. For example, high water temperatures and low water salinity can reduce the energy intensity of membrane desalination. The wide range of priorities that decision-makers around the world have for water supply presents an opportunity to quantitatively evaluate where desalination might fit local and regional needs, whether by providing water with highly controllable quantity and quality, relieving stress on freshwater resources, creating jobs and industrial development, or some other means. Desalination is not a universal solution to water supply problems, as it does not address issues like inadequate distribution systems, poor sanitation, or weak governance systems, but this work postulates that sites exist where desalination can increase the availability of high quality water in an economically, socially, and environmentally sustainable manner.

Despite the high cost and importance of desalination infrastructure, to the authors' knowledge no integrated analytical framework has been deployed that incorporates location-specific information to identify sites with favorable energy availability, feedwater characteristics, and societal needs and capacities that are compatible with sustainability goals. Previous treatments have considered elements like water demand, alternative supply, political preferences, and costs [17], and a systematic, global investigation of where natural conditions like feedwater characteristics might enhance feasibility for desalination adds to the literature. Since water treatment facilities are long-lived and difficult to modify, their construction can create a capital lock-in effect that constrains future changes to the original assumptions (such as the cost of energy, impacts of brine disposal, etc.). Thus, there is value in using a framework that enables better decision-making for site selection beforehand. In that spirit, the geographic information systems multicriteria decision analysis (GIS-MCDA) method presented here seeks to inform desalination facility site selection based on local natural conditions and human factors.

Recognizing that those considering desalination have diverse goals and work at a variety of scales, this work uses a highly scalable, quantitative, location-based method of synthesizing relevant data to aid decision-making. GIS-MCDA has been successfully applied in multiple environmental contexts [18], including landfill and power plant site selection (e.g. [19–21]). However, to the authors' knowledge, little GIS-MCDA work has been used to identify high potential sites for desalination rather than identifying optimal placement or selecting from among alternatives in a given setting (a detailed treatment of the latter is given in [17]). In a notable exception investigating where wind powered desalination facilities could be viable [22], the focus is on identifying areas where wind power potential is high and where indicators suggest a demand for desalinated water. This work seeks to extend the value of GIS-MCDA techniques for desalination facility site selection by also considering how natural conditions can actually reduce the energy intensity of desalination. Thus, where previous work has investigated where abundant renewable energy coincides with water demand, this framework additionally considers where feedwater characteristics make desalination inherently less energy intensive.

GIS-MCDA enables use of a range of factors, such as different fuel sources, natural conditions suited to different desalination technologies, and local economic priorities. To quantitatively demonstrate its value, this work presents a global example focusing on the energy intensity and high cost of desalinated water to identify regions where natural and societal conditions might improve the sustainability and economics of solar-aided seawater reverse osmosis (SWRO). In particular, regions where abundant solar energy, high ocean temperatures, and low ocean salinities coincide with urban centers, high water stress, and high water prices could be strong candidates for desalination.

While future work can repeat the analysis for other energy resources such as wind, geothermal, and waste heat, this initial trial restricts its consideration to on-site solar photovoltaic energy with grid backup. The major reasons for focusing on solar include global data availability and the relative uniformity of solar insolation in given areas. Off-site renewables (including off-site solar) are not considered because of the

Table 1
Energy embedded in water production varies from relatively low (for surface freshwater) to very high (for seawater desalination).

Water source	Energy intensity (kWh/m^3)
Surface water (typical)	0.06[a]
Pumped groundwater (CA)	0.14–0.60 (reported)[b]
Direct potable reuse of reclaimed water	<1.1[a]
Colorado River Aqueduct (CA)	1.6[b]
California State Water Project (CA)	2.4[b]
Seawater desalination (CA)	3.6–4.5 (estimated)[b]

Note that the energy intensity of reclaimed water varies greatly by intended use: direct potable reuse (listed in table) has the highest embedded energy, while reclaimed water for non-potable use can have as little as 0 additional embedded energy.

[a] Source: [10].

[b] Source: [9].

high potential that other users would be competing for the electricity or for generation sites and transmission capacity, reducing the advantage of siting a plant in a particular location. Brackish groundwater desalination is not considered largely due to a lack of suitable quality groundwater data on a global basis, though this method is highly suitable for such analysis in locations where brackish groundwater data are available.

Focusing the initial work on desalination's energy intensity is appropriate because energy requirements drive the operational costs of desalinated water [7], and high costs are among desalination's largest implementation hurdles. High energy needs also make desalinated water more vulnerable to high and volatile energy prices than a conventional, less energy intensive water supply. Additionally, many regions considering desalination are affected by the environmental impacts of energy consumption. Conditions like water scarcity, water supply volatility, and poor water quality that motivate the use of desalination are often exacerbated by energy-related air, land, and water pollution, including pollution leading to climate change. While individual regions might have specific concerns about local habitats or land use, desalination's energy intensity is broadly relevant at a global scale. One constructive way to address concerns about fuel price risks and energy-related environmental impacts is to identify locations where favorable feedwater characteristics reduce overall energy consumption per unit of distillate and where renewable energy sources can be used to supply at least part of the remainder.

