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Energy-water nexus in East Iraq: capacity potential analysis and spatial assessment for an integrated CSP solar power & RO brackish water desalination plant in Khanaqin area

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Abstract

In this research, an analysis of site suitability and potential desalination capacity for an integrated concentrated solar power (CSP) and reverse osmosis (RO) system can be established to overcome water-energy nexus problems such as water supply shortage, fossil fuel carbon emission, and increasing power consumption in Khanaqin area, East Iraq. Regarding various environmental and economic criteria, the analysis employed different methods and tools: analytical hierarchy process (AHP) method, additive weighting method for location selection (SL), and kriging interpolation with map algebra spatial analysis tools in ArcGIS software. The chosen criteria were assessed by using the rating method, and then the relative weight of each criterion was determined. Site suitability assessment results showed that only 0.05% of the study area, represented by thirteen sites, was highly suitable for the integrated CSP-RO system. Considering higher potential desalination capacity of the integrated CSP-RO system, the number of suitable sites was further refined, therefore only two plant sites were suggested for optimum desalination capacity. The current study helps to quantify factors related to establishing and operating combined CSP and RO plant, which aid for further insight investigations on solar and water resources availability of similar systems for different areas around the world.

Key words: AHP, groundwater, site selection, solar energy, surface water, water treatment

Highlights

- A process of site selection of integrated CSP-RO plant by combining AHP, additive weight and kriging interpolation in ArcGIS is presented.
- Economic and environmental criteria for site selection play a main role in the potential desalination capacity of an integrated CSP-RO plant.
- Synergies of site and operational characteristics in optimization of desalination capacity for an integrated CSP-RO plant.

INTRODUCTION

The energy supply issue is increasingly becoming important in Iraq and in many countries, as there is an acute and insurmountable problem of power shortage that has persisted for decades. One of the main reasons that made the power shortage insoluble is dependence on the regular ways of production. Besides, the growth of population and urbanization in Iraq increases the electricity demand and poses more challenges to the existing problem (Rashid *et al.* 2012). Renewable energies

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that can be generated from natural sources such as solar or wind energies may respond to the ongoing power problem in Iraq (Chaichan & Kazem 2018).

Diyala province in general, including Khanaqin area, is suffering from diminishing groundwater quality and increasing salinity, which affect both the urban and rural areas (Mohamad 2010). Surface water resources in the area are suffering from the same problem as well (Al-Hamdany & Al-Dawodi 2017). In the Khanaqin area, with the scarcity of freshwater resources, saline water became the main source of water supply for the people of the area. The groundwater in the area reaches a total hardness of 654 mg/L, while the surface water, Alwand River, reaches a total hardness of 724 mg/L (Issa & Alshatteri 2018). Water resources are considered to be brackish in nature when the total dissolved solids (TDS) range from 500 mg/l to 33,000 mg/l (Gray *et al.* 2011); therefore, water resources in the Khanaqin area, surface and groundwater, fall into this category.

The need to ensure continuous and reliable sources of power and safe water in the area pushes for more consideration of the relation between water and power. The growing population and scarcity of water resources and the degradation of the quality with the increasing consumption of water and power lead the decision-makers to search for solutions, some of which are exhaustive options like carrying water from distant areas or constructing a reverse osmosis (RO) desalination plant, one in which a semipermeable membrane only allows water molecules to move through while maintaining other constituents, which are then removed as waste. Another trend to resolve this ongoing water-energy problem is depending on sustainable energy sources.

The concentrated solar power (CSP) system is one of the most promising solutions in this field (Cavallaro *et al.* 2019). In CSP systems, the concentrated sun rays are used to generate the necessary heat and then the steam rotates power turbines (Lovegrove & Stein 2012). Combining these types of power plants with RO desalination plants provides a great opportunity to tackle many constraints related to the energy-water nexus in the area. Also, an integrated CSP-RO plant achieves environmental sustainability, by which the conventional use of fossil fuels that emit pollutants is replaced by a renewable and clean source of energy (Corona & San Miguel 2015).

In any design consideration of a water treatment plant, especially an integrated one with a solar energy plant, the spatial and water resources features of the concerned area should be involved in design calculations to reach an optimum design, as illustrated in Figure 1. In the literature, many works have been investigated in the technical, operational, economical, and environmental aspects of integrated CSP-RO desalination plants. Various schemes of CSP are being employed in the world: the parabolic trough collector (PTC), concentrated solar thermoelectric (CST), parabolic dish systems (PDS), and the linear Fresnel reflector (LFR) (Goosen *et al.* 2014). The PTC system

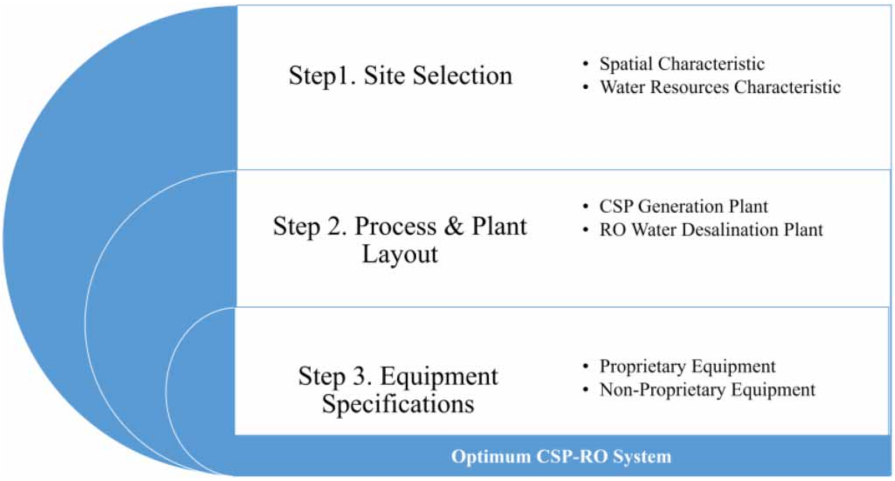

Figure 1 | Design consideration for an integrated CSP-RO water plant.

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showed more promising potential to generate electricity (Gharbi *et al.* 2011). The economic characteristics of CSP systems have been sufficiently explained (Weinstein *et al.* 2015). The issue that has been poorly touched on by many previous works regarding the optimization of integrated CSP-RO systems is embedding the geolocation factor in their calculations.

This work evaluates the optimization of the coupling between the CSP system and RO desalination locations in Iraq. Spatial variability and topography of the study area are investigated by using GIS (ArcGIS software, version 10.6.1; ESRI, Redmonds, CA) to assess the potential of an integrated CSP-RO system to solve the combined problem of power and clean water supply in the area. Temporal and spatial characteristics of water sources and solar irradiance have been taken into account in the evaluation. As a result, the aim of this research is to conduct a spatial and water resource capacity study in order to design an optimal CSP-RO desalination system.

