Applied Water Science (2024) 14:181
https://doi.org/10.1007/s13201-024-02246-8

ORIGINAL ARTICLE

Identifying managed aquifer recharge and rain water harvesting sites and structures for storing non-conventional water using GIS-based multi-criteria decision analysis approach

Ahmed Khaled Seif[1] · **Ali Masria**[1] · **Mohamed Ghareeb**[1] · **Ahmed Adel Saleh**[2] · **Karim Soliman**[2] · **A. I. Ammar**[2]

Received: 16 November 2023 / Accepted: 17 July 2024 / Published online: 29 July 2024

Abstract

In arid climates, conventional water resources are severely limited and stressed in the face of rapid population growth and future climate change. So, it is necessary to find alternative non-conventional water resources for use in drought situations. Additionally, the non-conventional water resources in these areas are not sufficient to meet future water demand. Therefore, non-conventional water resources can be adopted as a strategic reserve to bridge the gap between water supply and demand in case of emergency and drought events. These resources might include rainwater harvesting, treated wastewater, and desalinated seawater. Managed aquifer recharge (MAR) can be applied to store these resources in the hydrogeological system using Geo information System—Multi Criteria Decision Analysis (GIS-MCDA) approach for determining the suitable MAR location for storage. North-west Kingdom of Saudi Arabia area was chosen for this study because it is extremely arid, has high potential for social and economic development, and it has newly constructed non-conventional water infrastructures distributed throughout the area including water desalination plants, Tertiary Sewage Effluent (TSE) waste water plants, and flash-flood storage dams. To identify the suitable MAR site location and structure, different data related to aquifer hydrogeology, surface hydrology, hydrometeorology, and water quality were applied. Then, GIS-MCDA holistic approach was applied with aid of ordered weighting average (OWA) technique. Finally, two maps were created to show the MAR location and structure type. Potential map indicates that ~ 18.85% of the area is suitable for MAR installations. About 0.17% of the total area exhibited very high potential, where infiltration ponds can be applied, 1.86% had high potential for construction of check dams with diversion channels, and 16.82% had moderate potential for installation of recharge wells. Additionally, 56 MAR structures were proposed and a map showing their locations has been created. Thus, results indicated that the study area is promising for MAR installation. These maps could aid the decision makers to propose a sustainable development plan for the future water resources of the area.

Keywords Strategic water reserve (SWR) · KSA vision-2030 · GIS-MCDA · Rain water harvesting (RWH) · Desalination · Tertiary sewage effluent (TSE) · Managed aquifer recharge (MAR)

Abbreviations

ASR	Aquifer Storage Recovery
ASTR	Aquifer Storage Transfer Recovery
GIS	Geo Information System
GWL	Groundwater Level
KSA	Kingdom of Saudi Arabia

✉ Ahmed Khaled Seif
akahmed@ju.edu.sa

✉ Ali Masria
aatef@ju.edu.sa

Mohamed Ghareeb
mmghareeb@ju.edu.sa

Ahmed Adel Saleh
ahmed_saleh@nwrc.gov.eg

Karim Soliman
karim_soliman@nwrc.gov.eg

A. I. Ammar
abdallah_ammar@nwrc.gov.eg

[1] Department of Civil Engineering, College of Engineering, Jouf University, Sakaka, Saudi Arabia

[2] Water Resources Research Institute, National Water Research Center, Giza, Egypt

LULC	Land use Landcover
MAR	Managed Aquifer Recharge
OWA	Ordered Weighting Average
RWH	Rain Water Harvesting
SAT	Soil Aquifer Treatment
SWR	Strategic Water Reserve
TSE	Tertiary Sewage Effluent

Introduction

Storing non-conventional water resources can alleviate water scarcity problems, ensuring a sustainable water supply for future generations, particularly during drought events and emergencies (Sallwey et al. 2019). Non-conventional water resources, encompassing rainwater harvested using the rain water harvesting (RWH) technique, desalinated seawater, and reclaimed water such as tertiary sewage effluent (TSE), must be stored for use during emergencies and to support socio-economic development. The construction of storage infrastructures, such as large tanks, is prohibitively expensive, especially when designed to store substantial water quantities. Therefore, managed aquifer recharge (MAR) becomes an essential tool for storing unconventional water resources in arid and semi-arid regions (Rahman et al. 2012; Chowdhury et al. 2010). According to Dillon et al. (2009), MAR involves artificially injecting fresh water into aquifers of groundwater for recovering water or achieving environmental benefits.

To implement a system of MAR at a pointed site, comprehensive feasibility studies are necessary to assess the essential elements for a successful installation. These elements include the source of water for recharging like surface, storm, reclaimed, potable, and desalinated, the aquifer to store and recover water like type of geological strata, setting of hydrogeology, hydrochemistry characteristics of groundwater, and aquifer water mineralogy, and a suitable site for installing of MAR like topography, hydrogeology, type of soil, land use, and climate (Gale 2005).

Geographic information system (GIS) and remote sensing (RS) tools are widely employed to select structures for both RWH and MAR. These tools facilitate the acquisition, representation, and analysis of thematic layers in the study area characterized by spatial variability (surface hydrology, topography, hydro-geology, and hydrochemistry) (Jha et al. 2007). Through RS and GIS, potential maps can be created for delineating the most feasible RWH and MAR sites to decision makers.

Various decision-making methods have been applied for creating the potential maps, including statistical methods (Manap et al. 2014; Razandi et al. 2015; Guru et al. 2017), machine learning (Naghibi et al. 2016; Kordestani et al. 2019; Díaz-Alcaide and Martínez-Santos 2019), multi-criteria decision analysis (MCDA) (Chowdhury et al. 2010; Rahman et al. 2012; Valverde et al. 2016; Soliman et al. 2022), and groundwater numerical modeling (Russo et al. 2015). Most researchers combine GIS and MCDA to delineate feasible MAR and RWH sites. GIS-MCDA could be defined as a group of tools to assess and choose among different alternatives (Malczewski 2006). The combination, known as GIS-MCDA, involves overlaying and aggregating spatial thematic layers for providing essential information for the decision-making process (Malczewski 2006; Eastman 2000). In spite of the availability of combinations of several method, GIS-MCDA stands out as the most common approach among researchers (Sallwey et al. 2019).

The selected study area is North-west Saudi Arabia, characterized by an extremely arid climate where precipitation is significantly lower than potential evapotranspiration. The region comprises four provinces: Tabuk in the West, Al-Jouf in the North, Al-Hail in the South, and Al-Qassim in the South-east. These provinces are known for agriculture, serving as food logistics providers for other kingdom provinces. The study area is strategically planned for socio-economic development under the Vision 2030 national strategic project, featuring the construction of new cities along the eastern coast of the Gulf of Aqaba and a large railway system connecting the study area with other provinces.

Notably, the city of Neom, situated in Tabuk Province, is being constructed along the coast of the Gulf of Aqaba and the Red Sea. Neom is designated as an international digitalization and communication hub, focusing on recreation and tourism. Al-Jouf Province is a key food producer for Saudi Arabia and is part of the Vision 2030 strategic project, including a railway connecting Riyadh to Qurrayat for logistical transport. Al-Qassim Province is recognized for mining, livestock, and fruit production, experiencing socio-economic growth. Hail Province is known for tourism and agriculture.

Given the study area's strategic importance as the country's main food source and a national and international logistics transportation hub, the Saudi Arabian government has initiated various water infrastructure projects. These include over three desalination plants along the Gulf of Aqaba and Red Sea, more than 15 Tertiary Waste Water Treatment plants distributed across the study area (Fig. 1), and numerous dams for flood protection and water storage (Fig. 2).

Despite the presence of non-conventional water resources techniques, such as tertiary treatment plants and desalination, risks such as dam failure, plant malfunctions, and pipeline issues pose potential threats. To mitigate these risks and ensure a sustainable water supply, strategic water reserve plans are essential. Implementing a strategic water reserve in the hydrogeological system, utilizing managed aquifer recharge (MAR) structures in

Fig. 1 Waste Water Tertiary Treatment Plant at Hail. The TSE could be stored to be utilized further in case of emergency

Fig. 2 Al-Bar Dam in the Hail Province used to protect the urban areas from the severe flash-floods. The stored flash-flood water could be stored prior to be used in emergency situations

areas with high potential for storage and rainwater harvesting (RWH), becomes a cost-effective solution.

The concept of MAR was previously introduced by Zaidi et al. (2015), using artificial recharge terminology and GIS-Boolean logic to identify potential recharge zones. However, the study had limitations, such as not considering harvested rainwater for artificial recharge and lacking classification for recharge potential sites. Additionally, the study did not suggest specific locations or types of artificial recharge structures.

So, this study aims to address these gaps by identifying potential MAR sites and specifying MAR structure types. The methodology involves acquiring and processing relevant data, generating and validating MAR site potential maps using GIS-MCDA with fuzzy quantification of weighting factors, and specifying structure types based on MAR site potential and RWH for aquifer recharge. The objective is to provide accurate information for decision makers and water resource planners for formulating a sustainable water resources strategy for the study area.

To achieve the objective, the following methodology was adopted as follows:

(i) Data acquisition and processing: Different spatial data have been acquired related to aquifer hydrogeology (aquifer geometry, vertical permeability, saturated, and unsaturated thickness), meteorological data (precipitation), surface hydrology (drainage density, slope, infiltration rate), land use/land cover (LULC), and groundwater quality (salinity). The spatial data were converted to thematic layers before analysis process.

