Original Article

Selection of groundwater sites in Egypt, using geographic information systems, for desalination by solar energy in order to reduce greenhouse gases

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Abstract Although Egypt has already reached the water poverty limit, it possesses a high potential of brackish groundwater available from different aquifers. All Arab countries lie in the best sun-belt region in the world and Egypt has the highest number of sun hours all year round. Solar energy for groundwater desalination is an independent infinite energy resource; it has low running costs and reduces the contribution of greenhouse gases (GHG) to global warming. Perfect meteorological conditions and land space are available in remote areas, where solar desalination could supply freshwater for drinking, industry, and for greenhouse agriculture. The present study uses Geographic Information System(s) (GIS) as a spatial decision support tool to select appropriate sites in Egypt for groundwater solar desalination. Solar radiation, aquifer depth, aquifer salinity, distance from the Delta and the Nile Valley, incidence of flash floods, sand dunes, rock faults, and seawater intrusion in the North Delta, are the criteria that have been taken into consideration in the process of analysis. A specific weight is given to each criterion according to its relative influence on the process of decision making. The results from the application of the presented methodology

Keywords
Desalination; Solar energy; Groundwater; Hydrogeological map; GIS; GHG; Climate change; Egypt

Abbreviations: AHP, analytic hierarchy process; GHG, greenhouse gases; GIS, geographic information system; MCE, multi-criteria evaluation; MtCO2e, metric tons or tons of carbon dioxide equivalent; SDSS, spatial decision support systems; WLC, weighted linear combination.

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Introduction

Brackish groundwater desalination is one of Egypt's most potentially significant water resources. Most aquifer systems in Egypt contain high quantities of brackish groundwater [1]. Effective selection of a desalination plant location depends on considering several independent factors concerning geomorphology, hydrology, and solar radiation. The use of Geographic Information System(s) (GIS) as a tool in combination with a multi-criteria evaluation (MCE) method equips the spatial decision support systems (SDSS) to make appropriate site selections. The present study uses a weighted linear combination (WLC) method, as a kind of MCE, and an analytic hierarchy process (AHP), to make appropriate site selections in order to achieve sustainable development.

Egypt lies on the northeastern side of Africa, bordered on its northern coast by the Mediterranean Sea and on its eastern coast by the Red Sea. It comprises an area of about one million km², made up as follows: Nile valley and delta about 4% of the total; Eastern desert area about 22%; Western desert area about 68%; and the Sinai Peninsula area about 6%. The share of Nile water in Egypt is 55.5 billion m³/year, representing about 68%; and the Sinai Peninsula area about 6%. The share of available water resources; desalinated seawater comprises only 0.08%. Total groundwater plus treated groundwater is 20.65 billion m³/year (28% of available water resources), but it cannot be added to Egypt’s share of water as it is a reused source [2]. Egypt has already reached the water poverty limit and needs as much as share of Nile water in year 2050 to cover the shortage. Surface freshwater pollution has embarked on a critical path. One climate change scenario predicts that the Nile discharge may decrease to 3/4 of its present volume if carbon dioxide (CO₂) emissions double. Low cost solar water desalination is a strategic solution for Egypt. The number of desalination plants has increased in the last 30 years and generated 2333.963 m³/day in 2004 [1]. There is a trend in Egypt to apply desalination to meet the requirements of industry, tourism, petroleum, electricity, health and reconstruction. The desalination plants are located on the Red Sea coast, in south Sinai and on the northern coast [3].

The natural greenhouse effect raises the temperature of the planet to 33 °C, thus making it habitable. On average, 343 W/m² of sunlight fall on the earth, roughly 1/3 of which is reflected back into space. The other 2/3 reaches the ground, which re-radiates it as longer wavelength, infrared radiation. Some of this is blocked by GHG, thereby warming the atmosphere. Naturally occurring GHG include water vapor, CO₂, methane (CH₄) and nitrous oxide (N₂O). Reducing emissions of CO₂ could be achieved by switching to renewable energy [4].

Nature provides freshwater through the hydrologic cycle. The process is as follows: production of vapors above the surface of the liquids, the transport of vapors by winds, the cooling of air–vapor mixture, condensation and precipitation. This natural process is similar but on a small scale in basin type solar stills. Desalination of saline/brackish water to produce freshwater is easy and economical [5]. The solar still is a simple device that uses part of the collected solar thermal energy for evaporation of water contained in a basin within the still. The produced vapor condenses on the inner side of the cooler external sides and is collected as distilled water [6].