MATERIALS AND METHODS

The study area

Khanaqin area is located between latitudes 34° 17′ 15″- 34° 24′ 35″ North and longitudes 45° 16′ 30″-45° 30′ 10″ East. As shown in Figure 2, Khanaqin district covers an area of 60,000 m^2. The population of the area is 150,000 inhabitants, with a few industrial constructions. The physiographic features of the area mainly comprise an alluvial plain with some foothills in the Northeast that have a higher altitude of 200 m a.s.l. (Issa 2019). Alwand River is the only river system in the area. Alwand dam was established on this river in 2012, creating the Alwand Lake, which stores about 37 million m^3 of water used during droughts of Alwand River in the summer season (Almada Paper 2012). The climate of

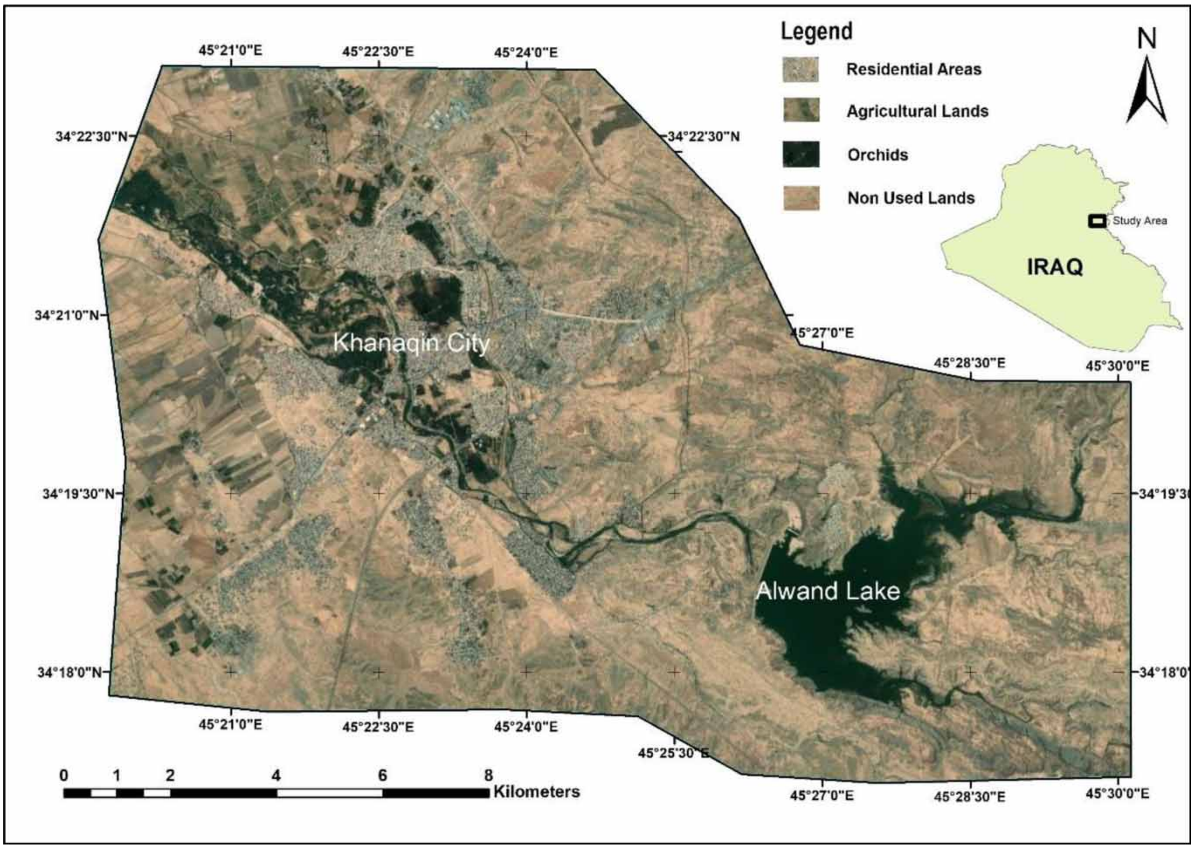

Figure 2 | The study area showing the Khanaqin city and Alwand Lake locations, the coordinate system of the map is according to the World Geodetic System 1984 (WGS84) geodetic system.

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the study area is continental semiarid by potential evaporation (Kharrufa 1985), and hot semi-arid climates according to the climate classification by Köppen-Geiger (Peel *et al.* 2007).

Spatial analysis

The potentials of the integrated CSP-RO system were estimated, spatially resolved, of solar irradiance with surface or/and groundwater resources in Khanaqin area by using a geostatistical analysis tool of ArcGIS 10.6.1.

Data collection

Data were obtained from different sources: the yearly and daily total solar for the photovoltaic electricity potential, over 0.01 degrees cells for latitude and longitude, was obtained from freely available online solar resource maps from The World Bank Group (2017); TDS concentrations for groundwater wells and surface water in the area was collected using a potable TDS measurement device; groundwater well locations and depth were acquired personally. The other spatial data were obtained from 1:2,000 topographic maps, GPS survey, ASTER, and free online available satellite images provided by Google Maps imagery ©2021, Maxar Technologies, CNES/ Airbus, Imagery CNES/ Airbus, Landsat/ Copernicus, Maxar technologies (Resolution 15 m per pixel) (Google Maps 2021).

Configuration of the integrated CSP-RO system

The configuration of the integrated CSP-RO system (Figure 3) was adapted from Gastli *et al.* (2010). From different solar water desalination plants, this convenient and also economical type meets the requirements for water quality and area characteristics.

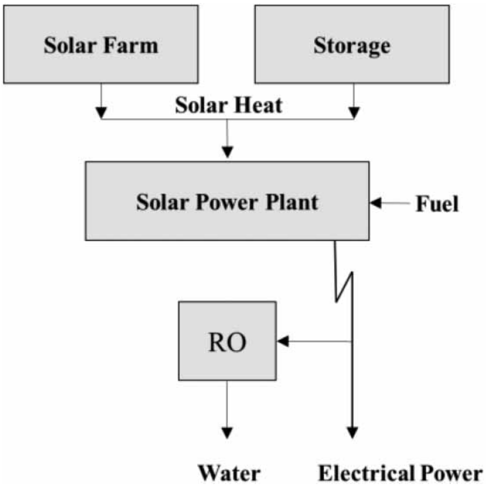

Figure 3 | Configuration and power generation of the integrated CSP-RO system.

Methodology

The analytical hierarchy process (AHP) was used to determine the best location to establish the integrated CSP-RO system (Saaty & Vargas 2012). The site selection step was the first and essential step for the integrated CSP-RO process design. Furthermore, the site selection comprises three main stages: determining the most significant weighting factors regarding the integrated CSP-RO system efficiency; checking the validity of weighting factors that were chosen in stage one; using the ArcMap 10.6.1 analysis tools to identify the optimum location (where a higher water treatment rate

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can be achieved at the lowest economic cost). After that, the potential capacity of the integrated CSP-RO system was estimated depending on several assumptions.

Factors identification

Factors affecting the site selection process are determined as follows and presented in Figure 4.