(ii) Identifying the MAR sites: MAR sites were identified using the GIS-MCDA method. To achieve this method, the following steps were conducted:

- Checking MAR elements: Main elements required for installing MAR were checked (Land, water source, and suitable aquifer).
- Constraint mapping: The infeasible location for installing MAR was eliminated at this step.
- Suitability mapping: The locations were classified according to its suitability for installing MAR (very high, high, moderate, and low).

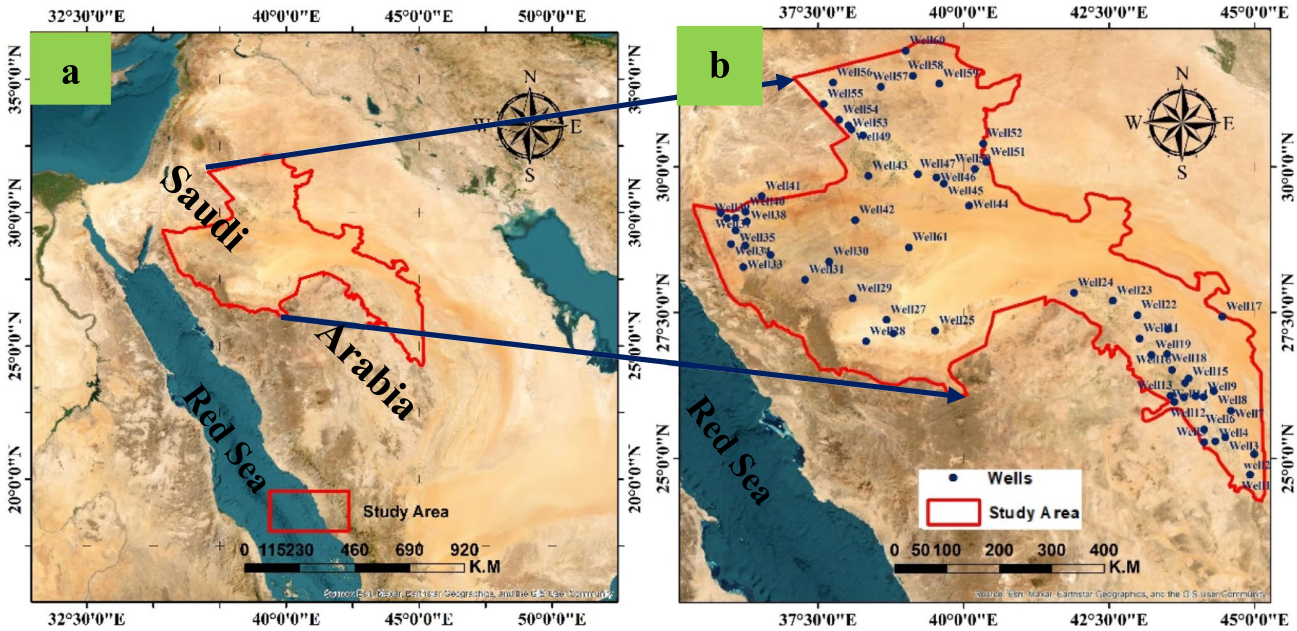

Fig. 3 **a** General location map of the study area and **b** distribution map of the boreholes used in this study (modified after Masria et al. 2023)

- Validating MAR suitability map: The map was validated and adjusted using sensitivity analysis.

(iii) Specifying MAR structure types: MAR structure types were identified based on specific criteria.

Description of selected study area

The chosen area is positioned between latitudes 24°N and 32°N and longitudes 36°E and 45°E, situated in the northwest region of Saudi Arabia, as illustrated in Fig. 3. Within this expanse, five primary towns span four provinces: Tabuk Town in Tabuk Province, Quaryyat and Sakaka towns in Al-Jouf Province, Hail in Al-Hail Province, and Biryda in Al-Qassim Province.

The climate conditions in this region are characterized as extremely arid, marked by low rainfall and high potential evapotranspiration. The cumulative annual rainfall is exceptionally low, ranging from less than 30 mm/y in the western portion to not exceeding 170 mm/y in the southeast parts. This limited precipitation directly impacts the actual infiltration rate into the soil during storm events. The majority of rainfall occurs irregularly in short durations with high intensity, primarily between October and April. The potential evapotranspiration rate is consistently high throughout the area, reaching approximately 2400 mm/year (Zaidi et al. 2015). The mean monthly temperature during the summer season varies from 43 °C to 48 °C during the daytime and 32 °C to 36 °C during the night-time. In contrast, temperatures may drop to 0 °C in the winter season. These climate conditions contribute to the arid nature of the region, emphasizing the challenges associated with water scarcity and management.

Topographically, the western part of the area exhibits the highest elevations, surpassing 1800 m + MSL, primarily due to the presence of mountains. This western region features terrains bounded by valleys with elevations of around 800 m above MSL, characterized by flat reliefs. Generally, 85% of the area is marked by mild slopes, predominantly dipping toward the SE direction. The overall elevation, as depicted in Fig. 4(a), ranges between 900 m, in the West, and 400 m, in the East. This gradual dip serves as an indicator for describing surface morphology and understanding various surface operations, including runoff and the capacity of the infiltration of rainfall water (Daher et al. 2011).

Geology

Across the Arabian Peninsula, two distinctive geological units are present: The basement rocks (west) and the Phanerozoic sedimentary rocks (east). The latter sedimentary unit gradually thickens from W to E (Rodgers et al. 1999). The Saq Sandstone, composed of medium to coarse sandstone, occurred over the rocks of basement and outcrops to W. This formation, with a thickness ranging between 400 and 925 m, is considered the main and major groundwater aquifer in KSA, particularly to the north direction (AlSharhan 2001). Laboun (2013) and Al-Dabbagh (2013) described the main stratigraphic

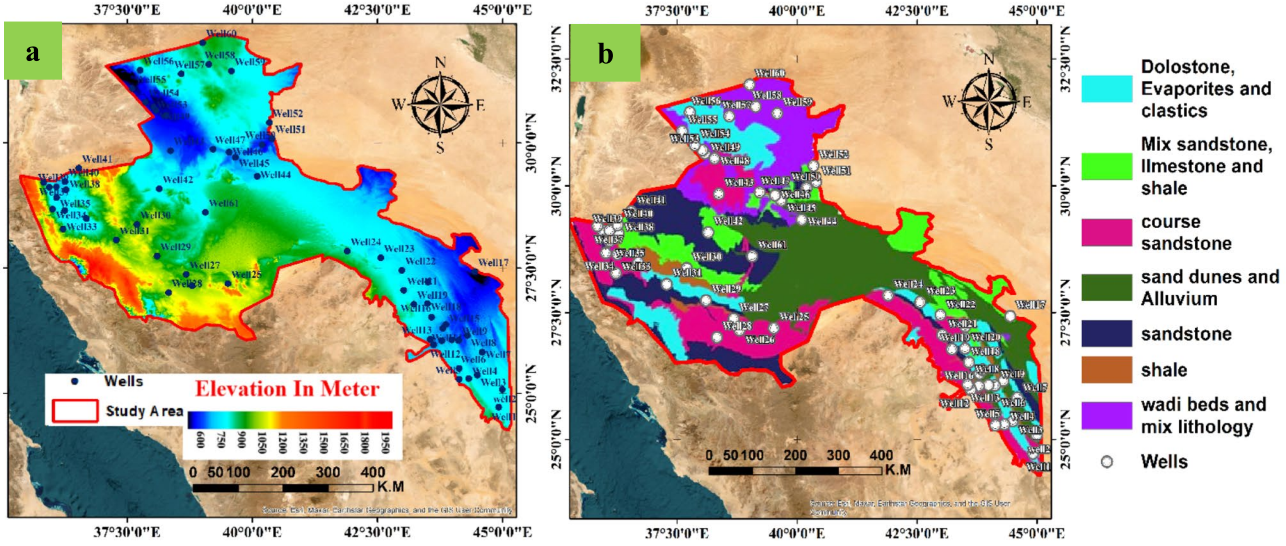

Fig. 4 **a** Surface topographic map (modified after Masria et al. 2023) and **b** subsurface aquifer sediments distribution map (modified after Ahmed et al. 2015 and Masria et al. 2023)

succession of the area, encompasses the periods of Cenozoic, Mesozoic, and Paleozoic. Figure 4(b) illustrates the distribution of subsurface aquifer sediments along the study area.

The Cenozoic sediments primarily consist of Quaternary Eolian deposits, comprising sand, silt, and clay, along with basaltic flows and carbonate rocks with a thickness ranging between 135 and 230 m. The sediments of Mesozoic are dominated by limestone with intercalation of shale and sandstone with a thickness ranging from 2324 to 2462 m. About 116 m thick of shale separates the previous sediments from those of the Paleozoic era. The sediments of Paleozoic represent in fractured shale limestone (170 m, Kuff formation); sandstone (80 m–85 m, Unayzah formation); siltstone (190 m–270 m); sandstone (300 m–410 m, Jubah formation); limestone with intercalation of shale and sandstone (270 m–280 m, Al-Jouf formation); sandstone (230 m–250 m, Tawil formation); shale, sandstone, and siltstone (450 m, Qalibah formation); sandstone, siltstone, and shale (140 m–160 m, Tabuk formation); and sandstone and shale (260 m, Qassim formation) then followed by sandstone (400 m–930 m, Saq formation). The total thickness of the Paleozoic sediments ranges between 2490 and 3265 m.

Consequently, the entire stratigraphic succession total thickness in the area ranges between ~ 4949 m and ~ 5957 m. In major sedimentary basins, this thickness may exceed ~ 8000 m. The geological composition of the area provides insights into the diverse sedimentary layers that contribute to the hydrogeological characteristics of the area.

