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ORIGINAL ARTICLE

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Identification of potential managed aquifer recharge sites in hyper-arid environment using GIS and analytical hierarchy process

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Abstract

Utilizing aquifers as groundwater storage reservoirs is an effective strategy for water management in water scare regions. The success of managed aquifer recharge (MAR) relies on the assessment and modeling of site-specific hydrogeological characteristics, including groundwater salinity, transmissivity, storativity, slope, soil properties, proximity to water recharge networks and road accessibility, etc. This study employs a GIS-based multi-criteria evaluation technique, integrating both ground and remote sensing datasets. The results indicate that a significant portion of the total land area, approximately 7,414.11 km^2 (64%), can potentially be utilized for MAR practices, while the remaining 36% is restricted due to various constraints, such as built-up areas, roads, agricultural lands and nationally protected areas for conservation. The available 64% of land is further categorized into subclasses ranging from highly suitable to least suitable areas. Most of the highly and moderately suitable regions are located in the northern central parts of the country where seasonal surplus treated wastewater and desalinated water may be used to recharge groundwater. Furthermore, MAR technology can also be used to tackle saltwater intrusion in the coastal areas by injecting seasonal surplus desalinated and treated wastewater. These findings suggest that MAR technology has a high potential to facilitate aquifer water storage and recovery in the country, which can contribute to sustainable water resources.

Keywords Groundwater · MAR · TSE · MCDM · GIS · Qatar

Introduction

Freshwater is a vital natural resource in the State of Qatar, particularly given the harsh environmental conditions characterized by erratic rainfall, lack of freshwater resources and high temperatures (Bilal et al. 2021). Adding to these natural constraints, rapid population growht and shifts in socioeconomic conditions have placed considerable pressure on both the demand and supply sides of the water sector. According to the Planning and Statistical Authority report, the population of Qatar has increased significantly over the last 35 years from just 373,395 in 1986 to 2,748,162 in 2021 (Planning and Statistics Authority 2023). The national population is expected to further increase as more workforces will be needed to achieve the developmental goals under Vision 2030 along with the expansion of oil and gas industries. This expected increase in population will also increase the demand for natural resources, particularly food and water. Though most of the food is imported about 90% (Mustafa 2017), local food production has witnessed a significant increase since the Gulf Rift in 2017 (Hassen et al. 2020). The area under fodder crops has increased by 46%, vegetables by 39% and cereals by 26% between 2016 and 2021 (Planning and Statistics Authority 2020). As a result of population growth and socioeconomic development per

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capita water increased from 216 in 2016 to 246 cubic meters per year in 2021 (Planning and Statistics Authority 2021). In addition, groundwater resources in the State of Qatar have undergone extensive exploitation in recent decades, primarily for agricultural use. An annual water deficit of 11 million cubic meters is predominantly caused by over-abstraction of groundwater for irrigation (Planning and Statistics Authority 2019). This over-abstraction of groundwater has encouraged seawater intrusion (SI) into the coastal aquifer, resulting in further degradation of the precious water resource.

One effective approach to managing SI involves employing artificial recharge methods in coastal aquifers. Groundwater artificial recharge can be achieved through two primary methods: surface and subsurface infiltration systems, which requires injection wells and surface water channels (Lu et al. 2021; Shi et al. 2020; Werner et al. 2013). Artificial recharge of groundwater is a viable method for controlling SI and improving groundwater levels (Yuansheng & Zhaohui 2009). Their approach involved the transportation of river water to inner lakes through a pre-constructed canal, forming an integrated methodology aimed at ensuring the long-term sustainability of the flow system in the coastal city of Haikou, China. Similarly, treated wastewater was used to manage SI in the coastal aquifer of Belgium (Vandenbohede et al. 2009). Another study revealed that the injection of recharge water at the toe of the saltwater wedge leads to a more effective repulsion of saltwater (Luyun Jr et al., 2011). Furthermore, the primary advantage of utilizing injection wells lies in their flexibility to be in areas within multilayered coastal aquifers where the subsurface geology is unsuitable for surface infiltration ponds. Many regions, for instance Palo Alto (Sheahan 1977), Belgium (Vandenbohede et al. 2009), Oman (Shammas 2008), Cyprus (Koussis et al. 2010), Los Angeles (Bray & Yeh 2008), Greece (Siarkos et al. 2017), have successfully mitigated SI by deploying hydraulic barriers that inject freshwater and treated water along coastal zones.

Qatar has implemented various measures to conserve water resources. These measures include the reuse of wastewater for irrigation and recreational purposes, rainwater harvesting, water-efficient technology and aquifer recharge of groundwater. In addition, the government has put efforts to increase its strategic water reserves by the construction of mega water reservoirs which can supply fresh water for seven days. The mega reservoir project will add 17 million cubic meters of potable freshwater to the national freshwater reserves by investing 4.6 billion USD (Christian Klein 2017). However, seven days of portable freshwater may not be enough in the event of natural and anthropogenic disasters which could possibly affect water intake to the desalination plants. Disruptions to desalination plants in the Gulf can arise from natural calamities like red-tide outbreaks and human-induced incidents such as oil spills. These events may potentially disrupt plant operations for periods ranging from days to months. A case in point is the 2008 red-tide occurrence in the Persian/Arabian Gulf, which persisted for more than eight months and led to the temporary closure of desalination plants in Qatar and other Gulf nations for several weeks. The bloom entered the Persian Gulf, extending to waters in the coastal areas of UAE, Qatar and Iran. Its extensive and severe impact affected over 1200 km of shoreline (Al Busaidi et al. 2008).

Groundwater storage presents a viable solution for storing surplus freshwater within aquifers, thereby enhancing overall water security (Zekri et al. 2021). The MAR technology has been extensively investigated, considering various options for groundwater recharge, for instance, freshwater, wastewater and stormwater (Khan et al. 2008; Zuurbier et al. 2014; Missimer et al. 2015; Al-Maktoumi et al. 2016; Zuurbier & Stuyfzand 2017; Wasif & Hasan 2020; Zekri et al. 2021). The MAR technique holds significant promise; nevertheless, its successful implementation relies on specific prerequisites, encompassing surface and subsurface conditions.

In the Middle East, several studies have utilized GIS-based multi-criteria decision making (MCDM) techniques to identify suitable sites for artificial groundwater recharge. In Saudi Arabia, one study found that approximately 14% of the total land area is viable for groundwater recharge (Zaidi et al. 2015), while another study by (M. Y. A. Khan et al. 2023) reported that 41% of the assessed area was appropriate for this purpose. Similarly, in Iran, research indicated that 5–18% of the land could be suitable for artificial recharge using GIS and remote sensing data (Mahdavi et al. 2013). In Iraq, a MCDM analysis revealed that between 12 and 72% of the land is suitable for groundwater recharge (Al-Abadi et al. 2020). In Oman, suitable land ranging from 3 to 59% was declared as potentially suitable for groundwater (Akhtar et al. 2022). Additionally, a study conducted in the UAE focused on mapping potential groundwater zones by considering geohydrological factors and applying multi-criteria spatial analysis (Al-Ruzouq et al. 2019). Similarly, in Qatar around 64% land was identified as suitable to recharge aquifer using floodwater (Aloui et al. 2024). More recently, GIS-based multi-criteria were used to evaluate biochar for water resource management in Qatar (Pradhan et al. 2024). These studies collectively highlight the importance of utilizing advanced geospatial techniques to address groundwater management challenges in arid and semi-arid regions of the Middle East. This research study aims to identify potential locations for MAR projects in the State of Qatar, employing a GIS (geographic information system) mapping approach and multi-criteria decision making. The primary objective is to pinpoint suitable sites based on predefined criteria and potential constraints that could impact the execution of aquifer management initiatives in the future. Furthermore, potential coastal areas will also be assessed for freshwater injection to minimize the possible effect of seawater intrusion.