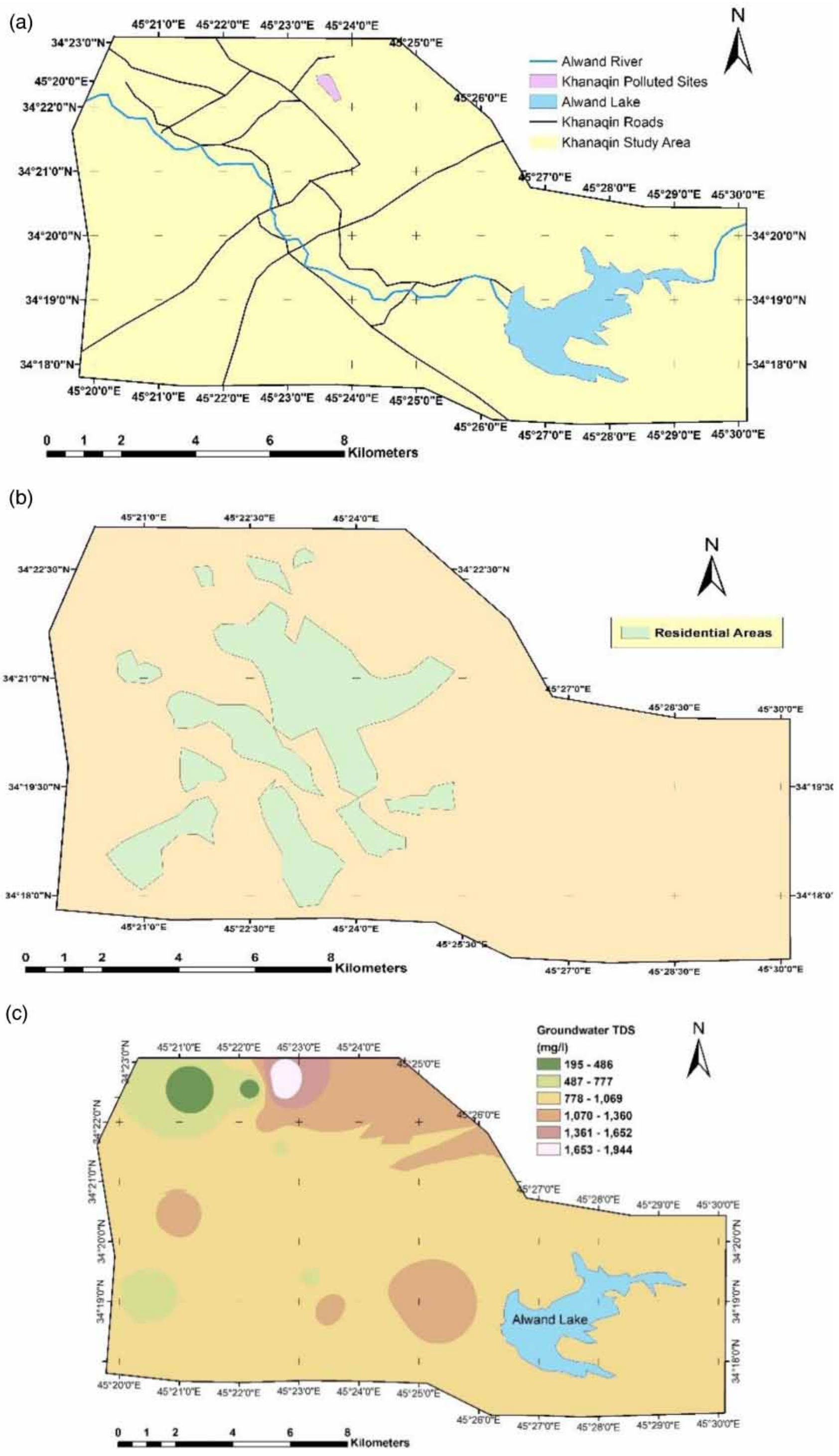

Figure 4 | (a) Roads, water resource, and possible polluted area map of the study area. (b) Residential areas map of the study area. (c) Groundwater TDS map of the study area. (d) Groundwater level map of the study area. (e) Solar irradiance map of the study area. (f) Slope degree map of the study area. *(Continued.)*

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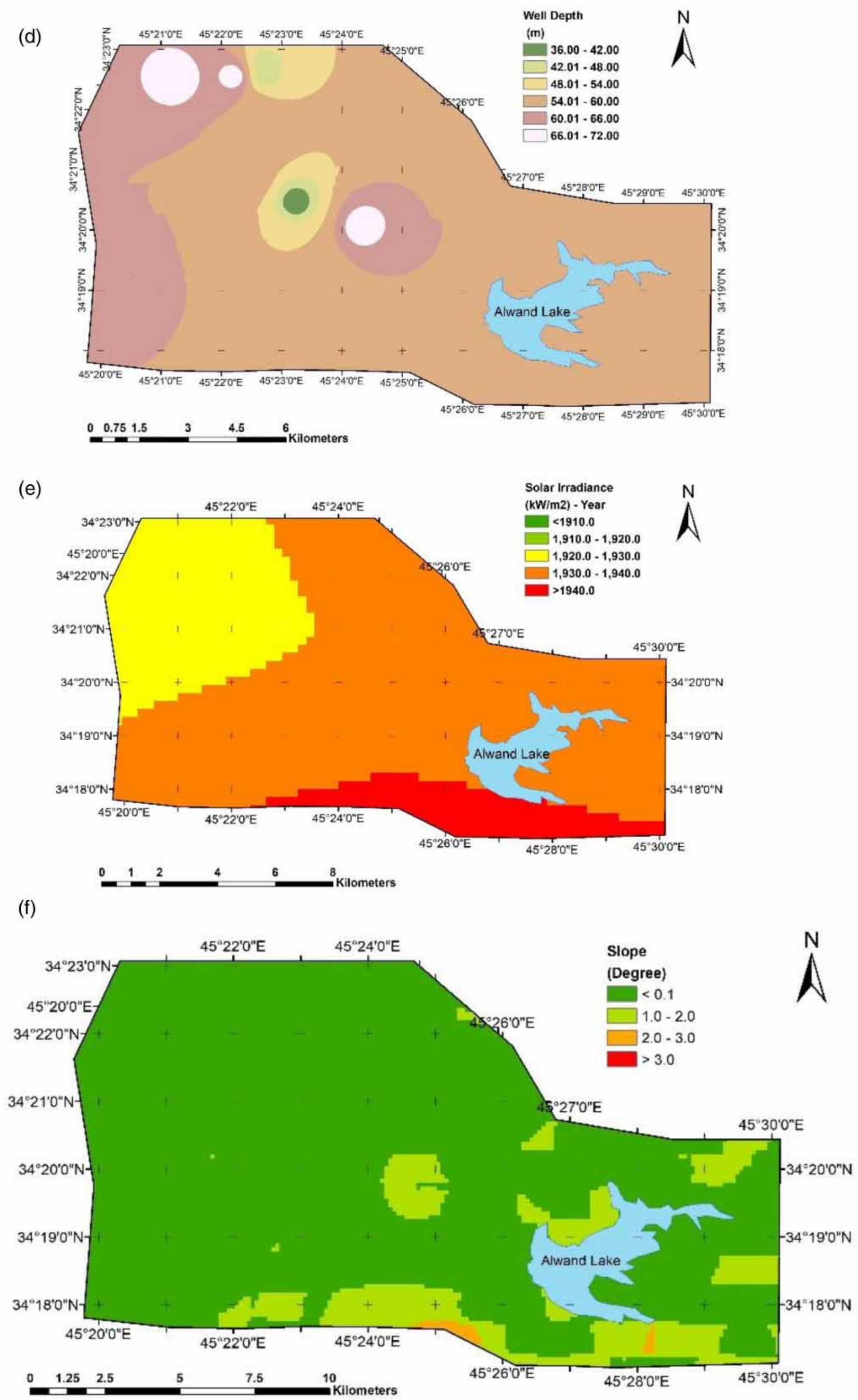

Figure 4 | Continued.

Annual average solar irradiance. High levels of solar irradiance have a higher potential to produce power, which is essential for solar RO water desalination systems to treat brackish or saline water (Eltawil *et al.* 2009).