Hydrogeology

The hydrogeological system in the study area has been characterized, including details on the formations type, average thickness, groundwater depth, and hydraulic conductivity (groundwater movement rate) based on data from MoWE (2008) and Izrar et al. (2015). The descriptions for each formation are as follows:

1. Saq Formation:
    - Type: Coarse-grained sandstone
    - Thickness: Ranges from 400 to 930 m
    - Depth to groundwater: Varies from 65 to 297 m
    - Hydraulic conductivity: Low (~ 4.36 m/d)
2. Qassim Formation:
    - Type: Sandstone with shale
    - Thickness: ~ 260 m
    - Depth to groundwater: Ranges from 30 to 250 m
    - Hydraulic conductivity: High (~ 9.5 m/d)
3. Qassim Formation to Sarah Sandstones of Tabuk Formation:
    - Type: Sandstone and shale
    - Thickness: Ranges from 140 to 260 m
    - Depth to groundwater: Ranges from 85 to 240 m
    - Hydraulic conductivity: Very low (~ 0.864 m/d)
4. Qalibah Formation and Tawil Sandstones:
    - Type: Shale, sandstone, and siltstone
    - Thickness: Ranges from 230 to 450 m

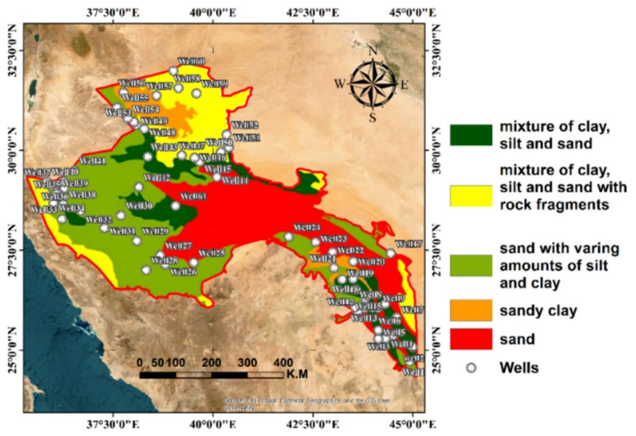

Fig. 5 Surface soil texture cover of the area (Modified after Zaidi et al. 2015; Masria et al. 2023)

- Depth to groundwater: 120 m
- Hydraulic conductivity: Very high (~ 21.64 m/d)

5. Jubah Formation:
   - Type: Sandstone
   - Thickness: Ranges from 300 to 410 m
   - Depth to groundwater: Ranges from 120 to 150 m
   - Hydraulic conductivity: Very low (~ 0.56 m/d)
6. Khuff Formation:
   - Type: Fractured shaley limestone
   - Thickness: ~ 170 m
   - Depth to groundwater: Varies from 192 to 250 m
   - Hydraulic conductivity: Low (~ 4.36 m/d)
7. Secondary Mesozoic, Tertiary, and Quaternary Sandstone and Limestone (STQ):
   - Depth to groundwater: Varies from 15 to 290 m
   - Hydraulic conductivity: Very high (~ 17.49 m/d)

Regarding to the hydrogeology of the unsaturated zone, the distribution of surface soil cover (Fig. 5) indicates the soil texture characteristics which reflects the hydrogeological characteristics of the unsaturated zone. Areas with a mixture of clay, rocky clay, sandy clay, silt, sand with clay, and silt are characterized by low effective porosity and hydraulic conductivity. These areas are considered unsuitable for recharging of groundwater, rainwater percolation to the aquifer, or efficient drainage. Conversely, sediments rich in varied sizes sand, gravel, and little content of clay and silt are conducive to drainage, where both their effective porosity and permeability are high, as shown in the pictures (Fig. 6). These pictures refer to the surface sediments which include sand, gravel, and rock fragments (wadi deposits).

In terms of groundwater recharge and discharge, estimates by Groundwater Development Consultants (1979) suggest a recharge rate of ~ 15% of the precipitation value in the area. Additionally, BRGM (1985) has independently estimated that nearly 7 mm of precipitation contributes to recharging the subsurface sediments in this area.

However, the groundwater resources are heavily exploited. The annual groundwater exploitation in the year 2008 for various aquifers is as follows: Saq aquifer ~ 1400 Mm^3/y, Kahfah aquifer ~ 190 Mm^3/y, Quwarah aquifer ~ 100 Mm^3/y, Tawil aquifer ~ 20 Mm^3/y, Jubah aquifer ~ 100 Mm^3/y, Khuff aquifer ~ 100 Mm^3/y, STQ aquifer ~ 150 Mm^3/y, and Al-Jouf aquifer ~ 5 Mm^3/y (MoWE, 2008). A comparison of groundwater abstraction to natural recharge indicates that the annual abstracted groundwater rate in the area of study exceeds the annual groundwater natural recharge (MoWE, 2008), which has been estimated by Mohamed et al. (2022) as approximately 4200 (±) 150 Mm^3/y.

The Saq aquifer stands out as a crucial source of groundwater supply, while the other aquifers are locally significant. The water table, or piezometric level, in the year 2015 varies from 500 to 838 m (+ MSL). Salinity levels in 2013 ranged between 350 and 700 ppm, classifying the water as fresh and suitable for municipal and irrigation purposes. (Zaidi et al. 2015). Despite these conditions, the demand for groundwater extraction raises concerns about sustainability and the need for effective management strategies to ensure long-term water availability.

Materials and dams methods

Data acquisition and processing

The data necessary for this study were gathered through a comprehensive review of the literature pertaining to the study area. Delineating the managed aquifer recharge (MAR) sites involves considering numerous factors, as highlighted in the literature review conducted by Sallwey et al. (2019). These factors include aquifer hydrogeology, surface hydrology, economic and environmental management, hydrometeorology, and water quality (groundwater salinity). Additionally, thorough investigation of the study area should be conducted to ensure the reliability of the data and determine the current study area conditions.

The data of aquifer geometry (saturated thickness) for this study were sourced from an analyzed deep geophysical fieldwork conducted by Stern and Johnson (2010), as shown in Fig. 7(a). The data of the unsaturated zone thickness were sourced from a 3D Fence diagram created by Masria et al. (2023) depending on borehole, as distributed in Fig. 7(b), data as input, providing a comprehensive

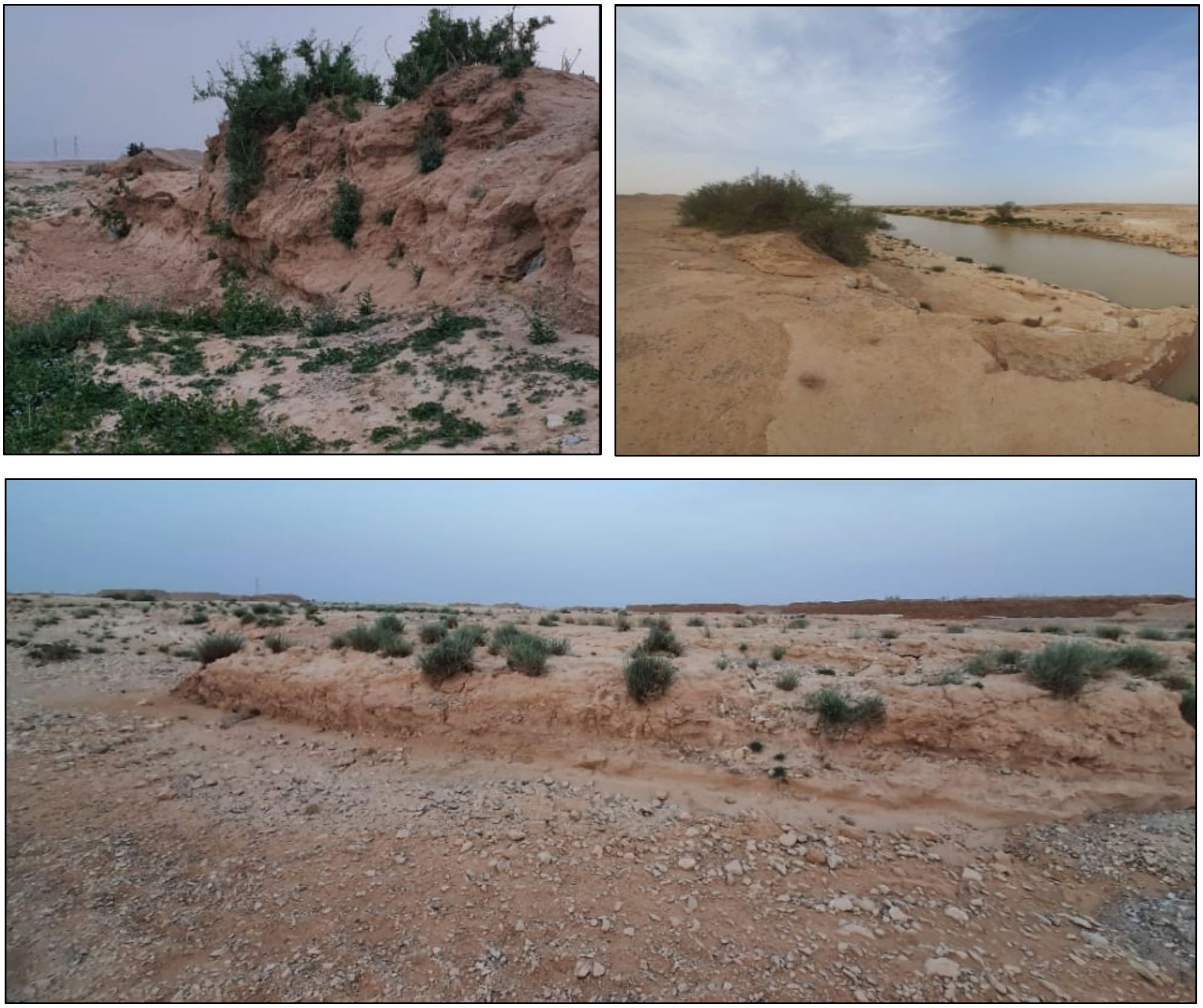

Fig. 6 Pictures for showing the surface sediments (sand, silt, and gravel with rock fragments) cover most of the area of study

representation of the unsaturated zone thickness and depth to the aquifer surface, as shown in Fig. 8.