Materials and methods

Study area

Qatar is a small arid peninsula that stretches northward from the main Arabian Peninsula. It has a border with Saudi Arabia and the United Arab Emirates in the south. The majority of the area is flat ranging from 0 to 107 m above sea level (Fig. 1) (Bilal et al. 2024a; Bilal et al. 2021). Dunes, limestones and salt flats are the dominant topographic characteristics. The weather is hot and humid with a slightly cooler winter. Rainfall is scarce usually less than 79 mm per year with annnual mean temperature of 27.43 °C, there are no surface water resources, and water is mainly provided by desalination and groundwater extraction (Bilal et al. 2021). Groundwater in Qatar is primarily recharged by three sources, recharge wells and irrigation recharge (44%), artificial recharge (31%), and recharge from annual rainfall (25%) (Planning and Statistics Authority 2019). Agriculture is the prime and largest consumer of groundwater, accounting for 86%, followed by an outflow to the sea (8%) and municipal and industrial abstraction (7%). Despite recent efforts to artificially recharge groundwater, there is still about 11 million cubic meter shortfall in the groundwater budget (Planning and Statistics Authority 2019).

Available data

The effectiveness of MAR technology relies on a range of factors, which have been categorized as follows: (a) surface

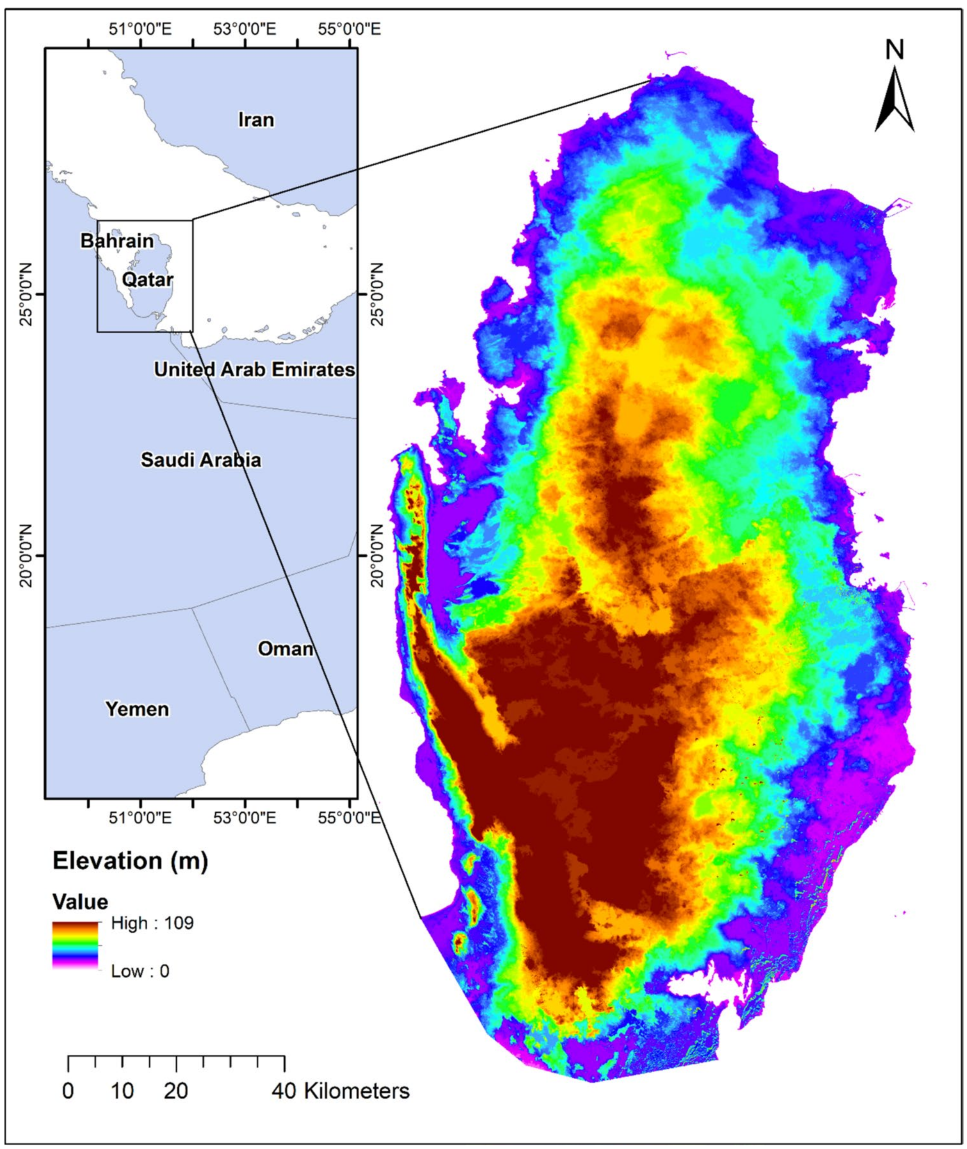

Fig. 1 Study area map with elevation based on digital elevation model 30m

parameters, which pertain to topography and land usage; (b) subsurface parameters, focusing on storage characteristics of the aquifers, and the last one is (c) socioeconomic parameters (Bunsen & Rathod 2016; Murray & Harris 2010). Within each of these criteria, individual factors were reclassified into appropriate categories within a GIS environment, primarily utilizing methods like Jenks Natural Breaks or inherent data groupings. These categories were then standardized to a common scale ranging from 2 to 8, where 8 signifies very low suitability, and 2 signifies very high suitability. Standardization serves the purpose of converting each criteria map into a consistent scale, facilitating easy comparison (Yalew et al. 2016).

Surface parameters

The analyzed variables in this study encompassed land use and land cover, soil types, slope and elevation. Land use data were sourced from Landsat-8, while elevation and slope data were obtained from the Shuttle Radar Topography Mission (SRTM) digital elevation model at a resolution of 30m. These datasets are available freely to the public and can be accessed at the USGS Earth Explorer (https://earthexplorer.usgs.gov/). The downloaded tiles of the digital elevation model were treated in the ArcMap software (Bilal 2019; Bilal et al. 2024b). The images underwent reclassification based on the prevalent land cover features in the study area. Categories such as built-up areas, farms, natural parks and roads were identified, classified and converted into raster format for subsequent analysis (Fig. 2).

Subsurface parameters

Subsurface parameters play a crucial role in determining the capacity for groundwater storage and depend on the characteristics of the aquifers such as porosity and transmissivity (Murray & Harris 2010). Subsurface parameters consist of storativity, transmissivity, salinity and depth of water table. The geological indicators of transmissivity and storativity were deduced from experiments conducted earlier in the State of Qatar (Schlumberger Water Services 2009). Salinity map was generated from the samples collected during field visits to the monitoring and injection wells (Fig. 3).

Socioeconomic parameters

Proximity to roads, built-up areas, wastewater networks and freshwater networks were used as an indicator for access and cost management. Road networks were extracted from Landsat-8 image and reclassified using the ArcMap software. To further protect the raods and buil-up a 500m and 1km buffer zone was considered. Freshwater networks and treated wastewater networks were also digitized (Fig. 4).