TDS concentration. Feed water salinity level is the most substantial factor considerably controlling the cost of RO desalination operation, lower feedwater salinity is favorable as it makes the integrated

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CSP-RO system work at lower power and lower osmotic pressure difference requirements (Aydin & Sarptas 2020).

Groundwater depth. Water table depth is a significant factor as the lower depth indicates the lower pumping cost for groundwater to solar RO water desalination systems (Salim 2012).

Slope. Areas of a high slope may decrease the host capacity of solar systems, so the maximum acceptable slope limit should be less than 3% (Uyan 2013). In the Northern hemisphere, flat or slightly south-facing lands are preferred for solar power plants (Koc *et al.* 2019).

Distance from residential areas. Water treatment plant sites close to residential areas are preferable to reduce treated water pumping and distribution costs; nonetheless, installing an integrated CSP-RO system site near residential areas, less than 500 m, could cause an undesirable environmental impact on those areas (Uyan 2013).

Distance from roads. The closest location to main roads means lower cost of installation and the site is easier to reach (Sánchez-Lozano *et al.* 2013).

Distance from possible polluted sites. To avoid any possibility of feedwater that is influenced by polluted sources like a sanitary landfill, a suitable buffer has been adopted in site selection for the integrated CSP-RO system.

Distance from water sources. A closer site for the integrated CSP-RO system to both surface and groundwater sources reduces the operation and pumping costs. Surface water sources (Alwand Lake) are an important criterion for the CSP-RO siting, which is the main source of water besides groundwater in the area. Alwand River was not included in the planned CSP-RO site selection criteria because the river is facing problems of high pollution rate, drying up in summer season, and intermittent discharge rate (Abdulrahman 2017).

Weighting of factors

The factors weighting of the integrated CSP-RO system were specified according to many criteria. These factors mainly belong to the environmental and economic main groups. The environmental criteria comprise the distance from water resources and distance from possible polluted water sources. While the economic criteria involve the distance from residential areas and roads, TDS concentration, groundwater depth, slope, and annual average solar irradiance.

The weighting parameters have been chosen to achieve the main objective of optimum efficiency of the integrated CSP-RO system. According to AHP, these weighting parameters are listed in Table 1 with their priorities to identify the optimum location of the integrated CSP-RO system, with an integer value rating from 1 to 9. The importance of each parameter may vary according to the decision maker's opinion and case study condition.

A pairwise matrix, matrix A, would be constructed based on priority values (Saaty & Vargas 2012) as presented in Table 1, as the following Equation (1).

$$matrix\ A = \begin{bmatrix} a_{1,1} & \dots & a_{1,n} \\ \dots & a_{i,j} & \dots \\ a_{m,1} & \dots & a_{m,n} \end{bmatrix},\ a_{i,j} = \frac{w_i}{w_j} \tag{1}$$

where w_i and w_j are the priority value for the elements i and j, respectively.

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Table 1 | The priority of site selection factors for the integrated CSP-RO system

Factor	Criteria	Priority	Symbol
Distance from water resources	Environmental	7	w_1
Distance from possible polluted sites (sanitary landfill)	Environmental	8	w_2
Distance from roads	Economic	5	w_3
Distance from residential areas	Economic	7	w_4
TDS concentration	Economic	7	w_5
Groundwater depth	Economic	6	w_6
Slope	Economic	8	w_7
Annual average solar irradiance	Economic	9	w_8

Table 2 presents the established pairwise matrix regarding the site selection of the integrated CSP-RO system. After the pairwise matrix A was constructed, the weighting step, including the eigenvalue for the ith vector, equals the geometric mean of the ith row elements product, and the priority vector equals the normalized weights of each criterion, and are calculated as shown in Table 2. The priority vector is calculated by Equation (2) (Chabuk *et al.* 2016).

Table 2 | The pairwise comparison matrix for integrated CSP-RO system site selection[a]

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	Eg_i	Wr_i [b]
w_1	1.00	0.88	1.40	1.00	1.00	1.17	0.88	0.78	1.00	0.12
w_2	1.14	1.00	1.60	1.14	1.14	1.33	1.00	0.89	1.14	0.14
w_3	0.71	0.63	1.00	0.71	0.71	0.83	0.63	0.56	0.71	0.09
w_4	1.00	0.88	1.40	1.00	1.00	1.17	0.88	0.78	1.00	0.12
w_5	1.00	0.88	1.40	1.00	1.00	1.17	0.88	0.78	1.00	0.12
w_6	0.86	0.75	1.20	0.86	0.86	1.00	0.75	0.67	0.85	0.11
w_7	1.14	1.00	1.60	1.14	1.14	1.33	1.00	0.89	1.14	0.14
w_8	1.29	1.13	1.80	1.29	1.29	1.50	1.13	1.00	1.28	0.16

[a] $\lambda_{max} = 8.460$, CI = 0.0657, RI = 1.41, and CR = 0.0466 < 0.1.
[b] Wri is the normalized relative weight of ith criterion.

$$Pr_i = \frac{Eg_i}{\sum_{i}^{n} Eg_i} \tag{2}$$

where Eg_i is the eigenvalue for the ith vector, Pr_i is the ith priority vector, and n is the number of columns or rows within matrix A. The consistency of the developed comparison pairwise matrix, λ_{max}, the consistency index, CI, and consistency ratio, CR, is determined as proposed by Saaty (1980); the value of the random index, RI, was obtained for $n = 8$ from the table of the random index for matrices of various sizes proposed by Chang *et al.* (2007).

The calculated CR of 4.66% is less than the standard level of 10%, indicating consistency of the system in the pairwise comparison, meaning that the consistency is approved.

Classifying and rating

Based on the decision maker's opinion, all the relevant factors in the site selection process for an integrated CSP-RO system can be quantitatively classified into major grades or classes (Table 3). Therefore,

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Table 3 | Rating values for the factors related to site selection of integrated CSP-RO system

Factor	Units	Weight/Wr_i	Priority	Buffer zone	Rating
Distance from water resources (Alwand Lake)	(m)	0.12	7	<100	10
				100–250	8
				250–500	6
				500–1,000	4
				1,000–1,500	2
				>1,500	0
Distance from possible polluted sites (sanitary landfill)	(m)	0.14	8	>3,000	10
				1,500–3,000	8
				1,000–1,500	6
				500–1,000	4
				300–500	2
				<300	0
Distance from roads	(m)	0.09	5	<100	10
				100–200	8
				200–300	6
				300–400	4
				400–500	2
				>500	0
Distance from residential areas	(m)	0.12	7	<500	0
				500–600	10
				600–700	8
				700–800	6
				800–900	4
				>900	0
TDS concentration	(mg/l)	0.12	7	<500	10
				500–750	8
				750–1,000	6
				1,000–1,500	4
				1,500–2,000	2
				>2,000	0
Groundwater depth	(m)	0.11	6	<2	10
				2–10	8
				10–40	6
				40–60	4
				60–80	2
				>80	0
Slope	(degree)	0.14	8	<1.0	10
				1.0–2.0	6
				2.0–3.0	4
				>3.0	2
Annual average solar irradiance	(kWh/m^2)	0.16	9	>1,800	10
				1,700–1,800	8
				1,600–1,700	6
				1,500–1,600	4
				1,400–1,500	2
				<1,400	0

the eight site selection related factors investigated in this work are of quantity type. The rating of site selection factors is given as an index, an integer value for each range is prescribed in scales. The designated indices range from 10, the maximum rating, to 0, the minimum rating (Al-Madhlom *et al.* 2019).