Vertical permeability was determined as an important hydrogeological property for the unsaturated (vadose) zone by applying the resulting power regression relationship (Ammar 2012) between permeability and electrical resistivity and based on relationships between hydraulic horizontal permeability and vadose zone properties established by Masria et al. (2023). Numerical modeling of the resistivity of the unsaturated zone was used to ascertain the hydraulic parameters (Masria et al. 2023), and a Python script was developed to interpret the vertical permeability map, considering relationships with unsaturated thickness and soil texture. The vertical permeability map was derived by multiplying the horizontal permeability by the anisotropy factor (~ 0.1). Additionally, groundwater quality, represented by the salinity map of the saturated zone, was obtained from Zaidi et al. (2015) for the year 2013.

While most of the required data were successfully collected, some variables, such as surface water quality, hydrographs of flow discharge, environmental and economic impact assessments, and lineament density, were not included due to a lack of available data. The compiled data are presented in Fig. 9 in the form of thematic GIS layers, providing a spatial distribution of the variables gathered for the study. The absence of certain data points highlights potential limitations in the analysis and emphasizes the need for additional information in those specific areas to enhance the comprehensiveness of the study.

In terms of surface hydrology, the study area's slope was determined using SRTM digital elevation model data, with 90-m resolution DEM, from NASA (2018) processed in ArcMap software. The curve number data, reflecting surface

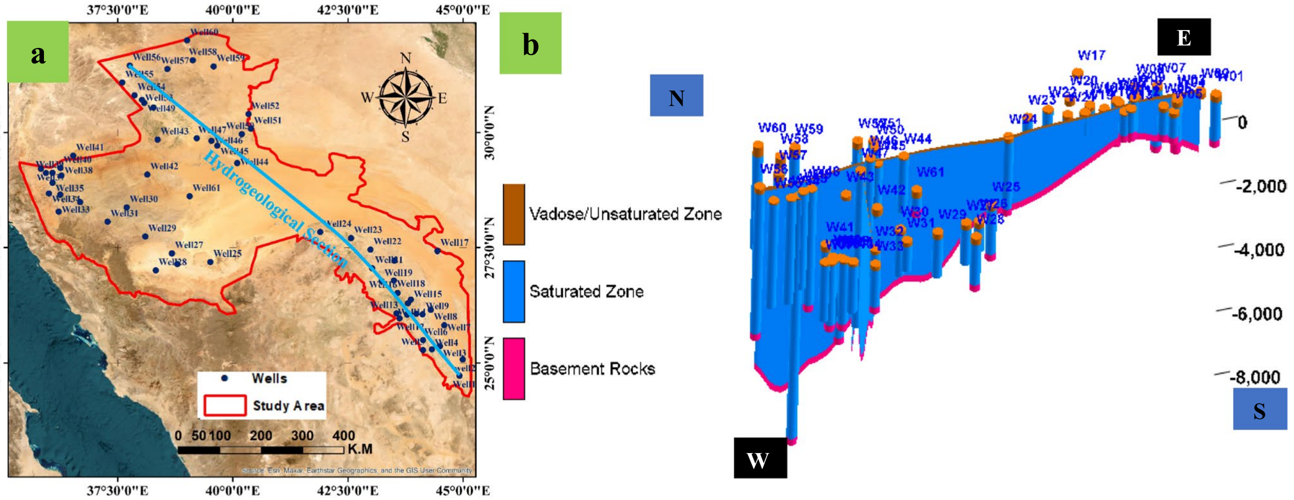

Fig. 7 **a** Map of well locations and direction of the two-dimensional hydrogeological. cross section and **b** hydrogeological cross section representing the unsaturated and saturated thickness

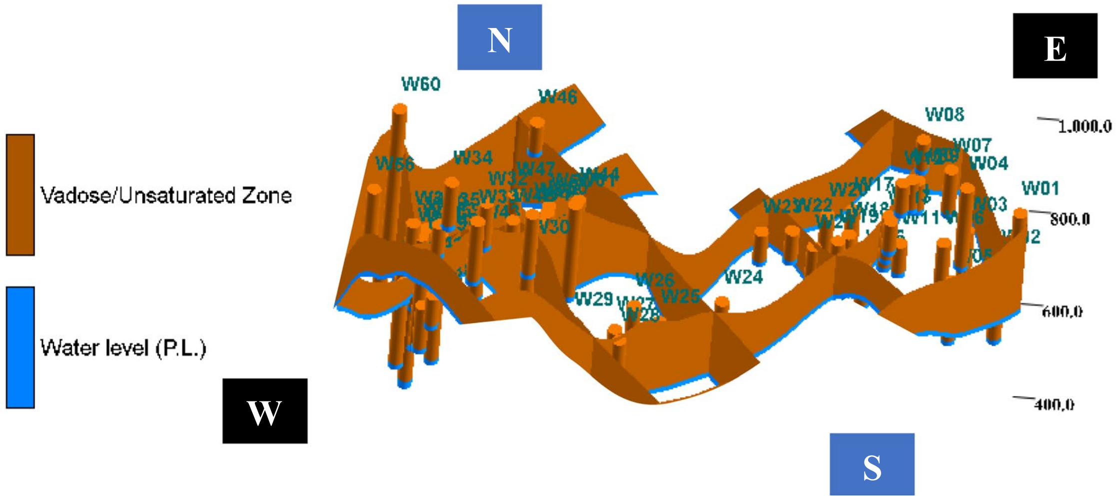

Fig. 8 3D Fence diagram for representing the thickness of unsaturated and groundwater level (GWL) along the area of study (Masria et al. 2023)

cover infiltration rates, were derived from the CN250 dataset produced by Jaafar et al. (2019), based on the relationship found by Chong and Teng (1986) between soil infiltration rate and curve number. Drainage density was calculated using HydroSHEDS streams and watersheds data from Lehner et al. (2008).

Key water resources, including mean annual precipitation depth and runoff flow accumulation, were obtained from Sharaf and Hussein (1996) and through the analysis of the flow network using DEM raster datasets, respectively. The locations of unconventional water resources plants, such as desalination and tertiary waste water treatment plants, were identified using Google Satellite Images. Dams were excluded from this study because the flooded water after dams could be utilized from economic point of view for different activities rather than artificially recharging it to the aquifer via MAR systems.

Identifying the potential MAR sites and Checking MAR elements

In many studies, the selection of the best MAR site has been guided by specific methodologies (Saraf and Choudary 1998; Anbazhagen et al. 2005; Ravi Shankar and Mohan 2005). This study employs a unique approach by classifying the area into different zones based on feasibility of site before delineating the sites. The methodology follows a GIS-based holistic approach introduced by Rahman et al. (2012),