2. Approach and parameterization

This analysis focuses on solar-aided SWRO using on-site solar photovoltaic (PV) systems with a grid connection and thus examines global insolation, seawater temperature, and seawater salinity as relevant natural conditions. High solar insolation is desirable for power generation, and high feedwater temperatures and low salinity are associated with lower process energy consumption for SWRO [9]. Technical requirements for natural conditions vary by desalination technology and energy sourcing assumptions, so these parameters would likely be different for other applications. In addition to these natural conditions that could improve desalination's environmental and cost sustainability, water prices, water stress, and population density are used as indicators of economic viability.

The geographic information systems (GIS) approach used for this analysis filters global location-based data on multiple relevant decision criteria to rapidly identify macro regional trends that could contribute to economic and environmental sustainability of desalination. Advantages include the abilities to quickly add and remove information layers and easily change analytical thresholds depending on a user's need. As the method is easily scalable, users can start with high-level information (e.g. water temperature) and add constraints at increasing levels of detail in target areas. For example, a region identified as being broadly suitable can be further investigated by adding constraints, such as affordable land, distance from hazards, etc. [21]. Thus, a high-level set of constraints can be used to broadly down-select to promising regions, after which the criteria can be made more strict and more granular data used for fine-tuning the analysis. This scalability enables users to generate data-driven hypotheses that can be further tested.

2.1. Choosing parameters and setting threshold values: natural conditions

Colocating desalination facilities with favorable natural conditions can reduce the external energy input required to desalinate seawater, thus lowering costs and energy-related environmental impacts (the corollary is also true, in that locating desalination facilities where conditions are unfavorable will increase costs and impacts). This assessment of solar-aided SWRO focuses on conditions that allow for greater use of local solar resources or reduce the total external energy input needs for desalination.

The first natural parameter considered is solar energy availability, which can help reduce the fossil energy intensity of desalination. High insolation, defined here as an average global horizontal irradiance (GHI) greater than six kilowatt-hours per square meter per day (kWh/m^2/day), is considered favorable for solar PV-aided desalination (see e.g. [23,24] for descriptions of solar-powered desalination plant energy needs). Slightly lower GHI (5–6 kWh/m^2/day) is considered acceptable (see Fig. 2 for a global map of GHI).

Next, this work addresses feedwater characteristics that can reduce the overall energy intensity of SWRO. In particular, high sea surface temperatures (SST) and low ocean salinity are considered favorable for SWRO, with parameters summarized in Table 2.

SWRO removes salts and other contaminants from seawater via membrane separation. While RO is less effective at removing materials from water than some other desalination processes, like distillation, it is also far less energy intensive. A typical SWRO facility consumes 3 to 6 kWh(electric)/m^3 of distillate, compared to combined thermal and pumping energy requirements of 15 to 58 kWh(electric)/m^3 for thermal facilities [25].

Higher temperatures are correlated with higher flux, or rate of permeate passage through the membrane, for SWRO facilities [26], which means that energy intensity per unit of product water is lower when feedwater temperatures are higher, up to about 30 °C [9]. A rule of thumb is that for each increase of 1 °C, flux increases by about 3% [24]. Thus, regions with naturally high water temperatures (average annual SST greater than 25 °C) are considered favorable for SWRO facilities. SST ranges from about −2 °C to 30 °C globally [27], with a global average of 16.1 °C [28].

In addition to higher temperatures, low salinity feedwater corresponds to lower energy intensity for SWRO. This correlation is because lower salinity corresponds to a lower osmotic pressure difference between the feed and product water, so less energy is needed to force the water against the osmotic pressure differential. Thus, regions with low ocean salinity (where low is defined as below average) are identified as naturally favorable for RO desalination. Ocean salinity ranges from about 5 to 40 practical salinity units, with typical values around 35 [29]. Below-average ocean salinity tends to be found in areas with

Table 2
Parameters, threshold values, and data sources used to assess sites where seawater desalination could be environmentally and economically favorable are listed below.