Geospatial analysis

The spatial analysis in this work was performed by using ArcGIS 10.6.1. A total of eight layers for the criteria were prepared by using the interpolation tool. Each layer map was categorized into a

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particular scoring range. Then the layer maps were entered in the Map Algebra tool, applying Equation (3), a summation of the products of the ith criterion score by the normalized weight of the ith criterion, to identify location suitability.

Then, the objective function of location selection can be identified with Equation (3) proposed by Javaheri *et al.* (2006).

$$LS = \sum_{i}^{n} W_i S_i \tag{3}$$

where LS represents location suitability, S_i the score of the ith criterion, W_i the normalized relative weight of the ith criterion, and n is the number of criteria.

Model assumptions for the potential capacity of the integrated CSP-RO system

The required power for the RO desalination is stated by Equation (4), proposed by Aminfard *et al.* (2019)

$$P_{desalination} = P_{RO} + P_{pumping} \tag{4}$$

where, $P_{desalination}$ is the total power for the desalination plant (W), P_{RO} is the power for the RO desalination process (W), and $P_{pumping}$ is the power for pumping the feed water from sources and the treated water to the city (W).

$P_{pumping}$ in Equation (4) is written in more detailed form as Equation (5)

$$P_{pumping} = P_{pgw} + P_{psw} \tag{5}$$

where, P_{pgw} is the power for groundwater pumping to the RO plant (W) and P_{psw} is the power for surface water pumping to/from the plant (W).

The power for a RO desalination process is calculated by Equation (6), depending on a function derived by Stillwell & Webber (2016).

$$P_{RO} = Q_{Cap}\,(315.8 * TDS_{feed} + 13{,}680 * 10^3) \tag{6}$$

where, Q_{cap} is the treated water flow rate capacity of the RO system (m^3/s) and TDS_{feed} is the average TDS of feed water that comes to the RO plant (mg/l). Nonetheless, Equation (6) was derived for an empirical RO plant and it might not give an exact evaluation for RO energy intensity of the investigated RO plant in this study; this deviation is ignored as the equation is mainly used only for comparative purposes.

The P_{pgw} is calculated by Equation (7) adopted from Rubio-Aliaga *et al.* (2019)

$$P_{pgw} = \frac{(Q_{gr} * \gamma * W_D)}{\eta_{Mg}} \tag{7}$$

where, Q_{gr} is the groundwater feed (m^3/s), γ (where $\gamma = \rho.g$) is the specific weight of water ($9.81 \times 10^3\ N/m^3$), η_{Mg} is the pumping efficiency of the motor system (-), and W_D is well depth (m).

The power of surface water pumping P_{psw} is calculated according to Equation (8) as reported by Vieira *et al.* (2014)

$$P_{psw} = \frac{(Q_{sr} * \rho * g * H_T)}{\eta_{MS}\eta_P} \tag{8}$$

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where, Q_{sr} is the surface water flow rate (m^3/s), ρ is water density (1,000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), H_T is the total head (m), η_{MS} is the motor efficiency (-), and η_P is the pumping efficiency (-). The total head is the summation of the friction head loss h_f (m) and the geometrical head h_{geo} (m), as stated in Equation (9).

$$H_T = h_f + h_{geo} \tag{9}$$

The friction head loss h_f is determined according to the Darcy-Weisbach equation, as reported by Bai & Bai (2005) in Equation (10)

$$h_f = \frac{4fLv^2}{2gD} \tag{10}$$

where, f is the Darcy friction factor (-), L is the equivalent length of pipes used for surface water pumping (m), v is the design water velocity (m/s), g is the gravitational acceleration (9.81 m/s^2), and D is the diameter of the pipe (m).

The power generated from a solar system is estimated by Equation (11) proposed by Aybar *et al.* (2010)

$$P_{CSP} = \eta_S A_S R_{SP} \tag{11}$$

where, P_{CSP} is power generated from CSP (W), η_S is the efficiency of the CSP solar power plant (-), A_S is the surface area of the PV cells in CSP (m^2), and R_{SP} is daily solar radiation (W/m^2).

To estimate the potential capacity, the water desalination volumetric flow rate (Q_{cap}) for the thirteen sites of highest site suitability was determined using the analytical hierarchy process method (AHP).

Assuming that the values of P_s and $P_{desalination}$ are equal, and then solving the flowrate of total water feed (Q_T), Equation (12) was derived

$$Q_{cap} = \frac{\eta_S A_S R_{SP}}{\left[13{,}680 * 10^3 + 315.8 * TDS_{feed} + \frac{\gamma W_D}{\eta_{Mg}} + \left(\frac{\rho g}{\eta_{MS}\eta_P} * \left(h_{geo} + \frac{4fLv^2}{2gD}\right)\right)\right]} \tag{12}$$

The spatial variability of solar radiation, well depth, distance from surface water sources, TDS of feed water, and geometrical head are calculated by using ArcGIS 10.6.1, to solve Equation (12) for potential water desalination capacity Q_{cap} in the study area (Kjellsson & Webber 2015). Using the methodology presented, the design equations from 4 to 10 were applied with the derived mathematical model for estimation of water desalination potential capacity (Equation (12)).

RESULTS AND DISCUSSION

Site selection criteria

Slope

Most of the considered area is of a slope degree less than 1.0 (score 10), which is more suitable for the construction of a solar plant (Figure 5(a)).