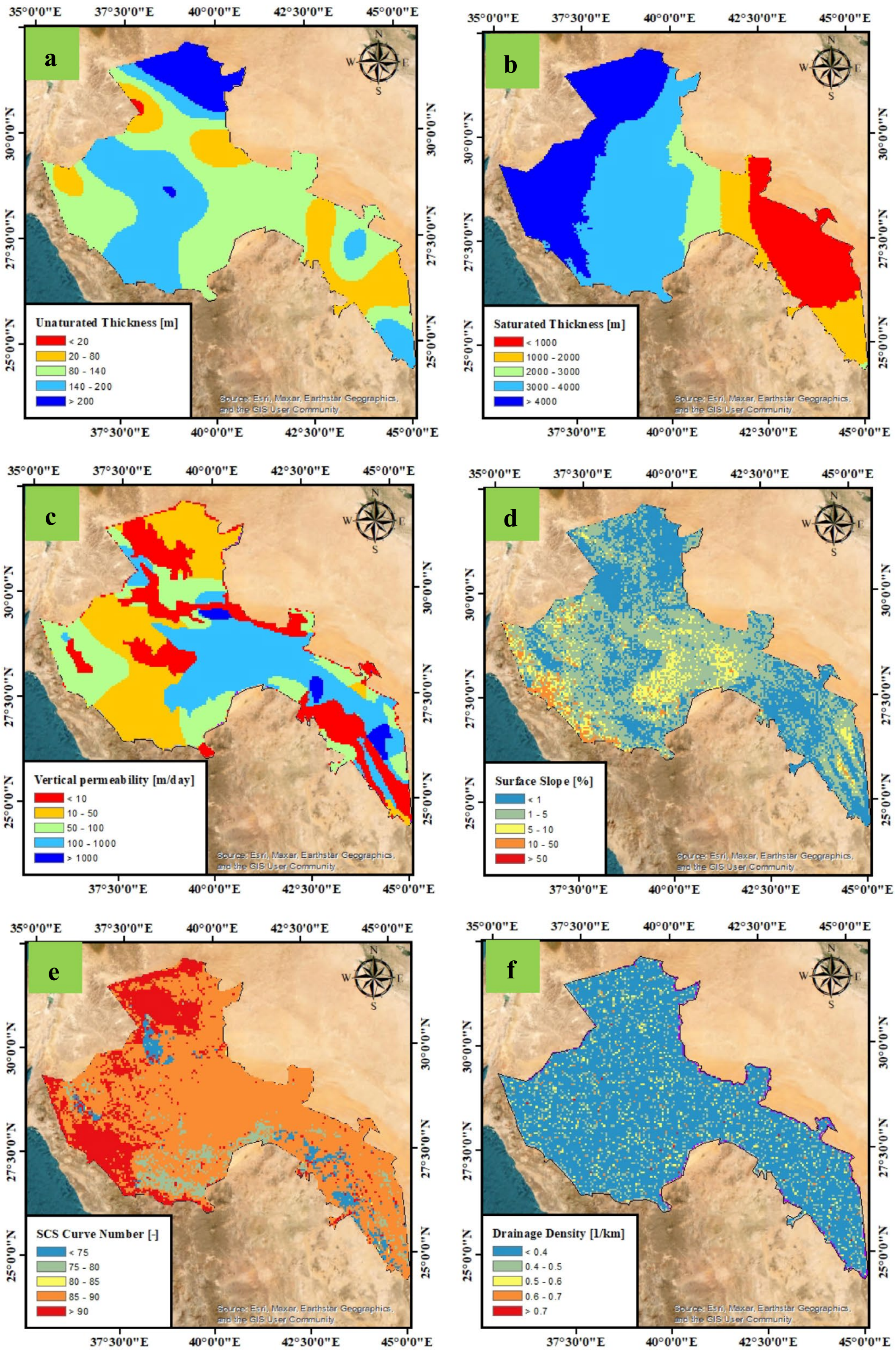

Fig. 9 Thematic GIS maps acquired and processed for this study (Raster grid resolution = 250 m), these maps include unsaturated thickness (**a**), saturated thickness (**b**), vertical permeability (**c**), surface slope (**d**), SCS curve number (**e**), drainage density (**f**), mean annuals precipitation (**g**), flow accumulation (**h**), water infrastructure location (**i**), salinity (**j**), Land use/Land cover (LULC) (**k**), and water-bearing formation (**l**)

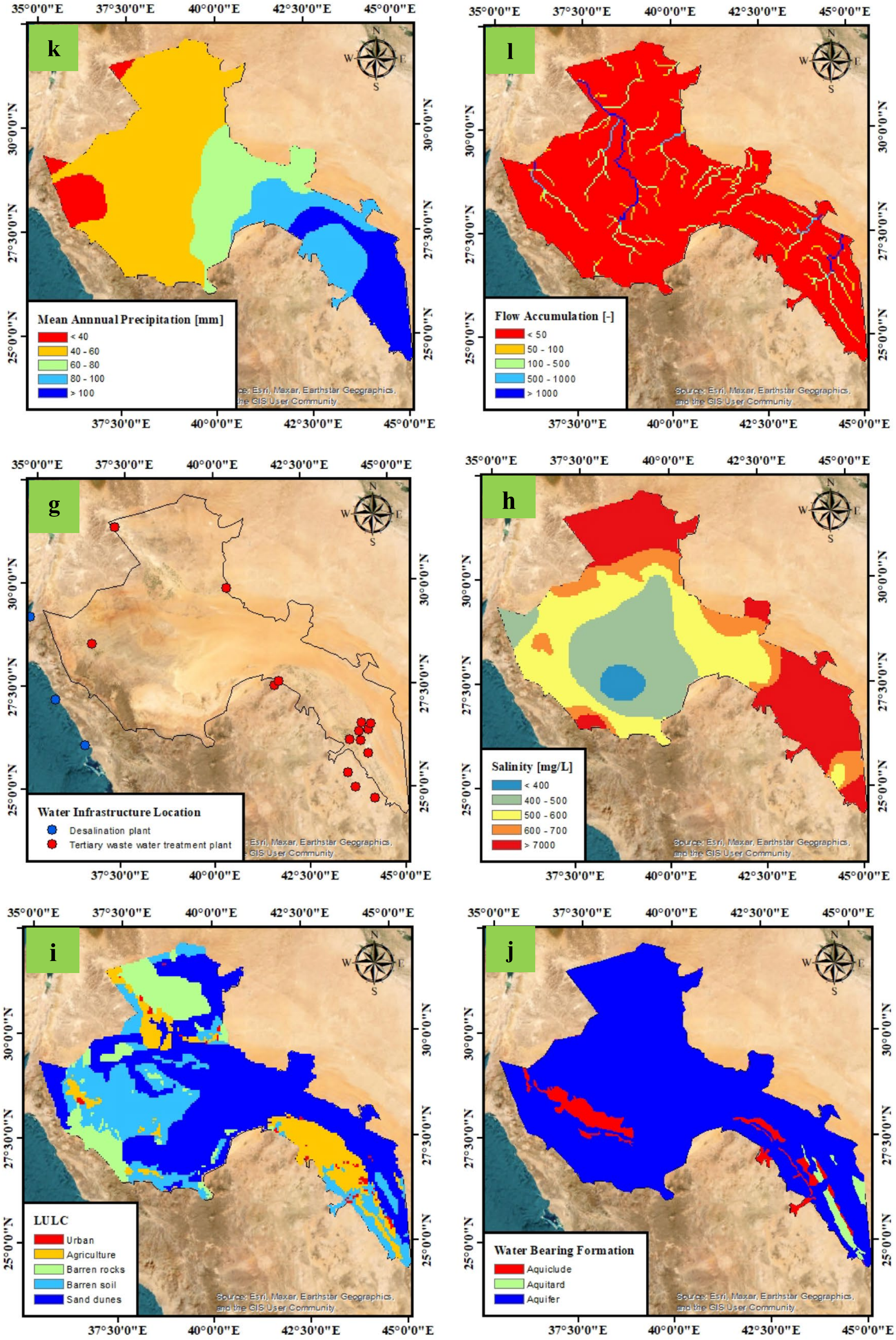

Fig. 9 (continued)

Table 1 The criteria validation (reviewed by Sallwey et al. (2019) for constraint mapping in the area

Constraint criteria	Validity in the area	Reason
LULC	Valid	Presence of different land use classifications (urban, agriculture, and bare land)
slope of surface	Valid	High slope values in some areas (> 3%)
Geology (water-bearing layers)	Valid	Presence of different water-bearing formation layers
Unsaturated thickness	Invalid	The unsaturated thickness at the study area is greater than 5 m
Soil infiltration rate	Valid	Some areas in the study area have low infiltration rate (< 0.25 m/day, runoff CN > 87)
Distance from pollution source	Invalid	source of pollution is the industrial cities and agriculture which were eliminated in the land use landcover criteria
Distance to water supply infrastructure	Invalid	Desalination plants, water treatment plants, and dams for storage purposes are spreading along the study area
Groundwater quality	Invalid	Threshold value for salinity is 3000 mg/L for an arid climate coastal aquifer (Anane et al. 2008) TDS in the area of study is lower than 1500 mg/L

encompassing the following steps: (1) checking MAR elements, (2) constraint mapping, (3) suitability mapping, and (4) sensitivity analysis.

Checking MAR elements

Checking MAR elements step involves assessment of the feasibility of installing MAR sites in a hydrogeological setting. According to Gale (2005), three essential elements must be present for a successful MAR site: a water source, suitable land, and an aquifer with adequate hydrogeological characteristics (flow and storage). In the case study, all three elements are available: non-conventional water resources serve as the water source, bare sandy soil as the suitable land, and high aquifers characterized by favorable hydrogeological conditions.

The subsequent steps in the holistic approach involve *constraint mapping, suitability mapping, and sensitivity analysis,* which collectively contribute to identifying and delineating the most suitable MAR sites in the area of study.

Constraint mapping

In this phase, feasible sites are filtered using a Boolean logic algorithm. The choice of Boolean logic in this process is based on its common usage among researchers (Sallwey et al. 2019). Boolean logic involves logical combinations of operations such as intersection, union, and complement. In this study, only the intersection operator was applied. The criterion values for the intersection operator are unity and null. The operator assigns a null value when the criteria fail to meet the constraints and vice versa (Rahman et al. 2012).

Prior to the application of this method, the constraint criteria were validated by using the criteria reviewed by Sallwey et al. (2019) (Table 1). Subsequently, the selected criteria were transferred from contouring maps to thematic raster layers with a pixel size of 5000 m applying ArcGIS 10.7.1 software. This process is essential for transforming the criteria into a format suitable for further analysis and constraint mapping.

Suitability mapping

Suitability mapping is a crucial step in GIS-MCDA analysis, as highlighted by Rahman et al. (2012). Unlike constraint mapping, suitability mapping does not eliminate unsuitable areas. Instead, its primary function is to classify the potential for a site to be installed in a particular location. During this process, weights are assigned to criteria, and these weights are combined to obtain a score for each site (Eastman 2000). The assigned weights are usually estimated by a technical expert or decision maker based on field experience (Sallwey et al. 2019). Suitability mapping involves four key steps: *(A) selecting criteria, (B) assigning hierarchy and weights to criteria, (C) normalizing criteria thematic layers, and (D) combining criteria thematic layers.*

Selecting the criteria The selection of criteria relies on the statement of problem and conditions of site (Sallwey et al. 2019). The complexity of the problem dictates the number of criteria chosen. In determining the criteria, Sallwey et al. (2019) conducted a review of mentioned studies to compile all possible criteria applicable to this process. The chosen criteria were then refined based on their suitability to the problem and the case study (Table 2). Thematic maps of the selected criteria were transferred from contoured maps to thematic raster layers with a pixel size of 5000 m by applying ArcGIS 10.7.1 software. This conversion is necessary to prepare the criteria for further analysis in the GIS-MCDA process.