	Scoping requirements		Geophysical conditions			Societal conditions		
	Energy source	Water source	Insolation (GHI)	Water temperature	Water salinity	Water stress index	Water price	City population
Data source	–	–	[33]	[27]	[27]	[1]	[29]	[30]
Reverse osmosis desalination	Solar PV + other grid	Seawater	>5 kWh/m^2/day	>25 °C	<50th percentile	>85th percentile	≥US\$1.50/m^3	≥1 million

Sources: Thresholds for natural conditions are based on solar-powered desalination energy needs (see e.g. [23,31]) and reasonable judgment of high values. For example, global average SST is about 16.1 °C [28], with a global range of −2 to 30 °C [27]. The water stress index threshold of 85th percentile is a conservatively high extension of the original source's characterization of the 75th percentile as "very high [water] threat" [1]. The price threshold of US2010 \$1.50/m^3 reflects conventional desalination costs of US2010 \$0.20 to \$2.15/m^3 [31] and the fact that water prices generally include distribution costs, overhead, and profit. Note that water prices reflect a 12 m^3/day connection, not the cost of the next available (marginal) water supply [29]. Cost estimates for solar desalination can be found in e.g. [8,15,32]. The analysis could easily be repeated with other thresholds and parameters.

high rainfall or meltwater input and low evaporation. Since high insolation often drives high evaporation rates, and since consistently high insolation is generally not colocated with high rainfall and large amounts of ice, low salinity coincides with high insolation in relatively few regions.

2.2. Choosing parameters and setting threshold values: societal conditions

After geophysical conditions (insolation, water temperature, and water salinity) are considered, existing societal conditions are incorporated into the analysis, as desalination makes sense only where there is demand for desalinated water. This analysis evaluates three societal indicators as proxies for demand for desalinated water: water stress (as measured by Vörösmarty et al. [1]), indicating absolute water demand; water prices in major cities around the world (as recorded by Global Water Intelligence [29]), indicating economic demand; and concentrated populations, indicating potentially advantageous opportunities for economies of scale [30]. Note that water price data are static representations of water prices for a connection consuming 12 m^3/day [23]. The prices used in this analysis reflect only current prices, not the cost of the next (marginal) water supply available, which is typically higher.

Coastal and near-coastal cities with water prices documented by Global Water Intelligence [29] are considered, with city populations over one million and water prices over US2010 $1.50 per cubic meter ($m^3$) considered most societally favorable for solar-aided SWRO (Table 2). The methodology could be repeated for other price points and population sizes, but these thresholds are chosen so as to highlight large cities that are more likely to secure the financing needed for large water treatment infrastructure with high water prices that could potentially support conventional desalination. Desalinated water is likely to have production costs lower than $1.50/$m^3$, but water prices generally include distribution costs, overhead, and profit. Conventional desalination generally produces fresh water at a cost of US2010 $0.20 to $2.15/$m^3$ [31]. While desalination powered by renewable energy typically costs more than conventional desalination with today's technology, advances in system performance change the cost outlook for future generations of treatment equipment. For example, it has been predicted that concentrating solar power (CSP) desalination plants could produce water with costs below US2010 $0.60/$m^3$ by around 2030 [32]. Other cost estimates for solar or solar-aided desalination can be found in sources such as [15] and [8]; studies indicate that prices are expected to drop with time and/or increased scale.

3. Methods

The GIS-MCDA method used here to quantitatively identify favorable locations for solar-aided seawater desalination proceeds by 1) choosing variables by establishing key resource constraints and socio-political performance requirements, 2) defining relevant threshold values to drive the analysis, 3) identifying appropriate geographically-resolved data sets, 4) integrating those data sets in a consistent and precise way, 5) conducting spatial analysis using GIS software tools, and 6) making and disseminating recommendations (Fig. 1). The ultimate output is a map or set of maps indicating appropriate sites given the chosen parameters. Applying this approach to the question of where solar-aided seawater desalination might be economically sustainable requires parameterizing natural and societal conditions using judgment to establish reasonable limits, then integrating these data to identify promising regions or sites.

This application focuses on identifying global regions where on-site PV-aided SWRO could be especially viable, and variables were chosen according to three objectives: 1) ensure sufficient insolation, 2) locate near feedwater with characteristics that reduce the energy intensity of SWRO, and 3) locate near potential markets for desalinated water. Specific criteria for each of these objectives and the thresholds used in this analysis and described in Sections 2.1 and 2.2 above are illustrated in Table 2 and described in Section 2.

Data sets for each criterion are selected for integration based on requirements for global coverage, sufficient geographic resolution, and publication date. These data sets include geographically-resolved layers for solar insolation [33], ocean temperature and salinity [27], prevailing water prices [29], water stress [1], and population centers [30]. Data integration is performed by reconciling projections and geographical resolution for software processing. Threshold values are determined based on reasonable judgment and prevailing expectations for performance and are listed in Table 2. Finally, these data and constraints are integrated using ArcGIS 10's Spatial Analyst Toolbox to produce world maps of high-potential sites using a Boolean overlay of parameters of interest, described in detail in Section 3.1 below. The primary GIS functions used are the Raster Calculator and the Less Than and Greater Than tools.