Suitability mapping methodology using analytic hierarchy process

The AHP approach was introduced by Saaty (1987); it is one of the most popular and widely utilized multi-criteria methods. This technique integrates the processes of rating alternatives and aggregating them to identify the most relevant ones. It is commonly applied for ranking a set of alternatives or choosing the best option from a given set. The ranking or selection process is conducted in relation to an overarching goal, which is further deconstructed into a set of criteria. In the AHP preferences are defined with relative grades expressed as numerical values, usually ranging from 1 to 9, as 1 suggesting equal importance, while 9 shows the criteria are strongly preferred. In this study, a total of 10 variables are selected, namely, (a) groundwater salinity, (b) distance from highways, (c) distance from freshwater networks, (d) slope, (e) distance from built-up areas, (f) distance from wastewater networks, (g) transmissivity, (h) elevation, (i) storativity and (j) soil types. These variables are reclassified into a common scale using the ArcMap software. Another step in the suitability analysis is the exclusion of those areas which cannot be utilized for MAR technology due to legal rules and regulations, for instance, areas such as built-up, protected areas, agricultural farms and roads. In addition, a buffer zone 0.5 km and 1km is added to the restricted areas for protection. The second step was to use the Weighted Overlay tool in ArcMap software to overlay several raster layers using a measurement scale and respective weights (Bilal et al. 2025). Input variables are classified into five classes, and each variable has its respective weightage. More information is given in the following Table 1.

Finally, a restricted area as a shapefile mask is used to exclude restricted areas from the analysis (Fig. 5). The weights calculated through the AHP represent the relative importance of individual criteria, determined by their assigned ranks. To ensure the logical consistency of the pairwise comparison matrix, the consistency ratio (CR) is computed using Eq. 1. This process helps detect and rectify any logical inconsistencies introduced through the matrix, which is often based on expert judgment. When the CR value exceeds 0.1, the judgment may be deemed unreliable, suggesting potential proximity to randomness and indicating the need for adjustments (Yalew et al. 2016).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

The CI denotes consistency index, and RI shows random index.

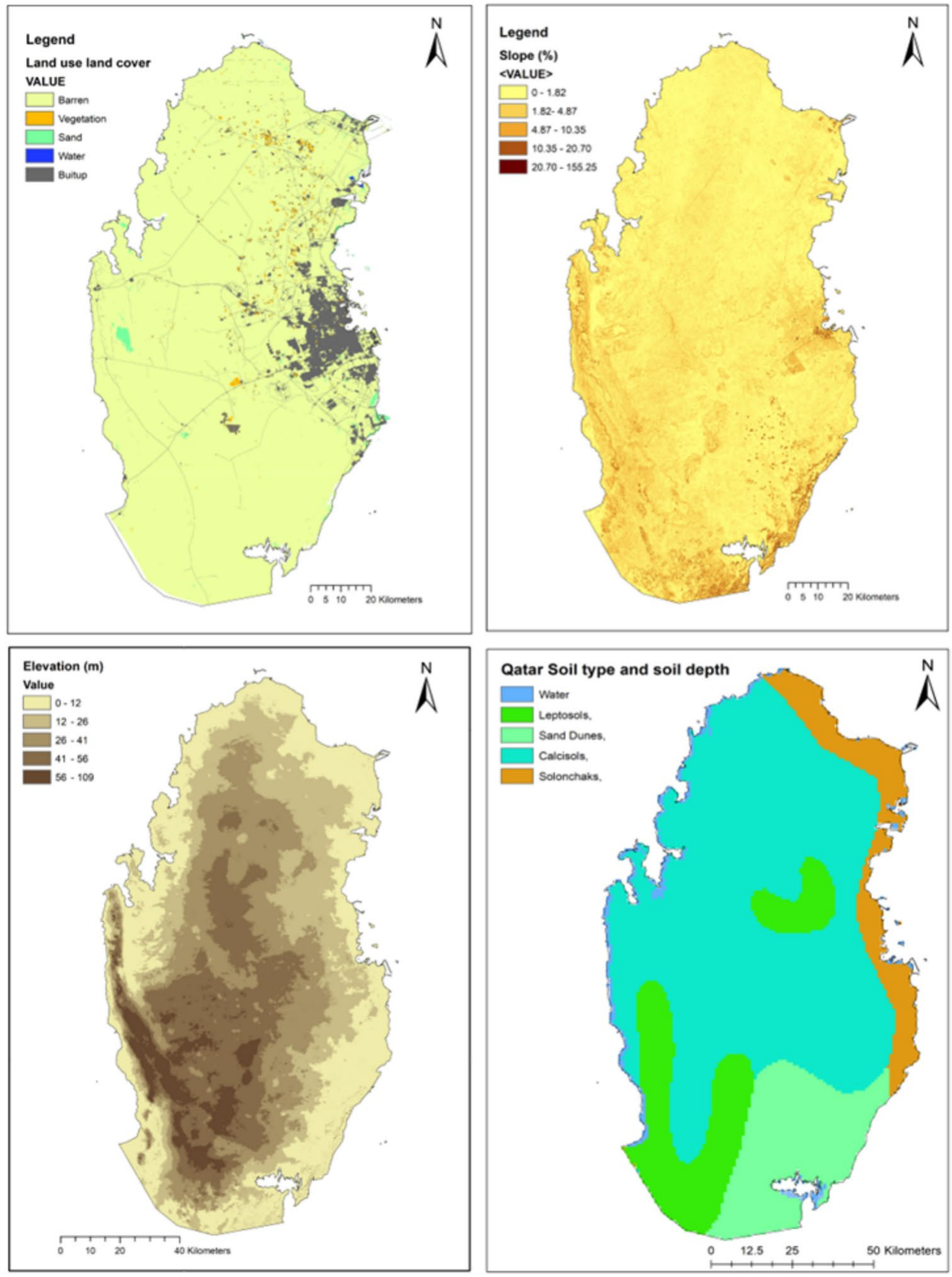

Fig. 2 Surface parameters land use land cover, soil types, elevation and slope

$$\mathrm{CI} = \frac{(\lambda \max - n)}{(n-1)} \quad (2)$$

λmax represents the maximum eigenvalue, and n is the number of criteria or counts. The pairwise matrix is utilized by summing each column, and each resulting sum is then multiplied by the corresponding weight assigned to the criteria, referred to as the criteria weight.