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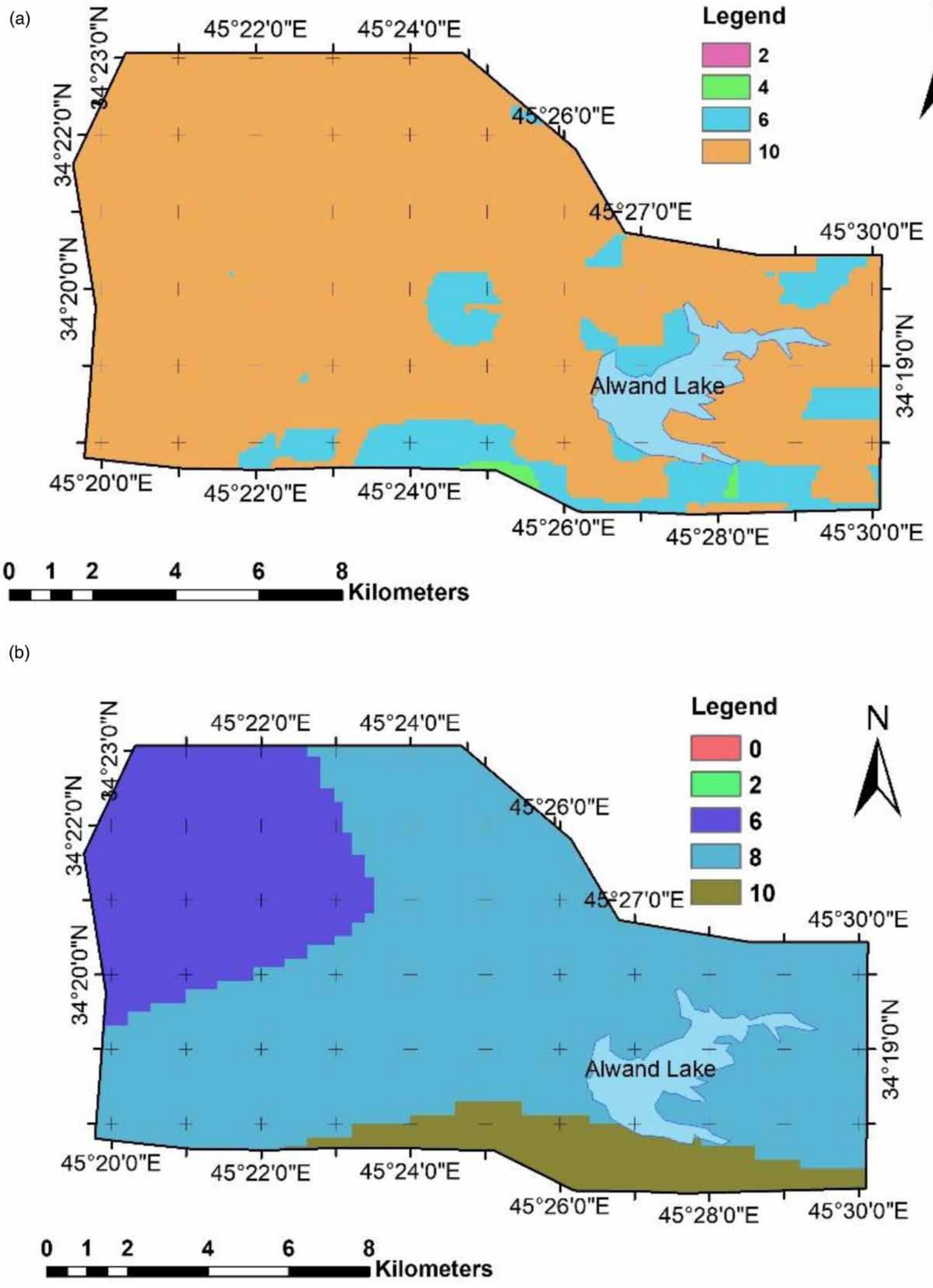

Figure 5 | (a). Site selection criteria rating map for slope of Khanaqin study area. (b). Site selection criteria rating map for solar irradiance of Khanaqin study area. (c). Site selection criteria rating map for groundwater depth of Khanaqin study area. (d). Site selection criteria rating map for groundwater TDS of Khanaqin study area. (e). Site selection criteria rating map for distance from surface water sources of Khanaqin study area. (f). Site selection criteria rating map for distance from roads of Khanaqin study area. (g). Site selection criteria rating map for distance from residential areas of Khanaqin study area. (h). Site selection criteria rating map for distance from the possible polluted site (city sanitary landfill) of Khanaqin study area. *(Continued.)*

Solar irradiance

Figure 5(b) of the resultant map for solar irradiance rating shows that the study area is receiving a sufficient and convergent annual solar irradiance (score 8), meaning that most of the area is suitable

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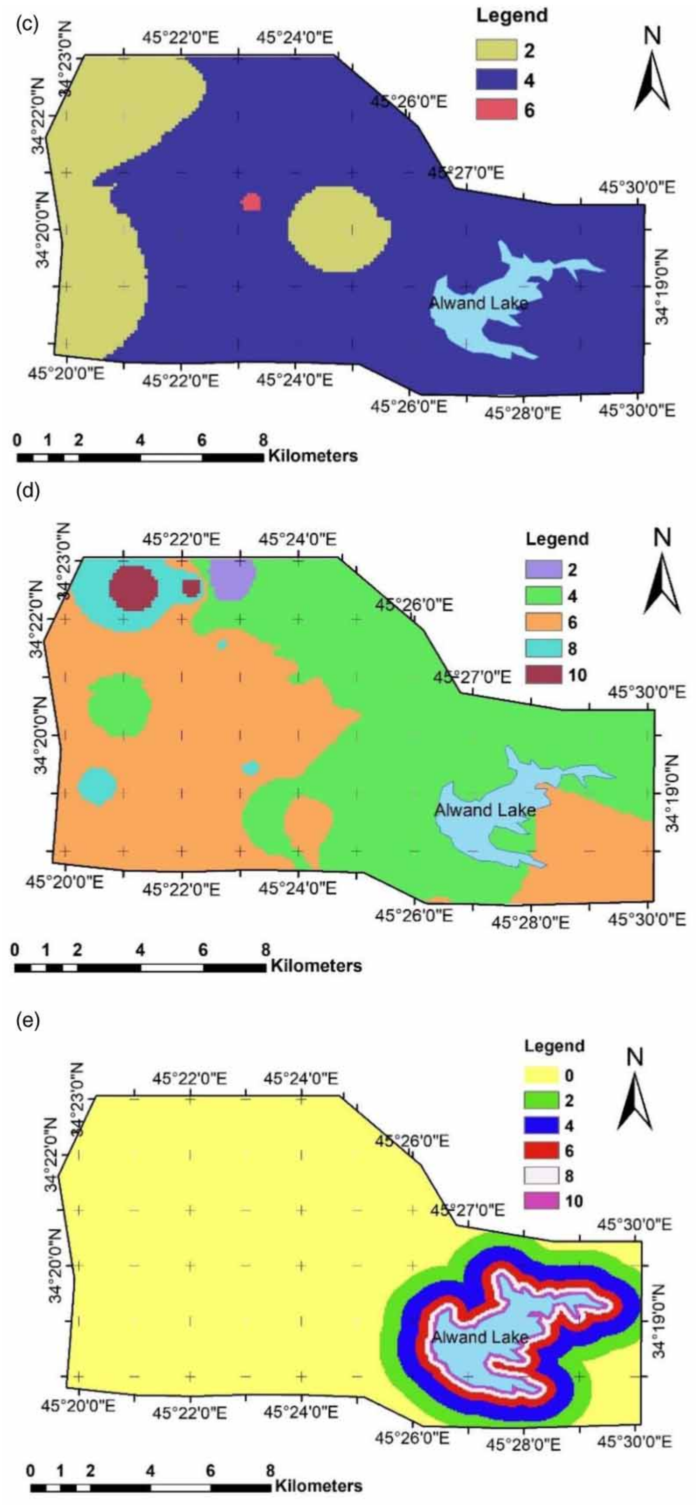

Figure 5 | Continued.

to establish an integrated CSP-RO plant. It is worth mentioning that a strip located south of the study area has slightly higher solar irradiation (score 10) than other parts.