3.1. Integrating raster data to produce map outputs

Multi-criteria decision analysis (MCDA) requires reconciling multiple and sometimes incompatible goals to come to a final decision that most closely meets a given situation's needs. Objectives can be as straightforward as “minimize energy use” or as complex as “ensure social acceptability,” and so MCDA uses quantitative, measurable attributes, or criteria, to indicate that an objective is met. The decision portion of MCDA requires aggregating criteria across objectives to identify the most favorable conditions, and that aggregation can be performed with different operators depending on situational need. For example, conditions might be considered favorable only if all objectives are met (an “and” operator), if any of the objectives is met (an “or” operator), or if some objectives are met (an “or/and” weighted operator), often implemented as ordered-weight averaging as proposed by Yager [34,35]. A detailed mathematical description of these aggregation techniques can be found in [35].

This analysis aggregates criteria using an “and” operator across the three objectives described above, more specifically stated as: 1) solar insolation is sufficient for use of PV for part of the SWRO electrical load, 2) feedwater characteristics lower the absolute energy requirements for SWRO versus typical installations, and 3) social attributes indicate that there is a market for desalinated water. Stated another way, regions are flagged as “excellent” locations for on-site PV-augmented SWRO if they fulfill all three objectives by meeting at least one criterion within each objective.

Specifically, this GIS integration uses a Boolean overlay to assess where solar-aided SWRO might be most favorable according to selected objectives. That is, for each criterion outlined in Table 2, the GIS software classifies a location as “meets criteria” or “does not meet criteria.” Those regions identified as “excellent,” are the result of progressive Boolean filters, first filtering to regions that meet or exceed solar insolation criteria, then filtering further to regions that meet or exceed energy intensity reduction criteria, then filtering finally to regions that meet or exceed social criteria. The resulting map is presented as Fig. 2, with some intermediate filters (e.g. “solar insolation criteria only” or “social criteria only”) included for illustration. Those regions that fulfill criteria under some objectives can be considered as possible candidates, and those that did not meet threshold criteria for any objectives are not considered particularly advantageous.

3.2. Operationalizing the technique for desalination facility siting

An expected benefit of the method is its flexibility: decision-makers can choose different criteria and threshold values to reflect their needs. For example, locations could be selected based on land prices and access to waste heat rather than insolation and water temperature. Societal priorities like water quality, supply security, or environmental preservation can also be weighted more or less heavily during raster calculations (Eq. (1)), enabling policy makers to incorporate a community's willingness to pay a premium to achieve various goals.