Groundwater geology of Qatar

The Paleogene rocks forming the near-surface aquifers in Qatar are composed of three primary formations: the Paleocene-Lower Eocene (Ypresian) Umm er Radhuma Formation, the Lower Eocene (Ypresian) Rus Formation and the Middle Eocene (Lutetian/Bartonian) Dammam Formation

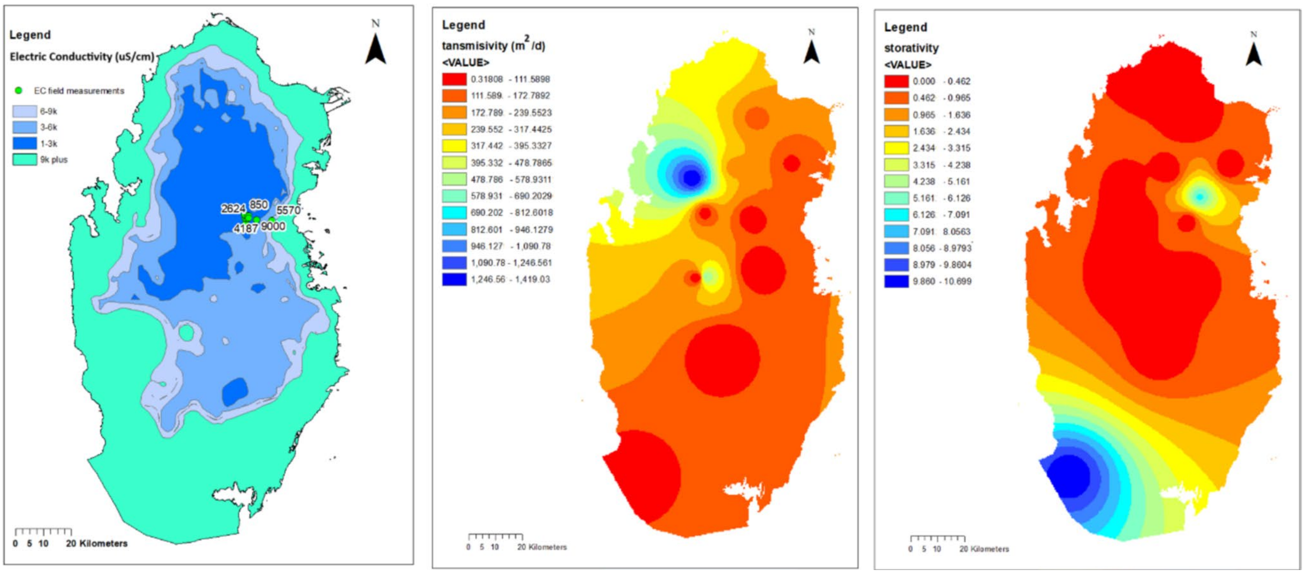

Fig. 3 Subsurface parameters salinity (uS/cm), transmissivity (m^2/day) and storativity (dimensionless)

(Al-Saad 2005; Boukhary et al. 2011; Eccleston et al. 1981). These Formations are generally horizontal and are affected by localized high-angle normal faulting (Rivers et al. 2019). These Paleogene Formations Umm er Radhuma, Rus and Dammam make up the near-surface aquifers of Qatar. The Umm er Radhuma and Rus Formations are found in northern and southern basin regions, which are divided by a fault induced in central Qatar. The southern basin experienced siliciclastic sedimentation during the deposition of the Rus Formation's Traina Member (Ypresian Stage), leading to gypsum deposition. In contrast, the northern basin remained in more typical marine conditions, leading to carbonate deposition (Rivers et al. 2019). The Umm er Radhuma Formation is a significant aquifer with a thickness ranging between 100 and 370 m (Boukhary et al. 2011; Eccleston et al. 1981). Descriptions of the Formation, based on borehole samples, highlight its composition of off-white dolomitic limestones over harder vesicular dolomite (Eccleston et al. 1981). In western Qatar, particularly in the Dukhan field, the Formation thins to around 130 m and is subdivided into three members (A, B and C). This Formation hosts a variety of both planktonic and large benthic foraminifera, indicating environments ranging from open marine to sheltered lagoons (Boukhary et al. 2011). The overlying Rus Formation varies in thickness across Qatar, ranging from 15 m in the Dukhan area to 122 m in the southwestern part of the country (Eccleston et al. 1981; Rivers et al. 2019). It is thought to have been deposited in shallower marine environments compared to the Umm er Radhuma Formation (Eccleston et al. 1981). South of the escarpment, the Rus Formation consists of dolomite gypsum clay cycles (Traina Member) that reflect restricted lagoon to supratidal environments (Al-Saad 2003). Toward the south, the Formation transitions to chalky dolomites and limestones, interspersed with minor gypsum, marl and clay (Al Khor Member), representing more open marine conditions (Al-Saad 2003, 2005; Rivers & Larson 2018). In the northern region (Fig. 6), the thick gypsum and clay layers of the Traina Member are absent, and dolomitic limestone dominates, suggesting normal marine deposition (Abu-Zeid 1991). The Dammam Formation, which is exposed across much of Qatar, has varying thicknesses, with some areas in central Qatar showing no Formation at all, while it reaches up to 40 m along the western coast (Abu-Zeid 1991). It is characterized by shaly to marly dolomitic limestone deposited atop yellow or green shale (Al-Saad 2005; Boukhary et al. 2011). This Formation is divided into five members, including the Rujm Aid Member (fossiliferous limestone), Midra Shale Member (argillaceous limestone), Alveolina Member (fossiliferous limestone), Umm Bab Member (marly dolomitic limestone) and Abaruq Member (dolomitic limestone) (Al-Saad 2003, 2005). The flow and storage properties of Qatar's near-surface aquifers are largely determined by the mineral composition of these Formations, which is influenced by sequence stratigraphy and the area's structural history (Rivers et al. 2019).

Results and discussion

The restricted areas where construction or drilling is not possible due to physical restrictions and legal rules and regulations are excluded from the MAR suitability estimation. In Fig. 7, the excluded area is depicted, this restricted area is sum of built-up, roads, farms and national reserves