The daily solar still production in Europe is about 3–4 l/m² [7]. As Egypt is considered one of the richest countries of the world in terms of solar energy potential, its productivity is expected to be higher and, in fact, has already reached 10 l/m² per day. The energy required to pump 1 m³ of shallow water to the surface is 12 kW h [8].

All desalination processes require the application of solar energy in some form or other. One of these applications is the humidification–dehumidification method in a greenhouse structure for desalination and for crop growth. This application is suitable for remote areas. The greenhouse is divided into two parts. In one part are crops of a type that are irrigated by saltwater. The saltwater trickles down the front wall evaporator to mix with the air in the greenhouse. This saline humid air passes through a second rear wall evaporator and is further humidified to saturation point. Saturated air passes through the condenser, which is cooled, producing distilled water that is piped to storage in the second part of the greenhouse. In this second part are crops that are irrigated by fresh distilled water. A wide shallow greenhouse, 200 m wide by 50 m length, produced 125 m³/day of freshwater [9].

The objective of the present work is to select appropriate sites in Egypt for groundwater solar desalination by using GIS as a spatial decision support tool to help decision-makers. A number of input criteria are used that influence the choice of sites. AHP is a structured technique that helps decision-makers to find a site that best suits their goal and their understanding of the problem. In this paper, MCE based on simple additive weighting criteria was used to support spatial decision making. AHP is a widely used MCE method. AHP assists the decision-makers to simplify the decision problem by creating a hierarchy of decision criteria that best suits their goal and their understanding of the problem [10]. The procedure for using AHP can be summarized as follows: model the problem as a hierarchy containing the decision goal, the options for reaching it, and the criteria for evaluating the options; establish priorities among the elements of the hierarchy; synthesize these judgments to yield a set of overall priorities for the hierarchy; check the consistency of the judgments; come to a final decision based on the results of this process [11].

Methodology

A GIS SDSS Model is developed by defining and proposing suitable areas of groundwater solar desalination depending on a number of governing factors. The first step in the method-
ology requires the development of a digital GIS database containing spatial information. A number of thematic maps are prepared from topographic maps, hydrogeologic maps, environmental parameters and previous reports. The thematic maps represent solar radiation, aquifer depth, aquifer salinity, distance from the Delta and the Nile Valley, the incidence of flash floods, sand dunes, rock faults, and seawater intrusion in the North Delta. The weight of each factor was based on its estimated significance. Based on the weight of each factor and its class, the input rasters are weighted by importance and added together to produce an output raster. The steps are summarized below:

1. A numeric evaluation scale of 1–10.
2. The cell values for each input raster in the analysis are assigned values from the evaluation scale and reclassified to these values. This makes it possible to perform arithmetic operations on the rasters that originally held dissimilar types of values.
3. Each input raster is weighted, or assigned a percent influence, based on its importance to the model. The total influence for all rasters equals 100%.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Relationship between priorities and numbers in AHP rating procedure.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Priority</td>
</tr>
<tr>
<td>1</td>
<td>Most appropriate</td>
</tr>
<tr>
<td>3</td>
<td>Strongly appropriate</td>
</tr>
<tr>
<td>5</td>
<td>Moderately appropriate</td>
</tr>
<tr>
<td>7</td>
<td>Inappropriate</td>
</tr>
</tbody>
</table>

* Even numbers indicate between category priorities.

Fig. 1 Classification of solar radiation in Egypt, modified after [15].
The cell values of each input raster are multiplied by the rasters’ weights.

The resulting cell values are added together to produce the output raster.

In this study land use is classified in terms of least distance from the Delta and the River Nile where most of residential, agricultural or industrial activities are found. They all need freshwater – for drinking, irrigation, or industrial production – and this is given the same weight. The North Lakes in the North Delta represent an unsuitable seawater intrusion and are eliminated from consideration. The rest of Egypt is almost all desert i.e. there is no forest. Areas prone to flash floods, areas of sand dunes and areas of rock faults were also all eliminated from consideration, as was the seawater frontage that reached 40 km near Tanta city in the Delta [12].

Theoretically, there are other factors to take into account, such as the exact location of existing production wells and their yields, abstraction, pumping cost, and potential economic return over a fixed time period. However, at present, data on such factors are either unavailable, or not valid. So it is difficult to overlay the exact location of existing production wells because in Egypt the groundwater law is not strictly applied and there are many un-licensed wells. But a new groundwater law is being discussed, and once it is applied better information on existing production wells will become available.