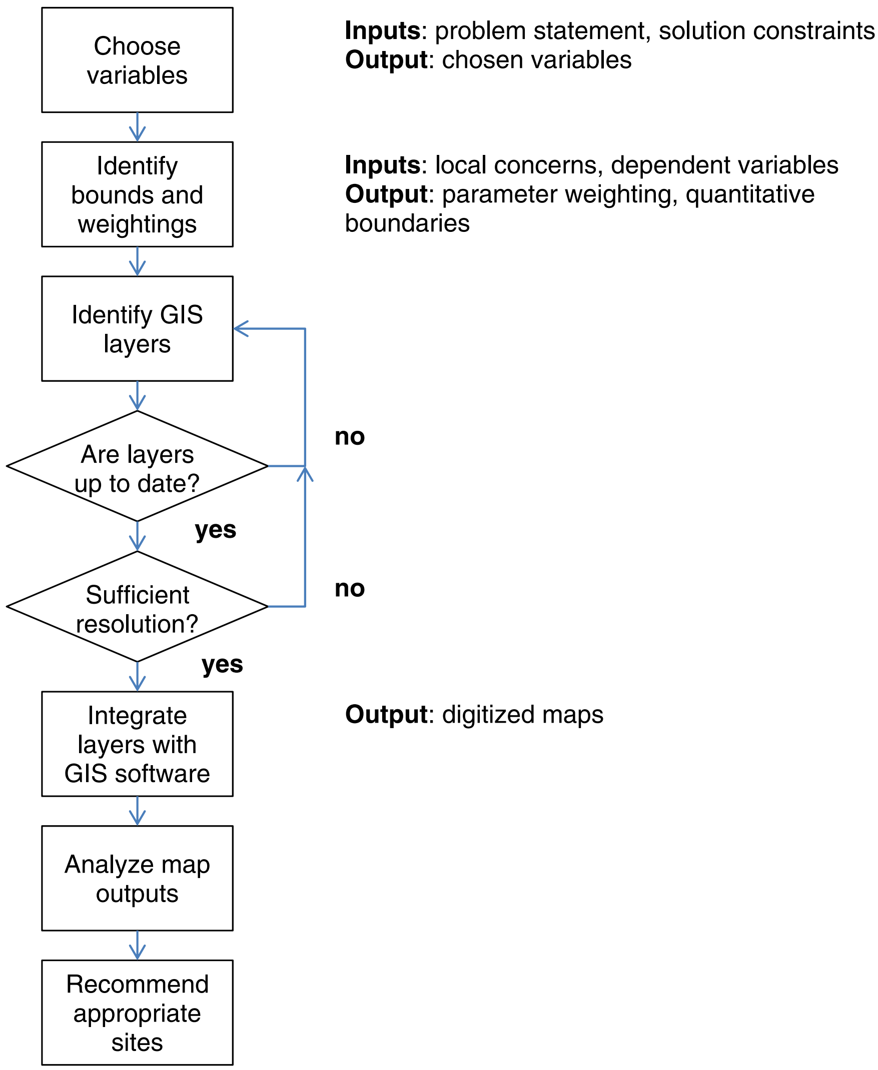

Fig. 1. The method demonstrated here uses GIS and multicriteria decision analysis tools to identify sites for desalination facilities that enable more sustainable desalination.

An application requiring higher resolution or incorporating, for example, weightings based on specific social priorities could define a more complex weighting function along the lines of

$$\text{score} = \boldsymbol{\alpha} \times A + \boldsymbol{\beta} \times B + \ldots + \boldsymbol{\omega} \times Z, \tag{1}$$

where $\boldsymbol{\alpha}, \boldsymbol{\beta}, \ldots, \boldsymbol{\omega}$ are weighting factors for scaled parameters $A, B, \ldots, Z$ (see e.g. [19,20] for a more detailed discussion). Though weightings contribute explicitly to how parameters are prioritized, it is noteworthy that the choice of scaling technique also affects prioritization because of the implicit value judgments required in comparing parameters with different metrics. For example, normalizing a parameter to its average or some other value (e.g. its maximum value) might capture relevant information differently for a linearly varying criterion and a criterion for which a specific threshold level is important for decision-makers.

The method can be applied at any scale for which there are sufficient data, including cities, countries, and larger regions depending on desire. An additional advantage is the use of maps as outputs, as these visualizations are intuitive and require little orientation. Since the map is digitized, raster calculation results can also be displayed alongside other layers of interest, such as residential zones, infrastructure, and alternative water supplies. While this method has the aforementioned attributes, it also has a few downsides. For example, as with any method, data quality and consistency are necessary to ensure useful, reproducible, and cross-comparable outputs. Furthermore, the thresholds for analysis remain subjective in some cases.

4. Findings

For this global evaluation, results were interpreted at a regional level based on a global map generated using the GIS integration described above (Fig. 2).

Global regions identified as naturally favorable for solar-aided SWRO facilities coincide with consistent influxes of freshwater to the ocean. High quality solar resources and warm water (GHI > 6 kWh/m^2/day and SST > 25 °C) are well distributed through the tropics (Fig. 2), but below-average ocean salinity is less common. The coincidence of high insolation, warm water, and below-average ocean salinity is found primarily at the mouths of major rivers (e.g. the Amazon and the Congo) and in the monsoon-fed Bay of Bengal and Gulf of Thailand (Fig. 2). This region notably includes major cities with high water stress indices (above the 85th percentile) like Bangkok, Thailand; Dhaka, Bangladesh; and Calcutta, India, indicating a possible demand for desalinated water to augment or replace existing sources and putting these cities into the category of “excellent” for the on-site PV-aided SWRO considered here [1].

Many regions with natural conditions somewhat favorable for SWRO (e.g. GHI > 5 kWh/m^2/day and SST > 25 °C) are more favorable