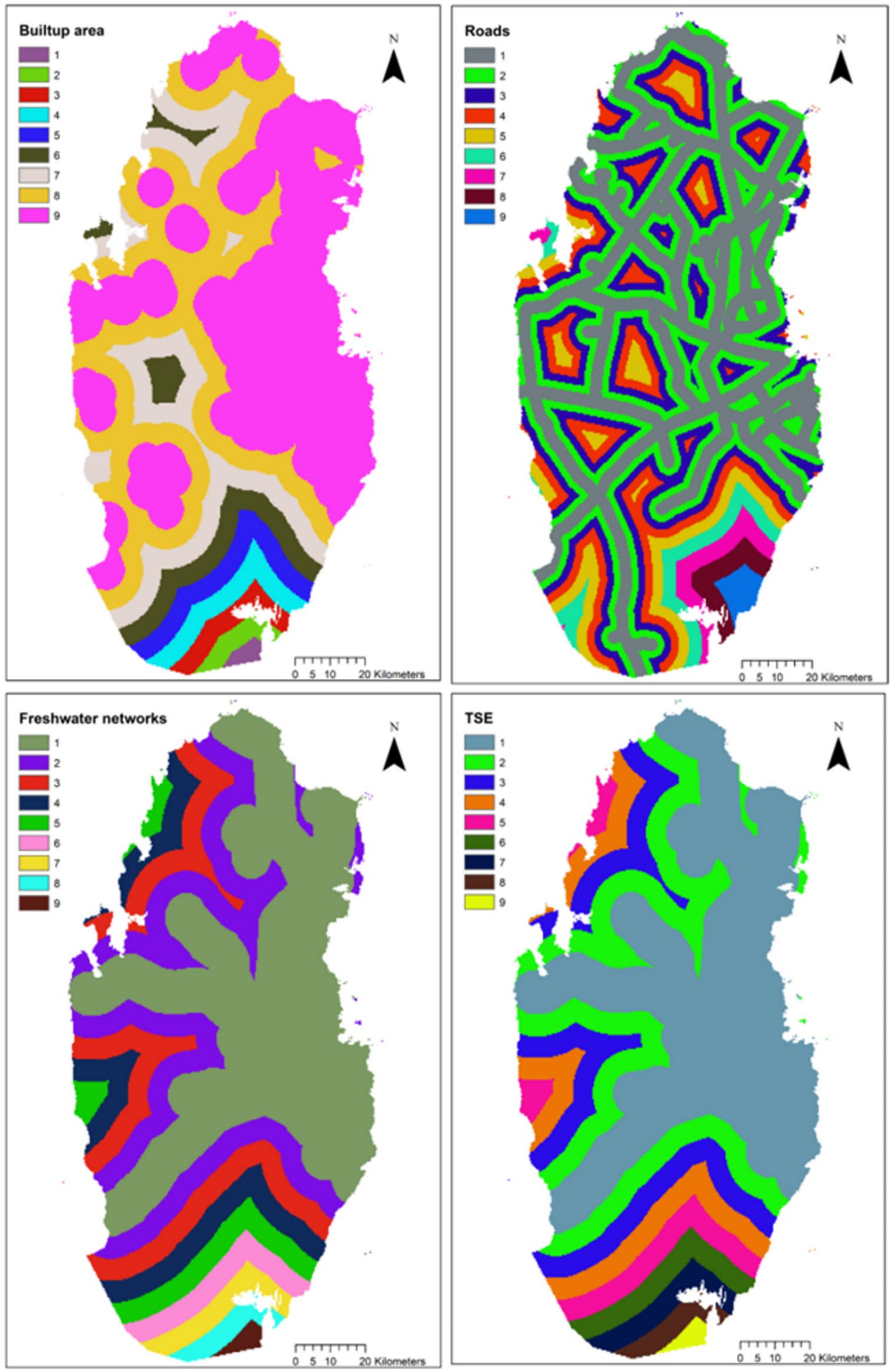

Fig. 4 Economic parameters include distance to built-up area, roads wastewater networks and freshwater networks (legends 1–9 indicate preference high to low)

areas or national parks dedicated for biodiversity conservation. Following the exclusion of restricted areas, roughly 36% of the total area, equivalent to 4196.80 km^2 (out of a total land area of 11,610.92 km^2), remains unavailable for potential MAR projects. The primary reasons for land exclusion include legal regulations related to urban areas, farms, natural protected areas and the designated buffer around them. A buffer of 500 m and 1 km was added to roads and built-up areas, while no buffer was considered for farms and protected areas. The State of Qatar has twelve national reserves. Most of the excluded areas comes under protected areas which consist of Al Reem Reserve, Khor Al Adaid

Table 1 Summary of the input criteria, classes and ranking

Criteria	Rank	Classes	Weight	Source
Soil types	Calcaric Regosols, Calcic Yermosols, Gleyic Solonchaks, Lithosols, Orthic Solonchaks,	1 2 3 4 5	0.07	Food and Agriculture Organization of the United Nations (FAO-UNESCO) (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/)
Slope (%)	0–5 5–8 8–15 15–30 > 30	1 2 3 4 5	0.06	U.S. Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) (https://earthexplorer.usgs.gov/)
Elevation (m)	12–26 26–41 41–56 0–12 > 56	1 2 3 4 5	0.04	U.S. Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) (https://earthexplorer.usgs.gov/)
Groundwater salinity (mg/L)	0–1000 1000–2500 2500–4000 4000–5000 > 5000	1 2 3 4 5	0.28	Ministry of Environment (Schlumberger Water Services 2009)
LULC	Barren land, Bushes/vegetation, Sand, Sand dunes/beaches, Built-up,	1 2 3 4 5	0.08	U.S. Geological Survey (USGS) Landsat-8, level-2. (https://earthexplorer.usgs.gov/)
Transmissivity (m^2/d)	1000–500 500–200 200–100 100–10 < 10	1 2 3 4 5	0.22	Ministry of Environment (Schlumberger Water Services 2009)
Storativity	10^{-1}–10^{-2} 10^{-2}–10^{-3} 10^{-3}–10^{-4} 10^{-4}–10^{-5} $< 10^{-5}$	1 2 3 4 5	0.25	Ministry of Environment (Schlumberger Water Services 2009)

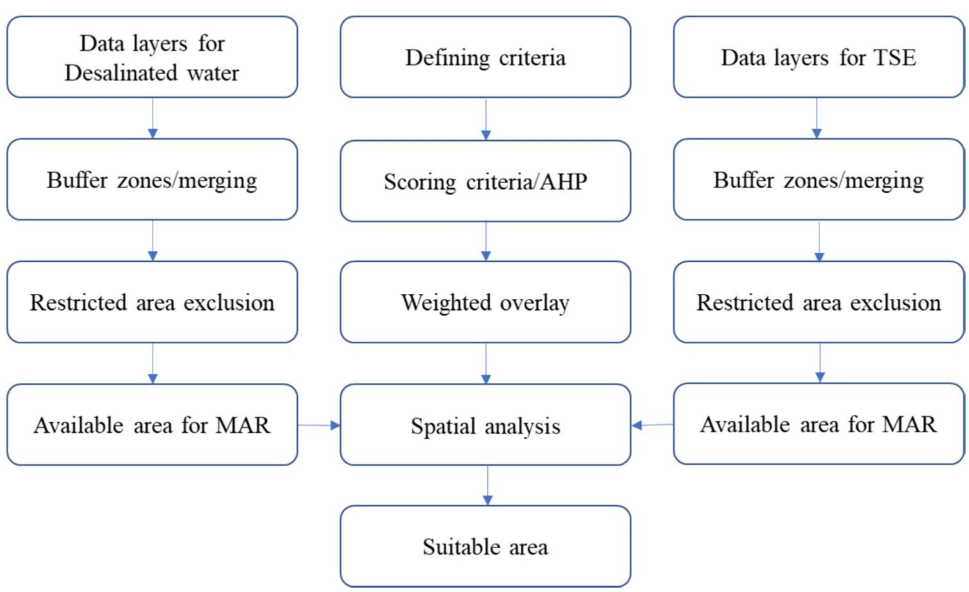

Fig. 5 Flow chart of the proposed GIS-based multi-criteria decision-making process

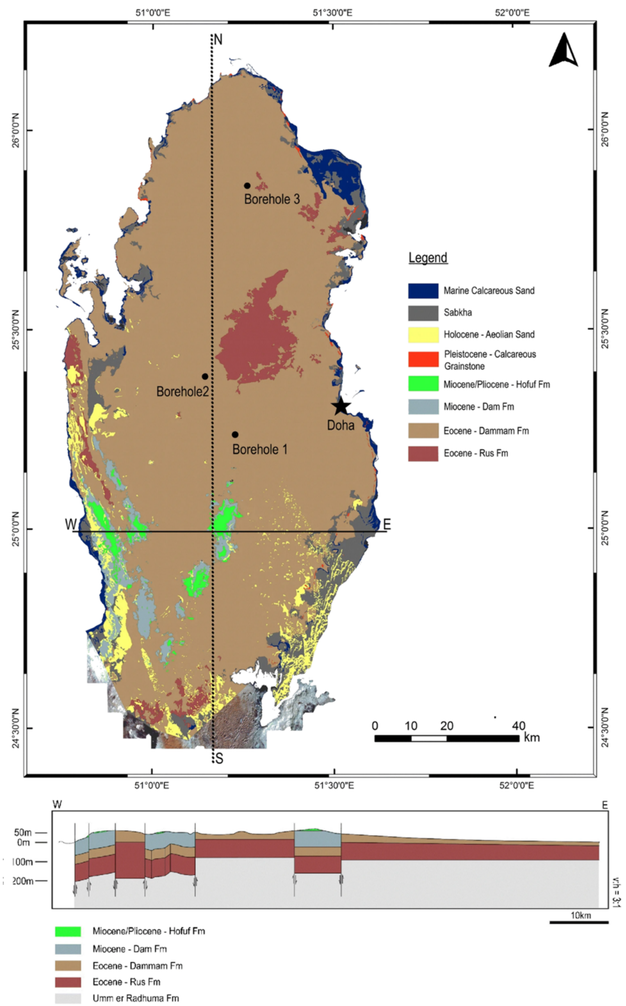

Fig. 6 Surface geology (top) and east–west geological cross section of Qatar near-surface rocks (bottom). Adapted from (Rivers et al. 2019)