Groundwater depth

Figure 5(c) displays the map of well depth rating in the study area, showing that the groundwater level in the area ranges from 10 to 80 m (scores from 2 to 6). Kriging interpolation tool in ArcGIS software was

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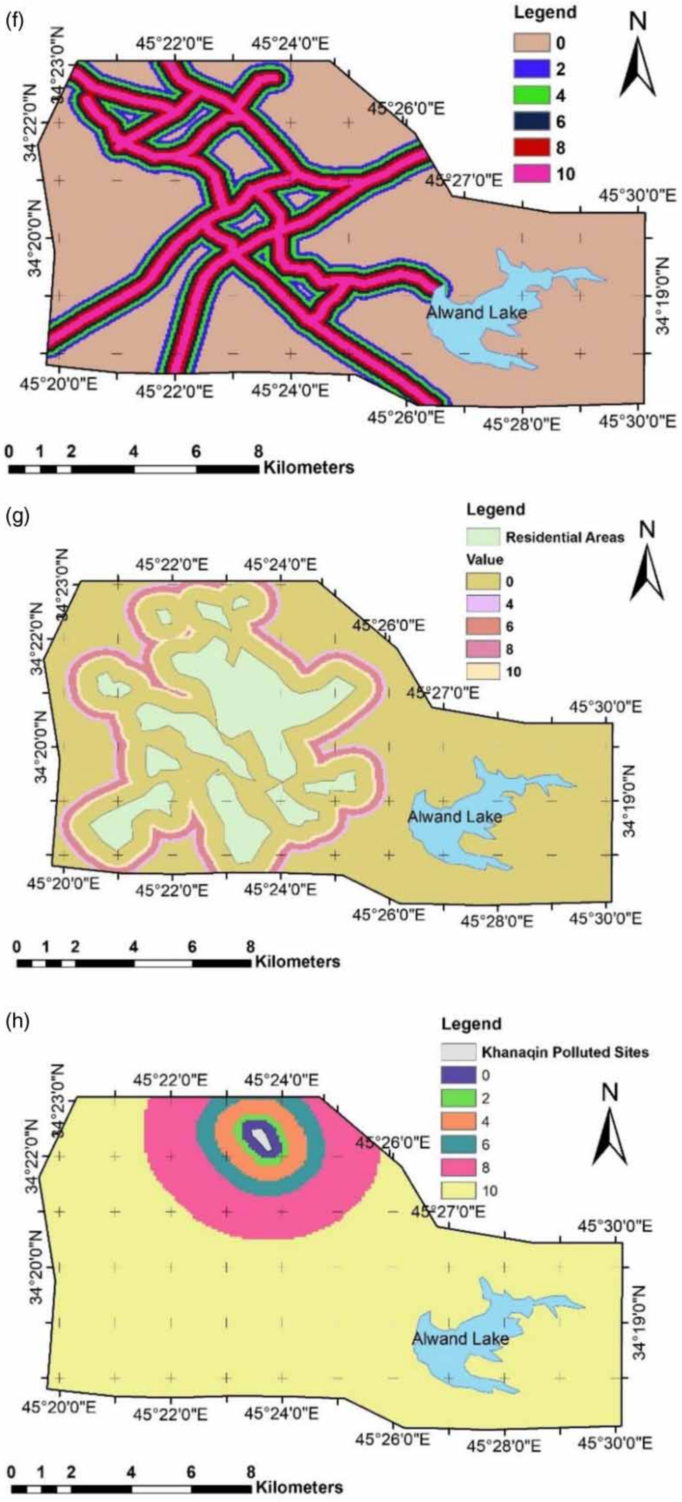

Figure 5 | Continued.

used to establish the map. Levels of groundwater indicate that a considerable pumping cost is needed to bring the groundwater up to the earth's surface in most parts of the area (scores 4 and 6).

Groundwater TDS concentration

To rate groundwater TDS concentrations of the Khanaqin study area, the Khanaqin area suffers from high salinity levels in the groundwater. Therefore a suitable rating for TDS concentration levels has

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been adopted to ensure low energy requirement and high efficiency of the integrated CSP-PR system. On this basis, a score of 0 was assigned when the TDS concentration of the groundwater exceeded 2,000 mg/l.

However, when the TDS concentration in the groundwater was in the range of 750–1,000 mg/l, a score of 6 was allocated to TDS level. A TDS concentration of less than 500 mg/al was given a 10 score as illustrated in Table 3. The results map for groundwater TDS concentration rating in the study area is shown in Figure 3(d).

Distance from water sources

Therefore, CSP-RO sites closer to surface water sources received higher scores. A distance of fewer than 100 m was allocated a 10 score, while the lowest grade of 0 was given to sites of farther than 1,500 m (Table 1); the results of distance rating from water sources are presented in Figure 5(e).

Distance from main roads

Establishing the planned CSP-RO system near main roads has economic advantages for decision-makers, where this criterion is created for distances from main roads in the study area. Then, sites farther from main roads received lower scores. Therefore, a score of 0 was given for locations from the main roads of >500 m, while the highest score of 10 was given to locations from the main roads of <100 m (Table 3), the results of rating for distance from main roads are presented in Figure 5(f).

Distance from residential areas

To avoid any disturbing public health because of the noise generated from the CSP-RO system, integrated CSP-RO sites should be placed at a proper distance from residential areas. Distances of <500 m and >900 m from residential areas were given a 0 score and a 10 score, respectively (Table 3). The results of the rating for distance from residential areas of the Khanaqin study area are shown in Figure 3(g).

Distance from possible polluted sites

To reduce pollution risks in groundwater sources, integrated CSP-RO system sites are preferred to be located away from possible point pollution sources such as sanitary landfill sites. Disposal of solid wastes at a distance less than 300 km from the CSP-RO system is supposed to pose a contamination risk. Therefore, the sanitary landfill site in the study area was buffered on this basis, where a 0 score was assigned to the distance to the sanitary landfill of less than 300 m, while a distance of more than 3,000 m was given a score of 10 (see Table 3). The result of the rating for distance from the sanitary landfill site of Khanaqin study area is shown in Figure 3(h).

The map of prospected integrated CSP-RO system site suitability based on the AHP method in the study area is illustrated in Figure 6. Based on the rating values obtained of relevant criteria, integrated CSP-RO system site suitability of the Khanaqin area was found to be within five main classes on a scale ranging from 0 to 10 (the maximum value is 10, the minimum value is 0): class 7 (high suitability), class 6 (high moderate suitability), class 5 (moderate suitability), class 4 (low suitability), and class 3 (very low suitability). The obtained results show that only of 0.05% the study area has high site suitability for the integrated CSP-RO system. For other classes of the study area, 1.16% has high moderate site suitability, 20.9% has moderate site suitability, 66.63% has low suitability, and 11.26% has very low site suitability for the integrated CSP-RO system. The map presented in

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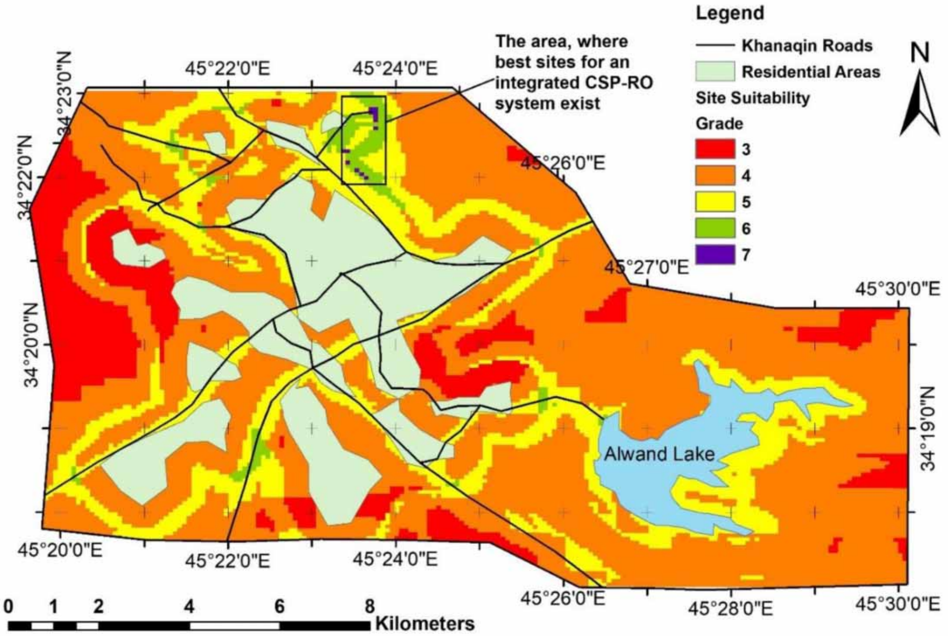

Figure 6 | Site suitability for an integrated CSP-RO system in the Khanaqin area.