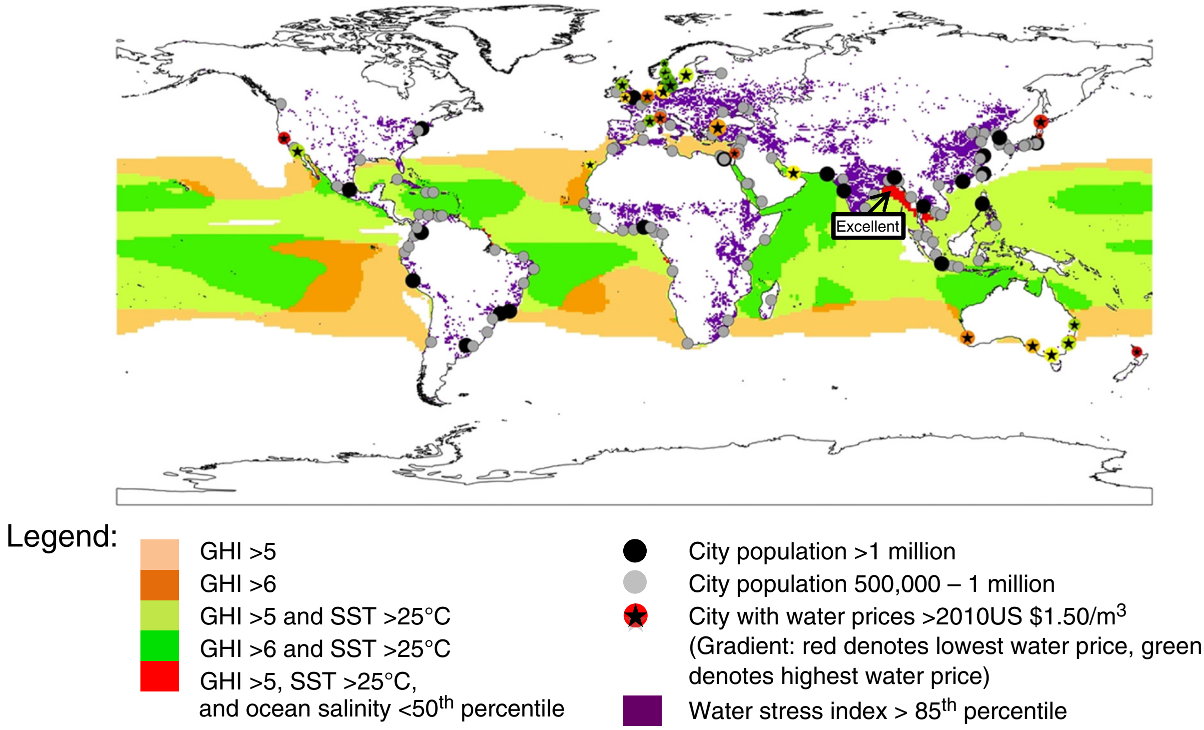

Fig. 2. This figure shows global solar insolation, sea surface temperatures, and ocean salinity in addition to major coastal cities and locations with high prevailing water prices to identify regions that show unusual promise for on-site solar photovoltaic-augmented seawater reverse osmosis desalination. Sites that meet criteria for insolation, feedwater promoting low energy intensity, and economic conditions promoting affordability are denoted "excellent" sites. Coastal sites meeting some conditions are considered possible candidates, while sites meeting none are not considered particularly suitable.

when societal considerations are incorporated. India, North Africa, Brazil, and the Caribbean have high population density and water stress, indicating that additional water sources will likely soon be needed. In addition to high water stress, Australia, the Middle East, and Southern California also have currently high water prices, indicating that the relatively high costs of desalinated water could be tolerated.

Some regions with favorable societal conditions (high water stress and high water prices) do not display characteristics favoring solar desalination, notably China, Japan, non-Mediterranean Europe, the northeastern United States, and northeastern Argentina (Buenos Aires) (Fig. 2). In fact, some of the cities with the highest water prices are in regions where solar-aided desalination is not categorically favorable, namely northern Europe, Japan, and Sydney and Melbourne in Australia [23]. However, desalination employing low-impact energy sources other than solar (for example wind or geothermal energy) or brackish groundwater could be viable in these regions.

5. Discussion

5.1. Relationship of results to real-world observations

One pattern made clear by the map produced for this example is that the most favorable natural conditions for solar-aided SWRO are found in regions where there is ostensibly plenty of fresh water: specifically, those regions where large rivers or monsoon rains discharge to the oceans (Fig. 2). Given that abundance of freshwater, it is nonobvious that desalination might be useful as a water supply until social factors are considered. High populations and extreme water stress demonstrate that the available water is heavily used, suggesting that additional supplies are needed.

The results presented here suggest that favorable solar resources and high water stress coincide mainly in the tropics and subtropics, where little desalination capacity has been deployed to date. Most of the world's desalination capacity is concentrated in regions like the Middle East and the United States where freshwater is highly limited, special needs (such as for industrial ultrapure water) exist, and there is sufficient wealth to support desalination [16]. Thus, it seems that cost competitiveness and a region's ability to pay for desalination are likely the largest historical factors in the decision to install desalination capacity, an observation reinforced by high-profile plans for conventionally powered desalination facilities in relatively wealthy areas like London and Southern California. Geophysically favorable conditions do not seem to be major drivers of desalination installations at this point. Notably, current water prices do not reflect the cost of the next available, or marginal, water supply, and so more regions might discover that desalination could be cost competitive in the future.