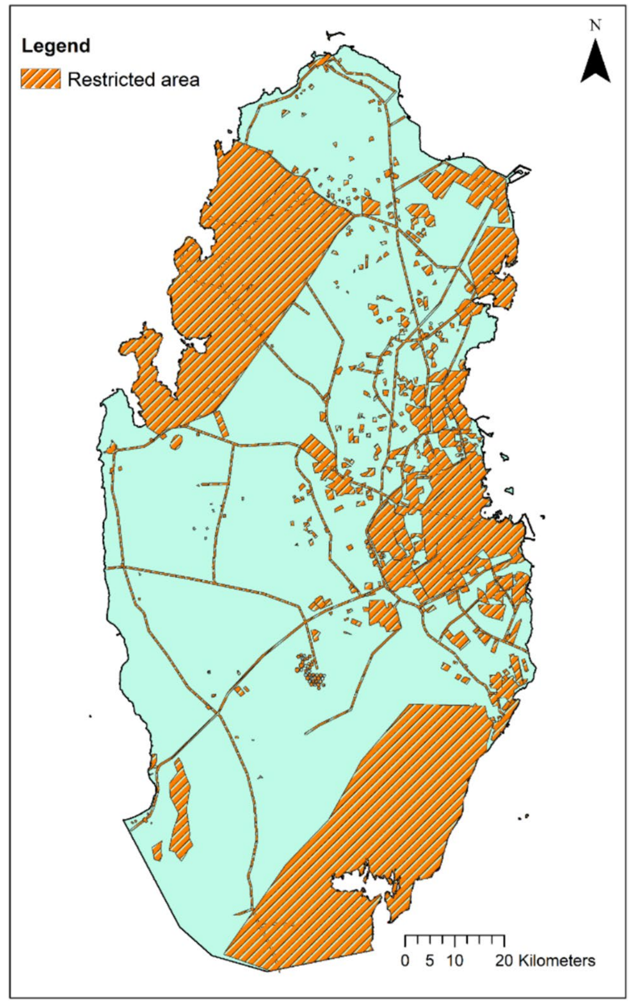

Fig. 7 Restricted and available land area for MAR

Reserve followed by smaller size reserves like Al Thakira, Al Eraiq and Al Rafa Reserves.

MAR land suitability using TSE

TSE is one of the freshwater resources in the State of Qatar which is predominantly used for the irrigation of crops and green spaces. Despite its use, there is an annual surplus of treated sewage effluent TSE which is dumped into lagoons and sea. According to the latest statistics about 13 million cubic meters of wastewater was dumped into lagoons in 2021 (Planning and Statistics Authority 2021). This surplus TSE can potentially be stored in aquifers and can be used in the peak summer when demand is freshwater is higher. Figure 8 shows the average monthly TSE surplus water availability 2020 to 2022. A comparatively larger portion of the surplus TSE is aavailable during winter months mainly December and January, while the least TSE is transferred to lagoons in the summer months, especially in June.

A land suitability analysis indicated considerable sites for artificial managed recharge (AMR) technology in the North and central. However, after applying constraints using a shapefile, the total available suitable area was significantly reduced. This reduction is consistent with findings from a similar GIS-based study, where 17.90% of the studied area was initially identified as suitable for artificial groundwater recharge (AGR). After agricultural and built-up lands were excluded, the total suitable area for AGR was reduced to 14.24% (Zaidi et al. 2015). Overall, highly suitable to moderately suitable areas are in the range of 0–14%, with one of the most suitable sites identified in the northwest covering 4 km^2. However, this area falls within a natural reserve and is masked by restrictions, excluding it from further consideration. The second most suitable area spans 22.39 km^2, which accounts for about 0.3% of the total suitable land. A larger suitable region, covering 1,058.26 km^2, was identified in the

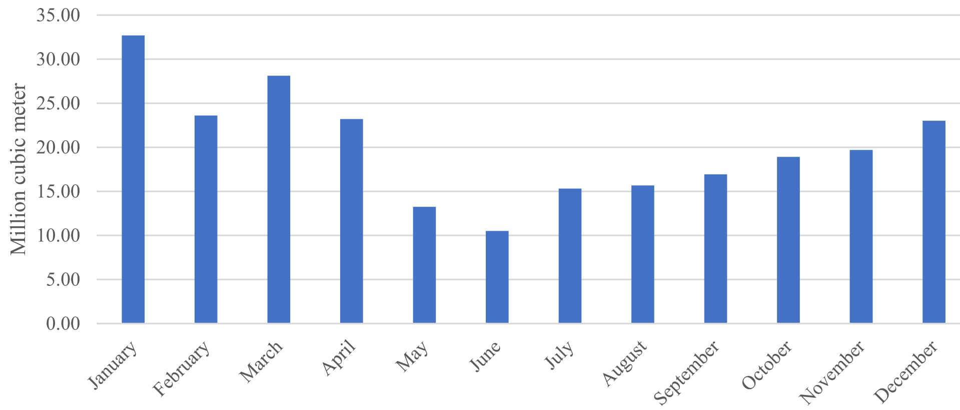

Fig. 8 Average monthly surplus TSE availability in million cubic meters of the last three years (2020–2022)

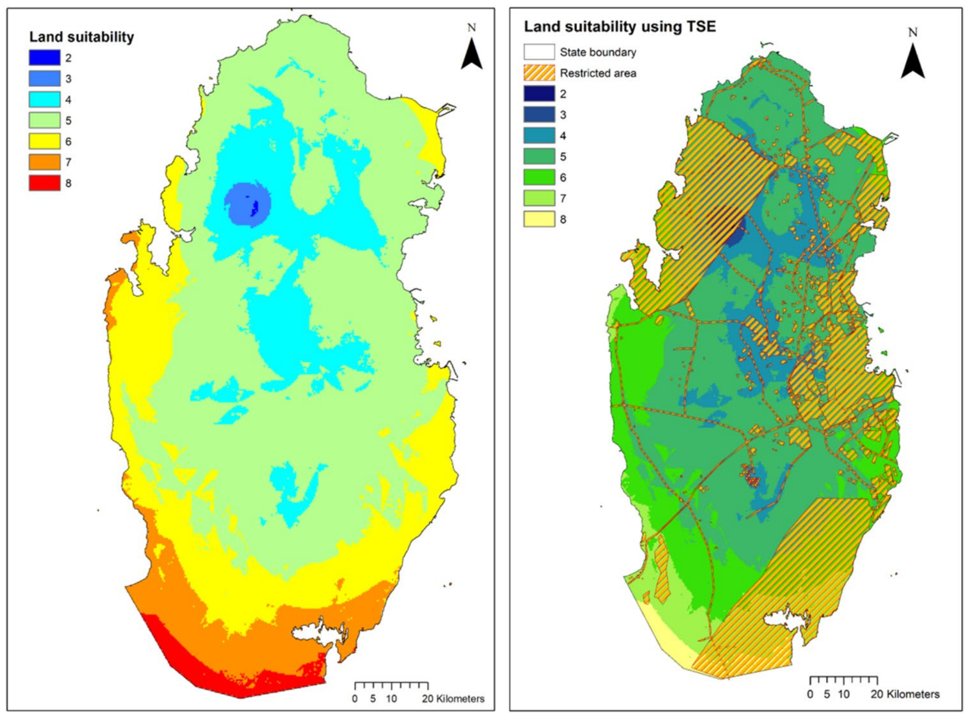

Fig. 9 MAR suitable sites using TSE, left without restrictions and right with constraints (legends 2–8 indicate suitability high to low)