Pumping cost is approximated by aquifer depth. The aquifers system in Egypt is classified into two types. The first type is the granular aquifers system, which includes the Nile Valley and Delta aquifer, coastal aquifer, Nubian Sandstone aquifer, and Mughra aquifer [13]. The second type is the fissured aquifer system, which includes the Fissured Carbonate aquifer.

Fig. 2 Classification of aquifer depth in Egypt, modified after [13].
The Nile Valley and Delta aquifer belongs to the Quaternary Period and consists of sand and clay layers. Its yield does not exceed 4 billion m$^3$/year and the digging depth ranges from 0 to 100 m; salinity ranges from 1500 ppm in the Nile Valley and the South Delta to reach 5000 ppm in the North Delta. The coastal aquifer belongs to the fourth geological age and consists of Oolitic limestone west of the Delta and calcareous sandstone in North Sinai. Its yield does not exceed 2 billion m$^3$/year and the digging depth is less than 2 m in Sinai, where its salinity exceeds 2000 ppm. The Nubian Sandstone aquifer covers 90% of Egypt. It belongs to the Paleozoic-Lower Cretaceous geological age and consists of shale and sandstone layers. Its yield exceeds 100 billion m$^3$/year and the digging depth ranges from 0 m to 500 m; its salinity ranges from 1000 to 4000 ppm. The Moghra aquifer belongs to the Miocene age. Its yield exceeds 1 billion m$^3$/year and the digging depth ranges from 0 to 200 m; its salinity ranges between 1000 and 15,000 ppm. The Fissured Carbonate aquifer covers 50% of Egypt. It is considered to be one of the poorest aquifers in Egypt. It belongs to different geological ages and consists of shale and sandstone layers. Its yield exceeds 100 billion m$^3$/year and the digging depth ranges from 0 m to 500 m; its salinity ranges from 2100 to 16,000 ppm [13].

In this study areas are classified in terms of a weighted linear combination: factors are combined by applying a weight to each followed by a summation of the results to yield a suitability map (Eq. (1)) [14].

\[ S = W_i X_i \]

where \( S \) is the suitability, \( W_i \) the weight of factor \( i \), and \( X_i \) the criterion score of factor \( i \).

The AHP decision making technique uses weights on a 7-point continuous scale, as illustrated in Table 1 and results in a classification of zonal areas for potential groundwater desalination. 

![Fig. 3](image-url) Classification of aquifer salinity in Egypt, modified after [13].
solar desalination. The zones are ranked in descending order to help decision-makers.

Results

The results of this study show that the higher the value of the solar radiation, the higher is the suitability of an area for groundwater solar desalination. Ten different classes of solar radiation are defined, see Fig. 1.

Aquifer digging depth is determined according to geomorphologic criteria. The depth of the water table must be taken into consideration as a highly important factor: the lower the value of the digging depth, the higher is the suitability of an area for groundwater solar desalination. This criterion categorizes an area into eight zones, varying from shallow to very deep. Suitable aquifer depths for low cost digging wells are classified as in Fig. 2.

Aquifer salinity is determined according to geomorphologic criteria. Seven different classes of aquifer salinity are defined: the higher the value of the aquifer salinity, the lower is the suitability of the area for groundwater solar desalination. Suitability of aquifer salinity for low cost desalination process is classified as in Fig. 3.

The distance of the area from the Nile Valley and Delta is determined according to hydrologic criterion. This criterion has a direct effect on land suitability for new sustainable development. Land further away from the Nile Valley and Delta gets lower preference. Accordingly, ten zones were classified, see Fig. 4.

A general environmental criterion was determined by reference to natural morphology and its impact on the prevention of sustainable development. Areas prone to flash floods, or comprising sand dunes or rock faults were eliminated from consideration, see Fig. 5.

![Fig. 4](image_url) Classification of distance from Nile Valley and Delta.
Discussion

The following weights were applied: solar energy 40%, aquifer depth 30%, aquifer salinity 15%, and distance from the River Nile and Delta 15%. Superposing all the raster type layers, including geomorphologic, hydrologic and solar radiation criteria, the final zoning (classified as most appropriate, fairly appropriate or inappropriate) were identified, see Fig. 6.