It is worth mentioning that the socio-economics and environmental factors were eliminated in this study owing to lack of data availability regarding these factors. However, the socio-economic and environmental factors play an essential

Table 2 The criteria validation for suitability mapping (reviewed by Sallwey et al. (2019)) in the area

Type	Criteria	Validity	Reason
Aquifer hydrogeology	Flow capacity (vertical permeability)	Valid	–
	Storage capacity (unsaturated zone thickness)	Valid	–
	Storage capacity (saturated zone thickness)	Valid	–
Water source	Precipitation	Valid	high spatial distribution of the rainfall
	Runoff	Valid	Presence of catchments where the outlet is located at certain parts of the catchment
Management	Benefits of Economy	Invalid	Lack of cost–benefit analysis study
	Environmental impact assessment	Invalid	Lack of study of environmental impact assessment
Surface hydrology	Geology	Invalid	Elimination of aquiclude and aquitard in the constraint mapping
	Geomorphology (surface slope)	Valid	presence of wide range slope
	Hydrography (drainage density)	Valid	presence of wide range drainage density
	LULC	Valid	presence of different land cover classification in the study area
	Soil Infiltration rate	Valid	presence of wide range infiltration rate
Water quality	Groundwater quality (salinity)	Valid	presence of salinity map of the aquifer
	Quality of surface water	Invalid	No presence of perennial stream or lake

role for specifying precisely and they have to be considered during the decision-making process.

Assigning hierarchy After criteria selection the, they were categorized into four hierarchical levels based on the priority of thematic maps. The hierarchy was established considering the following priorities: (1) hydrogeology of groundwater aquifer (vertical permeability and unsaturated thickness), (2) surface hydrology (surface slope and infiltration rate), (3) water and land source (precipitation, runoff (flow accumulation), (LULC)), and (4) secondary aquifer hydrogeology (saturated thickness, drainage density, and salinity). This hierarchy aligns with common practices in previous GIS-MCDA studies for selecting suitable sites for artificial recharge.

Standardizing criteria thematic layers To facilitate the combination of criteria for suitability mapping, the criterion values needed to be transferred to a uniform scale through a process called standardization. In this study, a step function was employed using normal distribution quantiles, classifying the distribution function of the thematic layers into five classes. The results ranged from 10% (assigned to very low suitable criterion values) to 90% (assigned to very high suitable criterion values), with 30%, 50%, and 70% representing low, medium, and high criterion values, respectively.

Combining criteria thematic layers After the processes of weighting and standardization, the overall score was estimated by combining the weighting factors. Ordered weighting average (OWA) was chosen for combining thematic layers. OWA, introduced by Yager (1988), incorporates a fuzzy linguistic quantifier capable of manipulating the weighting factor, as expressed in the following equation.

$$OWA_i = \sum_{j=1}^{n}\left(\left(\sum_{k=1}^{j} u_k\right)^{\alpha} - \left(\sum_{k=1}^{j-1} u_k\right)^{\alpha}\right)W_{ij} \quad (1)$$

where:W_{ij}: weighted factor for criterion value i, u_k: criteria weight reordered due to W_{ij}, α: parameter linguistic quantifier. $\alpha = 0$ when at least one of the criteria is satisfied resulting in no trade-off, whereas α=1 agree with to Weighted Linear Combination. If $\alpha = \infty$, then most of the criteria are satisfied resulting in no trade.

OWA was implemented through a pair-wise matrix for the four groups, considering the assigned hierarchy. The fuzzy quantifier (α) in OWA was determined by minimizing the number of cells characterized by very high MAR installation potential. An optimization function constrained α within the range of (0.3–1.0), ensuring the consistency ratio of the weighting factor did not exceed 10%. This constraint aimed to maintain consistency between the assigned weighting factors. The optimization technique's objective was to precisely identify sites with high potential for MAR installation.

The suitability score was applied to classify cells into five categories representing potential sites for MAR installation (infeasible, low, moderate, high, and very high). Infeasible sites were previously identified through the constraint mapping process. Feasible cells were classified as follows:

- Low (suitability score < 50)
- Moderate (50 < suitability score < 60)
- High (60 < suitability score < 65)
- Very high (suitability score > 65)

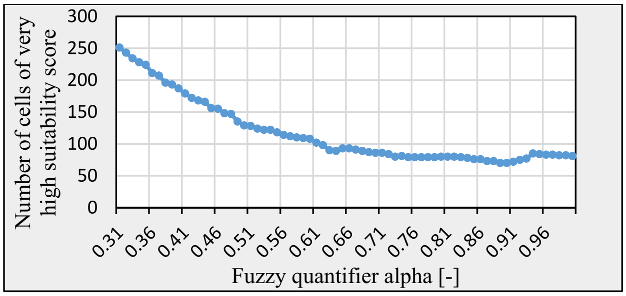

Fig. 10 Identifying the fuzzy quantifier (α) for the ordered weighed average via an optimization technique

Table 3 Weighting factors for the different categories before and after determining the quantifier alpha using optimization techniques

Criteria	Weighting factor before optimization process	Weighting factor after optimization process
Hydrogeology (primary)	0.25	0.2842
Surface hydrology	0.25	0.2472
Water and land availability	0.25	0.2382
Hydrogeology (secondary)	0.25	0.2304

Figure 10 displays the optimized α after the optimization process carried out by a Python script. The optimal α was determined as 0.9, and the consistency ratio was 9.99% (less than 10%). Based on these results, the weighting factors for different categories were calculated, as shown in Table 3. These optimized weighting factors were then multiplied by the standardized thematic layer values for generating the map of suitability for the area of study.

Validating the MAR suitability map

Sensitivity analysis was performed to validate the outputs and to identify the results uncertainty (Saraf and Choudary 1998). To conduct sensitivity analysis, the quantifier alpha's value was varied to observe changes in the results from the suitability map. The comparison focused on the area of low feasible sites. Table 4 presents the weighting factors at different alpha values used for the sensitivity analysis. The analysis of sensitivity aimed to gauge the impact of changes in the fuzzy quantifier alpha on the suitability map, specifically in the area classified as having low feasibility for MAR installation.

Specifying the MAR and RWH structures

In general, the MAR structures proposed by Dillon et al (2009) will be applied. These structures include different methods to enhance groundwater recharge. It can be categorized into spreading methods (infiltration ponds and basins, soil aquifer treatment (SAT), recharge due to irrigation), in-channel modifications (check dams, sand storage dams, subsurface dams, and recharge releases from dams), well and borehole recharge (dug wells and shafts, aquifer storage and recovery (ASR), aquifer storage, transfer, and recovery (ASTR), induced bank filtration, and harvesting of rainwater (Percolation tanks and roof top rainfall harvesting).

The selection of MAR structure types is contingent upon local hydrology, hydrogeology, and groundwater quality considerations (Gale 2005). It is crucial to align the choice of MAR structures with the specific characteristics of the study area to optimize their effectiveness in enhancing recharge of groundwater. In this study, the selection of MAR and rainwater harvesting (RWH) structures is based on the potential for MAR installation in different areas. The chosen methods align with the local site conditions, considering factors such as the bottom layer of the unsaturated zone, hydrological characteristics of watersheds, vertical permeability of the unsaturated zone, and the rate of infiltration of the surface cover.

1) **Spreading methods (Very high potential areas)**
   - *Infiltration ponds and basins:* These structures are proposed for areas characterized by very high potential for MAR installation. They involve creating ponds or basins to facilitate the water infiltration into the aquifer.
2) **In-Channel modifications (High potential areas)**
   - *Check dams with diversion channels:* Proposed for areas with high potential for MAR installation. Check dams are structures built across a channel to slow down water flow, enhancing infiltration. Diversion channels are constructed to transfer water from the streams during rainfall events to the check dams.
3) **Well and borehole recharge (Low potential areas)**
   - *Open wells and shafts:* Selected for areas with moderate potential for MAR installation. Dug wells and shafts are used to recharge of groundwater directly including the confined and unconfined aquifers, where ASR and ASTR techniques could be applied.

Excluded methods

- *Induced bank filtration:* Eliminated due to the absence of perennial streams in the case study area, a prerequisite for induced bank filtration.

Table 4 The values of weighting at different linguistic quantifier values for sensitivity analysis

Category number	Criteria	Alpha α=0.50	Alpha α=0.75	Alpha α= 1.00 (Optimum weighting)	Alpha α= 1.25	Alpha α= 1.50
1	Flow capacity (vertical permeability)	0.3770	0.2314	0.1421	0.0872	0.0536
1	Storage capacity (unsaturated thickness)	0.1561	0.1578	0.1421	0.1203	0.0979
2	Geomorphology (surface slope)	0.1055	0.1211	0.1236	0.1184	0.1089
2	soil infiltration rate	0.0904	0.1121	0.1236	0.1278	0.1270
3	Meteorology (precipitation)	0.0526	0.0685	0.0794	0.0863	0.0900
3	Meteorology (runoff)	0.0492	0.0663	0.0794	0.0891	0.0960
3	Land use (LULC)	0.0465	0.0644	0.0794	0.0917	0.1017
4	Storage capacity (saturated thickness)	0.0427	0.0608	0.0768	0.0910	0.1035
4	Hydrography (drainage density)	0.0408	0.0594	0.0768	0.0931	0.1084
4	Hydrogeology (salinity)	0.0392	0.0582	0.0768	0.0951	0.1130
Sum		1.000	1.000	1.000	1.0000	1.0000

- *Rainfall harvesting:* Excluded as it involves constructing structures in urban areas, which were eliminated during the constraint mapping process.

After determining the structure types, a map was generated to illustrate the location and type of MAR and RWH structures based on the identified potential for MAR installation in different areas. This mapping requires a visual representation of the proposed structures across the area of study, facilitating effective water resource management and planning.