northern and central parts of the study area, representing around 14% of the total suitable land (Fig. 9). This region is highly suitable due to its favorable groundwater quality, transmissivity and storativity, and most existing managed aquifer recharge (MAR) sites are also located within this area. The largest identified area, covering 4,397.25 km^2 (59% of the total suitable land), is considered moderately suitable. This area is concentrated mostly in the northern part of the region, including coastal areas in the far north. Two additional land areas, measuring 412.08 km^2 and 125.23 km^2, were identified as the least suitable (Table 2). These findings align with a previous study that proposed a large-scale artificial aquifer recharge plan using freshwater in Qatar, where recharge zones were similarly located in the northern part of the country (Mohieldeen et al. 2021). This consistency highlights the northern region's importance due to its favorable geological and hydrological conditions for groundwater recharge.

MAR land suitability using seasonal surplus desalinated water

Most of the desalinated water is produced through the MSF process as a cogeneration by-product with electricity generation. A small portion of desalinated water is produced through reverse osmosis which is comparatively expensive process. Water produced through desalination has seen a steady increase over the last three years from 637 million cubic meters in 2018 to 691 million cubic meters in 2020 with an increase of 8.4% in three years. Since there is a significant difference between summer and winter temperatures, the demand and supply for freshwater follow seasonality as

Table 2 Suitable MAR sites using TSE with respective land area

Class	Total suitable area (km^2)	Total suitable area (%)	Suitable area after restrictions (km^2)	Suitable area after restrictions (%)	Municipality
2	4.0287	0.03	0	0	Al Khor
3	108.523	1	22.392	0.30	Al Khor
4	1728.143	15	1058.262	14	Al Khor, Shahaniya, Um Salal, Al rayyan and Al Wakra
5	6130.253	53	4397.251	59	Al Khor, Shahaniya, Um Salal, Al rayyan, Al Wakra, Daayen
6	2361.897	20	1398.901	19	Al Khor, Shahaniya, Al rayyan and Al Wakra
7	1010.800	9	412.081	6	Shahaniya, Al rayyan and Al Wakra
8	267.2713	2	125.231	2	Shahaniya, Al rayyan and Al Wakra
Total	11,610.920		7414.118		

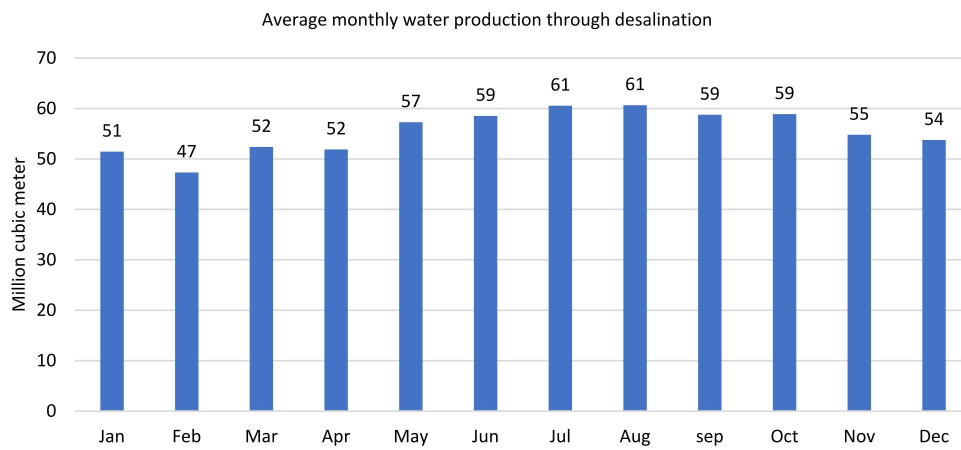

Fig. 10 Average monthly (last three years 2018–2020) freshwater production through desalination

seen in Fig. 10. Comparatively less desalinated water is produced in the winter period, especially during the month of February about 47 million cubic meters as compared to 61 million cubic meters in July and August both are hot months of summer (Fig. 9).

Based on utilization of seasonal surplus desalinated water, a land suitability map is generated for the potential MAR sites. As mentioned earlier only 64% of the land is available to be considered for MAR technology; the remaining is restricted to physical and policy regulations. Overall 0.1–22% of the available land falls in the range of high to moderately suitable for MAR technology. One of the most suitable sites is identified in the northwest, which is 5.16 km^2 and corresponds to only 0.1% of the total identified suitable land. The second most suitable area is 34.67 km^2, which corresponds to about 0.5% of the total suitable land. A larger suitable area of about 1645.88 km^2 is identified in the north and central areas which is around 22.20% of the total suitable area. A moderately suitable area which is the largest in terms of area corresponding to 59% of the total available land (64%) is mostly concentrated in the northern part including the coastal areas of far north (Fig. 11). The rest three identified land areas 4155.36 km^2, 1072.67 km^2 and 127.38 km^2 are considered as least suitable areas as shown in Table 3. These results are in agreement with the previous study conducted to identify potential groundwater suitable sites using floodwater in Qatar (Aloui et al. 2024). Although the study primarily focused on floodwaters resulting from extreme rainfall events, the majority of moderately suitable areas (36.50% of the total land) were found in the north–central regions of the country. The variation in suitability classes can be attributed to the differing weights assigned to various factors. More importantly, the current study focused solely on legally available land, excluding built-up areas and natural parks, which contrasts with previous studies where no such restrictions were considered (Aloui et al. 2024; Mohieldeen et al. 2021).