The lowest solar radiation occurs in the north of Egypt, where cloud increases. Solar radiation increases further southwards as clear skies predominate. Solar radiation decreases to a small extent over mountainous areas, especially in the Sinai and Red Sea mountains, due to the formation of orographic clouds [15]. Brackish groundwater is found under most of Egypt. The environmental benefits of solar energy compared with traditional electrical energy can be calculated according to the carbon market, which uses MtCO2e metric tons or tons of carbon dioxide equivalent. The power required to produce 1 m³ of desalinated water is 300 MJ emitting 12.83 kg CO₂ in a thermal desalination process, while in a reverse osmosis desalination process the values are 63.8 MJ and 4.4 kg CO₂, respectively. These emissions could be reduced by almost 99% using solar energy. Desalination of brackish groundwater by reverse osmosis is already practised in Egypt; the energy requirement ranges from 1 to 3 kW h/m³ and this produces MtCO2e from 0.0007 to 0.0021. The price of MtCO2e is 10€ and so this strategy would save 7€–21€ for every 1000 m³ of solar desalinated water [16]. The potential of groundwater solar desalination is greatest in Upper Egypt’s big cities (Assuit, Sohag, Qena, Aswan, and Toshka) and the ElKharga Oasis. All drainage water

Fig. 5  Flash floods, sand dunes and rock faults in Egypt, modified after [13].
in Upper Egypt, south of Cairo, flows back into the Nile and the irrigation canals; this amount is estimated at 4 km$^3$/year and can be treated by solar desalination. Discharged groundwater in Upper Egypt, south of Cairo, will reduce high level groundwater and so help inhibit water logging and soil salinization problems is the area. Additional amounts of groundwater can be discharged from Upper Egypt to south of Cairo. This additional groundwater will encourage vertical discharge of drainage water and as a result will permit dual use of surface water and groundwater. Also a decrease in the groundwater level of 3 m in the area from Upper Egypt to south of Cairo will put the aquifer under phreatic conditions allowing the storage of about 5 billion m$^3$ of water that could be used as an annual or seasonal reservoir of groundwater. This additional amount of water will decrease water release from the High Dam, especially in low level flood periods (such as 1979–1988) [13]. The South Sinai Coast at Suez Gulf, ElFaiyum, and BeniSuef are strongly appropriate areas. Remote areas of special interest are the North Western Coast, the North Sinai Coast, and the Southern Oasis, which are moderately appropriate as is the South Delta. Since the 1970s, approximately 1000 land holders have developed successful commercial farming based on groundwater irrigation on the desert fringes to the west of the Nile Delta along the Cairo-Alexandria Highway, between 45 and 80 km. These developments cause rapid aquifer depletion and increased groundwater salinity, making water quality and availability the main constraints to sustained agricultural activity in the area. Water extraction by the year 2002 reached 1080 million m$^3$ annually. Due to excessive extraction, the water table is expected to drop further, at an

![Priority of suitable areas for groundwater solar desalination in Egypt.](image)
average annual rate of 1–2 m/year. The main source of recharge is seepage from surface water canals and excess irrigation in the surface water areas [17]. The West Delta development area prefers to use surface water and Mediterranean Sea desalination rather than groundwater. Generally in the Delta region there is a huge amount of brackish groundwater and it is polluted from different discharges (especially agricultural and municipal). The increase in population in the Delta, together with agricultural and industrial development, has increased pollution of surface water and groundwater. The Delta is the most populated region in Egypt and the aquifer underlying it has the highest potential for drinking and domestic purposes [18]. Excess discharging of groundwater in the Delta would increase soil salinity and decrease the groundwater level in the Delta and the Western Desert Oases. This would result in an advance of the Mediterranean saline seawater front. This would decrease the fresh groundwater level and therefore increase the deep wells’ drilling cost and hence decrease freshwater in the Oasis, where the highest water level is ~30 m below sea level. It affects discharge in the Western Desert oases, especially Siwa, negatively [12]. For the Delta area low price brackish water desalination without increase groundwater discharge is suitable as a treatment process.

Conclusions and recommendations

A GIS Spatial Decision Support Model is developed for proposing suitable areas of groundwater solar desalination depending on a number of governing factors; suitable solar radiation; suitable aquifer depth for low cost digging wells; suitable aquifer salinity for low cost desalination process; nearness to the Nile Valley and Delta; unsuitable incidence of flash flooding or the presence of sand dunes or rock faults; unsuitable seawater intrusion in the North Delta. The results of this study determined areas for groundwater solar desalination with varying suitability, ranked in descending order to help policy makers in Egypt. Groundwater solar desalination is suitable for remote regions, reducing greenhouse gases. Also, it is useful for poor communities suffering from polluted water and water-borne diseases.

Further environmental and social studies are recommended to determine the priorities for the safe discharge of groundwater solar desalination in each governorate in Egypt. Preliminary plans for sustainable development according to the quantity and quality of desalinated groundwater can be discussed with the government and the public. Consequently, further studies are needed to determine the productivity of solar desalination in Egyptian conditions in different pilot areas in each governorate.

References