Results and discussion

Identifying the potential MAR sites

The identification of potential sites for installing MAR and RWH structures has been executed through the application of the GIS-MCDA holistic approach suggested by Rahman et al. (2012): (1) checking MAR elements, (2) constraint mapping, (3) suitability mapping, and (4) sensitivity analysis.

The MAR elements, encompassing the presence of a suitable water source, land, and an aquifer system characterized by high hydrogeological features in terms of flow and storage, are available in the case study. Constraint mapping was employed to screen out infeasible sites using four criteria: (1) land use and land cover (LULC), (2) surface slope, (3) surface soil infiltration rate, (4) water-bearing layers.

Furthermore, suitability mapping was applied after determining all the criteria based on the site conditions. Ten criteria were taken into consideration: (1) vertical permeability, (2) unsaturated thickness, (3) surface slope,, (4) infiltration rate, (5) precipitation, (6) flow accumulation, (7) LULC, (8) saturated thickness, (9) drainage density, and (10) salinity. The criteria were hierarchically classified according to their effectiveness on MAR functionality and standardized using a step function.

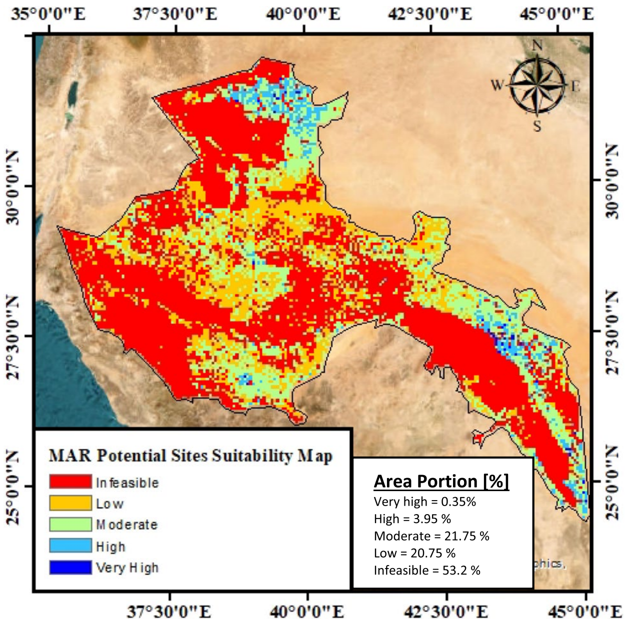

Fig. 11 MAR sites potential suitability map

The suitability map was created by calculating the suitability score for each cell in the study area using the ordered weighted averaging (OWA) method, where the alpha quantifier was optimized to minimize the number of cells classified as having a very high potential for MAR. It has been mentioned that high suitability scores for a specific cell indicated a high potential for installing MAR at that location (Fig. 11). The cells were classified into

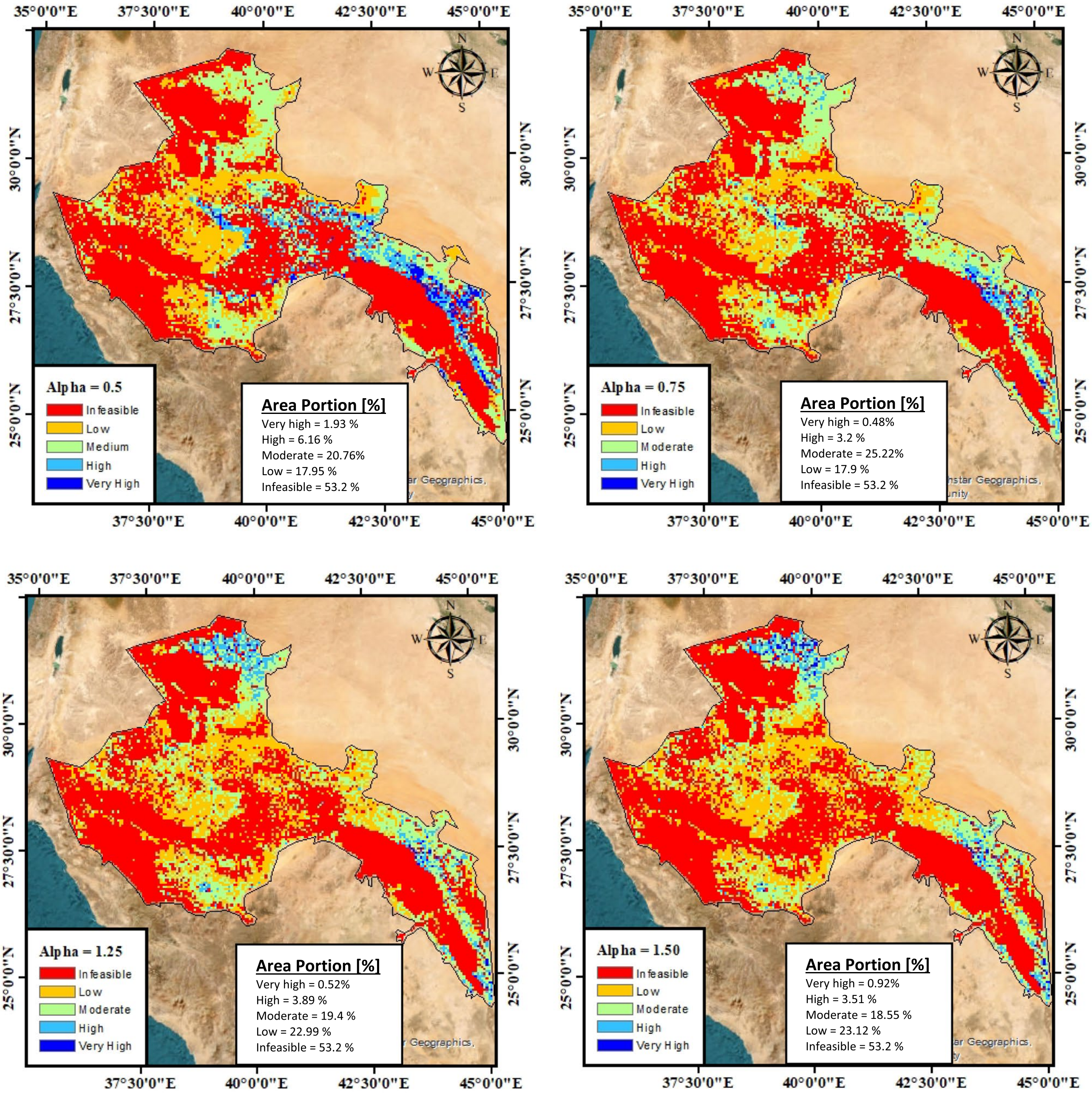

Fig. 12 Sensitivity analysis results maps (Alpha α = 0.50, 0.75, 1.25, and 1.50)

five classes depending on constraint mapping and suitability scores: infeasible, low, moderate, high, and very high. Figure 12 illustrates the MAR site potential map after the suitability mapping process. It has been revealed that approximately 53.2% of the area of study was deemed infeasible to install MAR sites, as these cells have been insulated during the constraint mapping process. The remaining 46.8% of the study area has been classified for their potential for installing MAR sites. It has been determined that the area percentage distribution for very high, high, moderate, and low potential sites is ~ 0.35%, 3.95%, 21.75%, and 20.75%, respectively.

Five main areas were identified as having high potential to install MAR sites. The sites of these areas are as follows:

Area 1: Northeastern corner of the study area, situated in Al-Jouf Province near Sakaka and Qurrayat cities (~190 km east from Qurrayat, ~170 km from Sakaka).

Table 5 Sensitivity analysis results

Site potential category	Percentage Area [%]				
	$\alpha = 0.50$	$\alpha = 0.75$	$\alpha = 1.0$	$\alpha = 1.25$	$\alpha = 1.50$
Very high	1.93	0.48	0.35	0.52	0.92
High	6.16	3.20	3.95	3.89	3.51
Moderate	20.76	25.22	21.66	19.40	18.55
Low	17.95	17.90	20.84	22.99	23.12
Infeasible	53.2	53.2	53.2	53.2	53.2

Area 2: In the center of the area between Tabuk and Sakaka cities, located in Tabuk province (~235 km from Tabuk and ~175 km from Sakaka).
Area 3: Southern portion of the study area, situated between El-Hail and Tabuk cities (~280 km from Tabuk and ~290 km from Hail).
Area 4: Located near El-Hail city in El-Hail Province (~130 km from El-Hail).
Area 5: Inside El-Qassim Province, situated at the east part of the area near Buraydah and Hail Towns (~125 km from Buraydah and ~190 km and ~180 km from Hail).
Area 6: South-east part of the area (~140 km from Buraydah).

Before validating the suitability map by determining the degree of uncertainty, a sensitivity analysis was conducted by using the OWA method, with the weighting factor adjusted to gauge the degree of change in results based on the fuzzy quantifier alpha. The alpha α varied from 0.5 to 1.5, and the results indicated minor changes in the suitability map based on the variation in alpha, as illustrated in Fig. 12. Table 5 presents the changes in the percentage area at different alpha values, with 'Alpha α = 1.0' representing the percentage area of the suitability map.

The aforementioned figures illustrate that certain areas exhibit a high degree of uncertainty. It has been noted that the map of suitability displays a high degree of uncertainty in the identified areas indicating a high potential for installing MAR sites. Therefore, the suitability map was adjusted to eliminate the cells categorized as very high, high, and moderate, which are characterized by a high degree of uncertainty. Figure 13 displays the modified suitability map after removing the uncertainty, as determined through the sensitivity analysis process. Meanwhile, Table 6 provides the percentage area of the site potential for installing MAR and rainwater harvesting (RWH) sites, specifying the suitable structure types for each category.