MAR as seawater intrusion barrier

Seawater intrusion is a phenomenon that occurs when saline water from the ocean infiltrates coastal aquifers, leading to a deterioration in water quality and compromising the availability of limited freshwater resources in the State of Qatar. This intrusion is primarily driven by overpumping of groundwater near coastlines, which creates a hydraulic gradient that allows saltwater to migrate inland, specifically in the north where most of the agricultural

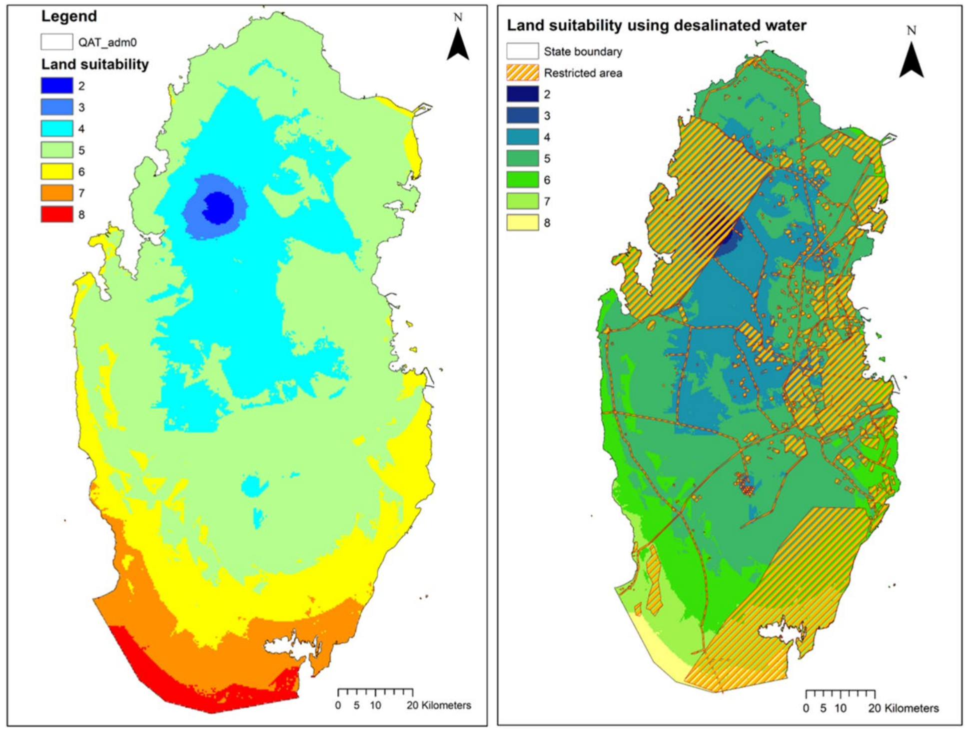

Fig. 11 MAR suitable sites using desalinated water, left without restrictions and right with constraints (legends 2–8 indicate suitability high to low)

Table 3 Suitable MAR sites using desalinated water with respective land area

Class	Total suitable area (km^2)	Total suitable area (%)	Suitable area after restrictions (km^2)	Suitable area after restrictions (%)	
2	50.444	0	5.163	0	Al Khor
3	150.595	1	34.670	0.5	Al Khor
4	2417.527	21	1645.88	22.2	Al Khor, Shahaniya, Um Salal, Al rayyan and Al Wakra
5	6007.719	52	4155.368	56.0	Al Khor, Shahaniya, Um Salal, Al rayyan, Al Wakra, Daayen
6	1771.006	15	1072.674	14.5	Al Khor, Shahaniya, Al rayyan and Al Wakra
7	938.082	8	376.725	5.1	Shahaniya, Al rayyan and Al Wakra
8	279.3999	2	127.386	1.7	Shahaniya, Al rayyan and Al Wakra
Total	11,614.77		7417.874		

activities exist. The groundwater safe yield amounted to 57.2 million m^3 per year (Planning and Statistics Authority 2019). However, the current groundwater abstraction reached 250 million m^3 per year, leading to depletion of aquifers, low groundwater levels and increased salinity. Since 2008, no wells in north Qatar have produced no saline water. The proportion of wells containing highly saline water (10–25mg/l), very high saline water (25–45mg/l) and brine (> 45mg/l) has risen from 11% in 1998 to 13% in 2014 (Planning and Statistics Authority 2019). By injecting freshwater into aquifers near coastlines, the hydraulic gradient that drives SI can be reversed or minimized. Using the seasonal surplus desalination and TSE for injection in the coastal areas can create a barrier of freshwater that may help to prevent seawater from infiltrating further inland. GIS-based analysis has identified potential areas for artificial groundwater injection in Qatar to mitigate and limit saltwater intrusion (SI), as illustrated in Fig. 12. The results indicate that the most suitable regions for managing saltwater intrusion are located in the southern and northwestern areas of the country, while abundant moderate suitable areas are found in the coastal regions across the peninsula. Important parameters like soil quality, transmissivity, storativity and groundwater salinity are considered in the present study. However, the success of aquifer recharge in mitigating SI depends on factors such as the rate of recharge, the hydrogeological characteristics of the coastal aquifer and most importantly groundwater abstraction.

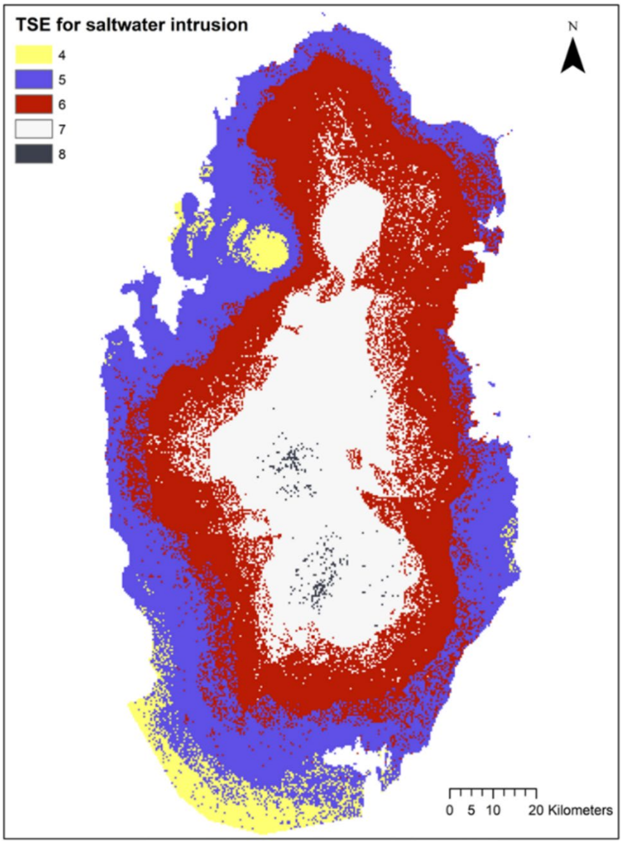

Fig. 12 Suitable sites for managing seawater intrusion in the coastal aquifer (legends 4–8 indicate suitability high to low)

Conclusion

This study provides a thorough assessment of potential sites for managed aquifer recharge (MAR) technology in Qatar, taking into account various hydrogeological, surface, subsurface and socioeconomic factors. The findings reveal that approximately 64% of the study area is suitable for MAR, with suitability levels ranging from very high to low. The remaining 36% of the area is excluded due to legal and environmental limitations. Among the suitable areas, the northern central regions, particularly Al Khor, Um Salal and Al Rayyan, stand out as the most promising for MAR deployment due to advantageous hydrogeological conditions. Comparatively, the use of surplus desalinated water for MAR has the potential to cover more land area than treated wastewater. However, treated wastewater is more readily available than the seasonal surplus of desalinated water, making it a more accessible resource for MAR implementation. Due to Qatar's arid climate and limited rainfall, the study highlights the need to incorporate alternative water sources such as treated wastewater and surplus seasonal desalinated seawater for artificial groundwater recharge. The utilization of these non conventional water sources not only help to replenish groundwater reserves but also contribute to reducing Qatar's annual freshwater deficit. However, the study also highlights the necessity of conducting detailed site-specific investigations within the identified suitable areas to ensure precise planning and implementation of MAR systems. The findings also suggest that MAR technology could be a viable solution for improving water resource management in Qatar and can serve as a model for other regions in the Middle East and Africa facing similar hydrogeological and climatic challenges.

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Declarations

Conflict of interest The authors declare that there are no known conflicts of interest associated with this publication.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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