Though historically solar resource availability does not seem to have been a major decision criterion for siting desalination facilities, some regions with existing desalination capacity also have favorable solar resources that could be used at existing or future plants: notably the Middle East, Persian Gulf, North Africa, and the Caribbean [16] (Fig. 2). Dubai and Abu Dhabi in particular have both high water prices and high quality solar resources. In fact, Abu Dhabi does have a solar desalination plant [36], though waste heat is more typically used due to its lower cost and higher energy density. Economics seem to have driven site selection for existing desalination facilities, but environmental concerns are also highly relevant [37] and could prove larger drivers in the future.

5.2. Effect of modeling approach on results

The results outlined for this example analysis are heavily and systemically influenced by certain modeling choices, which is typical for analytical work. In particular, the results are sensitive to the chosen spatial resolution, aggregation technique, and objectives themselves.

This work focused on identifying global regions that might be particularly well suited to PV-augmented SWRO as a demonstration of a top-down application of GIS-MCDA that is not constrained by predetermined site choices. Thus, the resolution is fairly low, and it is to be expected that incidental “excellent” sites exist outside the regions identified here. A higher resolution investigation would have likely resulted in identification of more sites with more variation in the degree to which they satisfy stated objectives. That is, there are likely individual sites within the “excellent” category that have solar insolation or economically supporting factors that significantly exceed the minimum criteria investigated here. A study using higher resolution data to evaluate particular sites where desalination plants could be built would also need to consider additional, locally relevant criteria, like proximity to existing infrastructure and hazards, land price, legal restrictions, and possible future considerations resulting from planned developments or climate change (see e.g. [21] for a high resolution example of a GIS-MCDA study for power plant siting). However, it is hoped that this initial low resolution effort is valuable in that it uses readily available global data sets to give a simple, initial indication of where higher resolution study is most useful.

Similarly, the choice to require that “excellent” sites meet all three stated objectives (to use an “and” operator) is somewhat simplistic. Furthermore, using a Boolean overlay with binary outcomes (condition is met versus not met) tends to deemphasize variability that could be operationally important. For example, meeting the objective of “feedwater enabling lower energy intensity” might be less important in a region with solar insolation and economic conditions far exceeding the minimum criteria evaluated here. In fact, a region with moderate insolation and typical seawater conditions but extremely high water prices and water stress might actually be most suitable for PV-augmented SWRO in the real world, but it would be not be classed as an excellent site because it does not meet all three objectives. The “anding” technique used here means that all three objectives are considered equally important, even if specific outcomes like total cost of water or total greenhouse gas emissions are more sensitive to certain criteria. A study with a more specific objective, such as “locations minimizing total energy input required for PV-aided SWRO” would likely use something like a weighted aggregation, where certain criteria are valued more highly than others. Despite the limitations, the simple technique of using progressive Boolean filters is a fast and clear method of showing how decision-making objectives influence what is considered suitable, as it is necessarily a subjective process to determine what makes a location “excellent.”

Finally, both the topic itself (on-site PV-augmented SWRO) and the objectives (high insolation, feedwater conducive to low energy intensity, and social conditions promoting economic feasibility) are highly specific and somewhat arbitrary. The answer to the question “Where does desalination make sense?” is extremely dependent on what society or particular groups consider sensible, the type of desalination in question, the energy systems involved, and other factors. For example, one obvious extension of this analysis is to evaluate where renewable-aided SWRO might make sense if renewable power can be supplied via a grid connection from a remote location.

6. Conclusions

This work can aid policy makers by demonstrating a simple, customizable tool for identifying favorable locations for desalination facilities based on selected criteria. Here, the method was used to identify regions where on-site solar photovoltaic-aided seawater reverse osmosis makes sense: regions where natural conditions like ample sunshine and feed water characteristics could reduce the energy-related impacts of desalination, where societal conditions like water stress, water price, and concentrated populations could make desalinated water economical, and where these natural and societal conditions coincide. While this work uses a global resolution to identify broad regions where desalination could make sense, decision-makers can use this technique for real, specific projects by adding much more detailed criteria [21] and by engaging their communities to determine what criteria should be the basis for optimization.

This work has demonstrated how an integrated GIS-MCDA framework can enable decision-makers to simultaneously incorporate economic, environmental, and other societally defined criteria when making desalination facility siting decisions. This example has also introduced the idea that GIS analysis can be used to find regions with feedwaters that are especially suited to desalination.