The modified suitability map indicates that the very high potential MAR sites are concentrated in **Area 5 and Area 6**, sharing a combined area of 0.17% of the study. These locations are suitable for implementing low-cost structures such as infiltration ponds, soil aquifer treatment, and recharge from irrigation to replenish the unconfined aquifer.

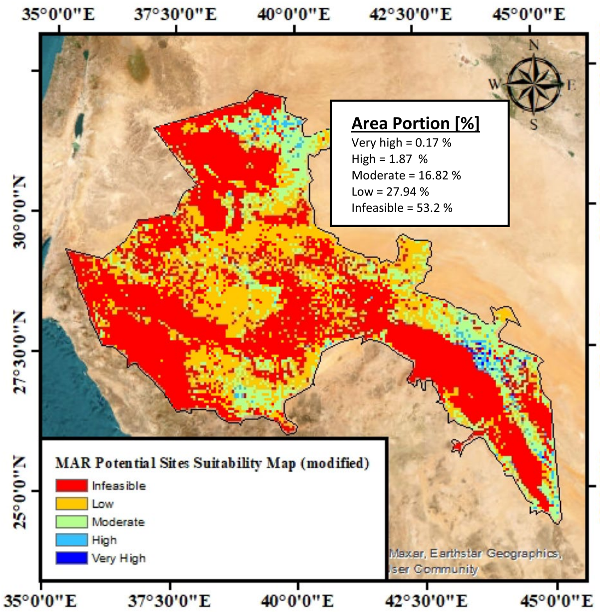

Fig. 13 Modified MAR sites potential suitability map

For high potential MAR sites, covering approximately 1.86% of the total area, in-channel modifications can be established based on-site conditions. This may involve the implementation of check dams, diversion channels, sand storage dams, subsurface dams, and surface dams with recharge releases.

Moderate potential MAR sites cover around 16.82% of the total area, where open (dug) wells and shafts could be utilized for recharging both unconfined and confined aquifers. Additionally, ASR and ASTR techniques could be applied to different aquifer systems in the study area. The remaining areas, contributing to nearly 81.14% of the area, are deemed unsuitable to install MAR sites.

The results of this study (Fig. 14) were compared with those conducted by Zaidi et al. (2015), where the suitable sites identified in this study are delineated. Firstly, the total

Table 6 MAR site identification results summary

Site potential category	Percentage area [%]	Adequate structure types
Very high	0.17	Spreading methods
High	1.87	In-channel modifications
Moderate	16.82	Well and borehole shaft
Total suitable sites	**18.86**	–
Low	27.94	–
Infeasible	53.2	–
Total unsuitable sites	**81.14**	–

Bold indicates total suitable and unsuitable sites

Fig. 14 Comparing this study site selection map with site selection map by Zaidi et al. (2015)

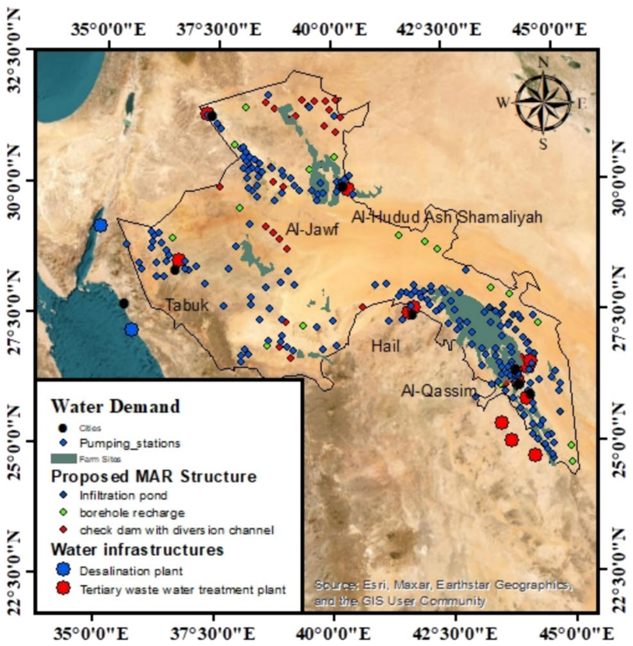

Fig. 15 Location map of proposed MAR and RWH structures

area percentage suitable for MAR installation is almost similar for both studies. The suitable area percentages for Zaidi et al. (2015) and this study are 14.24% and 18.86%, respectively, considering and without considering land use. Nevertheless, the location of the suitable sites is entirely different (Fig. 14). This difference might arise because Zaidi et al. (2015) considered only vadose zone thickness, surface slope, salinity, water-bearing formation, and LULC using a Boolean logic approach. In contrast, our study applied a GIS-MCDA holistic approach with a comprehensive analysis to determine optimal sites for MAR installation, considering additional criteria such as precipitation, runoff potential, infiltration rate, vertical permeability, saturated thickness, and drainage density. The latter reason of difference could be due to the difference of the technical approach as Zaidi et al. (2015) have only applied a simple deterministic boolen logic and on contrary, this study has been proceeded to determine the most appropriate MAR sites using advanced suitability with simple optimization technique.

Specifying the MAR and RWH structures

The MAR and RWH structures were identified by examining the bottom layer of the unsaturated zone, the hydrological system of the watersheds, the vertical permeability of the unsaturated zone, and the rate of infiltration of the surface cover. Figure 15. illustrates the proposed structures, which include 13 infiltration ponds, 25 check dams, and 18 recharge boreholes. Infiltration ponds are regarded as the most cost-effective method, as they involve low construction, operation, and maintenance costs. Conversely, recharge boreholes are the most expensive method, requiring energy for injecting water into the aquifer systems in case of these systems is low in effective porosity, permeability, hydraulic connection, and have high shale content such as shaly aquifers, as well as low in fractures density such as fractured shaly limestone. If these aquifer systems are high in effective porosity, permeability, hydraulic connection, and have low shale content such as sand and gravel aquifer and sandstone aquifer, as well as high in density of fractures such as high fractured limestone aquifer, the recharge of aquifer by borehole is suitable.

The location of these structures is strategically chosen in the proximately of infrastructures, cities/settlements, and irrigated farms allowing the strategic water reserve to be transferred for emergency water supply. Additionally, water pipe systems could be established in the study area to transfer non-conventional water, such as seawater desalination and reclaimed water, to these structures. This water can then be stored in the hydrogeological system along with rainwater harvested by these structures. The proposed location and type of the structures could be divided into user groups based on the decision makers' decision for different usages: agriculture, industry, and domestic use.

According to the previous results of this study, it is recommended to initiate pilot projects at specific locations to assess the feasibility of installing MAR in this area using these structures. This approach aims to mitigate the risk of structure failure due to potential issues such as clogging and recharge mounding problems and hydrogeochemical reactions that may take place between the recharged reclaimed water and the aquifer media or the native groundwater.

Conclusion

The study focused on assessing the potential for installing MAR and RWH structures in North-west Saudi Arabia to store non-conventional water resources as a strategic reserve in aquifer systems. This reserve is intended for use in emergency situations, such as severe drought events or the malfunctioning of non-conventional water plants. The locations and types of MAR and RWH structures were identified, aiming to artificially recharge various non-conventional water sources, including harvested rainwater, seawater desalination, and reclaimed water. The study found the study area suitable for MAR system installation due to satisfactory MAR elements, including water source, land, and aquifer system. Various MAR structures were deemed feasible for installation, excluding induced bank infiltration and urban rainfall harvesting due to the absence of perennial streams and focus on bare areas rather than urban settlements. The study focused solely on technical aspects, emphasizing the need for further investigations into socio-economic and environmental factors.

The GIS-MCDA holistic approach was employed because it is the most common method among the researchers to identify suitable site location, involving processing thematic GIS layers for available data. The suitability map, validated through constraint and suitability mapping, and sensitivity analysis, revealed around 53.2% of the area as infeasible for MAR installation. Suitable potential areas were determined based on criteria like vertical permeability, vadose zone thickness, surface slope, precipitation, and more. The modified map indicated very high, high, and moderate potential MAR sites covering approximately 0.17%, 1.87%, and 16.82% of the total study area, respectively, while around 81.14% was deemed unsuitable.

The results are considered as a cross validation of the artificial recharge selection map conducted by Zaidi et al. (2015). Nevertheless, comparing the selection map has indicated that the maps are different in terms of spatial distribution, although the area percentage distribution of high potential sites matches. Several justifications were found including that former study has used a simple Boolean logic and it lacks all the technical criteria such as hydrometeorology (precipitation and runoff), aquifer hydrogeology (vertical permeability and saturated thickness), and surface hydrology (drainage density), which could not be ignored to select site location for artificial recharge.

The results of this study referred to approximately 56 structures for suitable sites, including infiltration ponds, check dams with diversion channels, and recharge boreholes, were proposed. The generated maps serve as a resource for decision makers in planning sustainable water resource management. However, it is noted that the maps were established without considering decision rules, cost–benefit analyses, risk assessments, or environmental impact assessments. The study utilized one approach, but future validation studies could explore statistical methods, machine learning, and numerical modeling.

Further studies are recommended for assessing the feasibility of suggested structures in the field. Numerical modeling of unsaturated and saturated zones is suggested for understanding the effect of recharged water on native groundwater quality and the recharge efficiency. Pilot projects at specific locations are also encouraged to experiment the efficiency, safety, and feasibility of the artificial recharge process, including infiltration and injection tests.

Acknowledgements This work was funded by the Deanship of Scientific Research at Jouf University under Grant Number (DSR2022-RG-0107).

Declarations

Conflict of interest The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Ethics approval This paper has not been published or is being considered for publication elsewhere.

Consent to participate The authors declare that they are aware and consent to their participation in this paper.

Consent for publish The authors declare that they consent to the publication of this paper.

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose.

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