Figure 6 shows that there is only a very restricted availability of suitable sites for integrated CSP-RO systems in Khanaqin area depending on ArcGIS spatial analysis tools.

Regarding site selection criteria, the area of high suitability in the study area is consisting of thirteen sites. The selection of a more suitable one among these thirteen sites depends on on-site visiting, administrative, and legislation issues, some of these sites belong to private properties that need governmental involvement to solve land ownership issues.

The results show that using pair-wise comparison and the AHP approach to locate a water desalination treatment site is versatile, and errors can be effectively minimized. In the field of water and power, the findings also show the possibility of combining GIS and multi-criteria AHP methods.

Analysis of potential capacity for an integrated CSP-RO system

For an assumed surface area of 1,500 m^2 for photo-voltaic cells in the integrated CSP-RO system at the locations of the thirteen highest suitability sites. The desalination capacity evaluation is based on the optimal operating conditions of some site suitability relevant criteria included in Equation (12): TDS_{feed}, W_D, h_{geo}, L, and R_{SP}, where the low feed water TDS, shallow groundwater depths, low geometric head, short distance from water resources, and sufficient solar radiation would assist to reduce operation costs and increase desalination capacity. For the selected thirteen highest site suitability locations, it is obvious these privileges are not always available at a single site, and it can be challenging to distinguish which criterion is more influencing the optimization requirements.

Table 1 shows the resulted potential desalination capacity, as a volumetric flow rate of treated water, of an integrated CSP-RO system considering the criteria of highest site suitability. A 1,500 m^2 surface area of photo-voltaic cells in the CSP power system coupled with RO desalination plant produces treated water capacity ranging from 22,572.77 m^3/d (at site 3) to 22,821.68 m^3/d (at site 1). At optimal conditions, sites 1 and 13 would be the most suitable sites, while sites 3, 6, and 11 would be the less preferable sites for the integrated CSP-RO system.

Remarkably, in Table 4, sites with lower geometrical head have higher potential desalination capacity. The influence of other criteria such as TDS of groundwater, solar radiation, distance from surface water sources, and well depths wells have no significant impact on the potential desalination

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Table 4 | The potential desalination capacity of the CSP-RO system for thirteen sites of the highest site suitability[a]

Site No.	Longitude (WGS_1984_UTM_Zone_38N)	Latitude (WGS_1984_UTM_Zone_38N)	TDS_{feed} (mg/l)	W_D (m)	R_{SP} (W/m^2)	h_{geo} (m)	L (m)	Q_{cap} (m^3/s)	Daily Q_{cap} (m^3/d)
1	536,298.19	3,804,408.27	945.3	53.34	5,295	1	8,088.37	0.2641	22,821.68
2	536,382.71	3,804,408.27	937.7	53.53	5,296	6	8,040.77	0.2628	22,703.59
3	536,298.19	3,804,323.74	943.7	53.37	5,295	11	8,018.62	0.2613	22,578.46
4	536,382.71	3,804,323.74	936.0	53.56	5,296	9	7,970.88	0.2620	22,633.07
5	536,382.71	3,804,239.21	933.8	53.60	5,296	10	7,901.12	0.2617	22,611.71
6	536,382.71	3,804,154.69	932.5	53.62	5,296	11	7,831.36	0.2615	22,590.33
7	536,382.71	3,803,985.63	926.0	53.76	5,295	10	7,691.85	0.2618	22,616.54
8	535,791.02	3,803,478.46	952.6	53.18	5,291	8	7,633.82	0.2622	22,651.32
9	535,875.55	3,803,478.46	940.4	53.46	5,292	3	7,580.74	0.2637	22,780.98
10	535,875.55	3,803,224.88	912.7	54.15	5,291	7	7,384.40	0.2625	22,683.80
11	536,044.60	3,803,055.82	881.9	54.74	5,291	12	7,146.30	0.2613	22,572.77
12	536,129.13	3,802,971.30	870.2	54.93	5,292	7	7,027.28	0.2628	22,706.00
13	536,213.66	3,802,886.77	860.0	55.07	5,292	3	6,908.28	0.2640	22,811.89

[a] The potential desalination capacities were calculated on the basis of several assumptions: $\eta_{Mg} = 65\%$ was adapted from Aminfard *et al.* (2019); $\eta_{MS=}65\%$ and $\eta_P = 92\%$ were adapted from Cheng (2002); $V = 100$ m/s and $D = 1{,}100$ mm were adapted from Issa (2017); f = 0.0095 was calculated as per Bai & Bai (2005) for plastic pipes and friction loss (ε) = 0.002; and $\eta_P = 15\%$ adapted from Kjellsson & Webber (2015).

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capacity of the integrated CSP-RO system. The geometrical head manipulates the pumping efficiency, feed water quantity, and operation cost. Therefore, there is a strong correlation between the geometrical head and potential desalination capacity in the integrated CSP-RO systems.

From an environmental point of view, the application of an integrated CSP-RO system has pros and cons: generation of brine waste, and reduction of carbon emissions by replacing the hydrocarbon fuels with solar energy.

In this analysis, quantitative, environmental, and economic parameters were used to determine the study area's potentials, as well as the capacity of an intended integrated CSP-RO water desalination plant to function in the study area's extreme conditions.

CONCLUSIONS

The current study presents an outline for analyzing the site suitability and potential desalination capacity of a new integrated CSP-RO system in the Khanaqin area by optimizing the affecting environmental, economic, water resources, and operational criteria of the system. The applied method in this research is a combination method of the AHP method and geospatial analysis tools provided by ArcGIS such as Kriging interpolation and map algebra. The suitability indices for all locations in the study area was determined by the LS method. The AHP method analysis showed a higher relative weight for annual solar irradiance, while the lowest relative weight was for distance from roads. The Kriging interpolation method used for geospatial analysis for the study was performed by using a distance-weighted averaging approach. The resulting analysis identified 13 suitable sites, equal to 0.05% of the study area, which have high site suitability for establishing the integrated CSP-RO system. The result of potential desalination capacity analysis revealed that only two sites are appropriate for an optimal operation and higher desalination capacity of the system. The results of the multi-criteria AHP method combined with GIS can help policy makers evaluate and solve problems related to water desalination site selection more quickly.

This study could be applied to other areas in Iraq for similar or different site selection criteria to site and assess a combined solar power and desalination plant. For further studies, other interpolation approaches and different solar tools, instead of CSP, could be applied in further studies to compare outcomes and results with the current approach of analysis. The findings of this study show that using a combination of GIS and AHP in site selection applications, the combination of technical, environmental, and economic factors in future water desalination plants can be achieved more accurately.

The findings of this study provide decision makers in the study area with a wide range of options for considering an integrated CSP-RO water desalination plant. Future research should, in any case, cover the aspects of waste generation rate and potential remediation methods.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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