References

[1] C.J. Vörösmarty, et al., Global threats to human water security and river biodiversity, Nature 467 (2010) 555–561.
[2] T. Oki, S. Kanae, Global hydrological cycles and world water resources, Science 313 (2006) 1068–1072.
[3] United States Environmental Protection Agency, The Clean Water and Drinking Water Infrastructure Gap Analysis, Office of Water, 2002.
[4] C.J. Vörösmarty, P. Green, J. Salisbury, R.B. Lammers, Global water resources: vulnerability from climate change and population growth, Science 289 (2000) 284–288.
[5] R.I. McDonald, et al., Urban growth, climate change, and freshwater availability, PNAS 108 (2011) 6312–6317.
[6] World Health Organization, Progress on Sanitation and Drinking Water, WHO Press, Geneva, 2010.
[7] T. Younos, The economics of desalination, JCWRE 132 (2005) 39–45.
[8] I.C. Karagiannis, P.G. Soldatos, Water desalination cost literature: review and assessment, Desalination 223 (2008) 448–456.
[9] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res. 43 (2009) 2317–2348.
[10] H. Cooley, P.H. Gleick, G. Wolff, Desalination, With a Grain of Salt: A California Perspective, Pacific Institute, Oakland, 2006.
[11] National Resources Defense Council, Pacific Institute, Energy Down the Drain: The Hidden Costs of California's Water Supply, 2004.
[12] A.S. Stillwell, C.W. King, M.E. Webber, I.J. Duncan, A. Hardberger, The energy-water nexus in Texas, Ecol. Soc. 16 (2011) 2.
[13] National Academy of Sciences, Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use, The National Academies Press, Washington, D.C., 2010
[14] K.M. Twomey, A.S. Stillwell, M.E. Webber, The unintended energy impacts of increased nitrate contamination from biofuels production, J. Environ. Monit. 12 (2010) 218–224.
[15] A. Ghermandi, R. Messalem, Solar-driven desalination with reverse osmosis: the state of the art, Desalin. Water Treat. 7 (2009) 285–296.
[16] M. Folley, B.P. Suarez, T. Whittaker, An autonomous wave-powered desalination system, Desalination 220 (2008) 412–421.
[17] M.R. Mahmoud, H. Fahmy, J.W. Labadie, Multicriteria siting and sizing of desalination facilities with geographic information system, J. Water Resour. Plan. Manag. 128 (2002) 113–120.
[18] J. Malczewski, GIS-based multicriteria decision analysis: a survey of the literature, Int. J. Geogr. Inf. Sci. 20 (2006) 703–726.
[19] B. Şener, M.L. Süzen, V. Doyuran, Landfill site selection by using geographic information systems, Environ. Geol. 49 (2006) 376–388.
[20] G. Wang, L. Qin, G. Li, L. Chen, Landfill site selection using spatial information technologies and AHP: a case study in Beijing China, J. Environ. Manag. 90 (2009) 2414–2421.
[21] O. Omitaomu, et al., Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites, Appl. Energy 96 (2012) 292–301.
[22] E. Spang, The potential for wind-powered desalination in water-scarce countries, Digital Collections and Archives, , Tufts University, Medford, MA, 2006. (Available from Tufts Digital Library, Digital Collections and Archives, Medford, MA. http://hdl.handle.net/10427/35347).
[23] H.M. Qiblawey, F. Banat, Solar thermal desalination technologies, Desalination 220 (2008) 633–644.
[24] WateReuse Association, Seawater desalination power consumption, white paper, http://www.watereuse.org/sites/default/files/u8/Power_consumption_white_paper.pdf 2011.
[25] R. Semiat, Energy issues in desalination processes, Environ. Sci. Technol. 42 (22) (2008) 8193–8201.
[26] USBR (U.S. Bureau of Reclamation), Desalting Handbook for Planners, 3rd edition USBR, Washington, D.C., 2003
[27] National Oceanographic Data Center, World Ocean Atlas Data: NetCDF Format; Annual; 1 Degree, 2009.
[28] National Climatic Data Center, Global Surface Temperature Anomalies, National Oceanic and Atmospheric Administration, Washington D.C., 2011
[29] Global Water Intelligence, Water Tariff Survey, 2010.
[30] ESRI, ArcGIS Package, World Cities, 2011.
[31] G. Micale, A. Cipollina, L. Rizzuti, Seawater Desalination: Conventional and Renewable Energy Processes, Springer, Berlin, 2009.

[32] German Aerospace Center, Concentrating Solar Power for Seawater Desalination, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Stuttgart, 2007.
[33] National Aeronautics and Space Administration, Surface Meteorology and Solar Energy: Global Horizontal Irradiance Release 6.0, 2008.
[34] R. Yager, On ordered weighted averaging aggregation operators in multi-criteria decision making, IEEE Trans. Syst. Man Cybern. 18 (1) (1988) 183–190.
[35] N. Aydin, E. Kentel, S. Duzgun, GIS-based environmental assessment of wind energy systems for spatial planning: a case study from Western Turkey, Renew. Sust. Energy Rev. 14 (2010) 364–373.
[36] A. El-Nashar, Seasonal effect of dust deposition on a field of evacuated tube collectors on the performance of a solar desalination plant, Desalination 239 (2009) 66–81.
[37] S. Lattemann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination 220 (2008) 1–15.