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Geospatial techniques for identifying optimal rainwater harvesting sites to enhance agricultural productivity in hyper arid areas

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A R T I C L E I N F O

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A B S T R A C T

The increasing demand for freshwater, combined with limited availability and the exacerbating effects of climate change, poses significant global challenges to sustainable water supply. Addressing the widening gap between water supply and demand necessitates the adoption of innovative and sustainable water management strategies. As a renewable and locally available resource, rainwater holds considerable potential to alleviate water scarcity in arid and semi-arid regions. This study explores rainwater harvesting (RWH) as a practical strategy to address the annual groundwater deficit in the State of Qatar. A Geographic Information System (GIS)-based approach was employed to assess the potential of RWH implementation. The analysis integrated ground-based observations with satellite-derived datasets to identify suitable locations for RWH. To enhance the accuracy of the suitability mapping, legal constraints such as urban areas, parks, and farms as well as protective buffer zones were applied, resulting in a refined delineation of land realistically available for RWH development. The findings indicate that approximately 59 % of Qatar's land area is potentially suitable for RWH initiatives. Of this, 1.27 % was classified as 'very highly suitable', 27.27 % as 'highly suitable', and 49.50 % as 'moderately suitable'. Assuming the installation of engineered RWH wells with a recharge efficiency of 40 % and annual rainfall of 67 mm, the estimated net groundwater recharge from these three suitability classes could reach approximately 107 million m^3 annually. These results highlight the substantial contribution that RWH can potentially make toward reducing Qatar's national freshwater deficit. The outcomes of this research support the strategic expansion of RWH infrastructure and provide a basis for informed decision-making in future water resource planning across the country.

1. Introduction

Water is essential for all forms of life and plays a critical role in socio-economic development. The increasing population, climate change, global warming, and frequent droughts are exerting significant pressure on the freshwater water resources (Chiew et al., 2011). The growing demand for water across irrigation, industrial, and domestic sectors is intensifying global water scarcity (Boretti and Rosa, 2019). In Qatar, this scarcity poses a significant challenge to agriculture.. The primary sources of water for irrigation include groundwater, which is depleting rapidly (Bilal et al., 2021), and desalinated water, which is energy-intensive and expensive. Recharge from annual rainfall in arid regions differs geographically, influenced by the local hydrogeological characteristics. In Saudi Arabia, recharge from precipitation has been estimated at 3 % and 4 % of the total annual precipitation (Bazuhair and Wood, 1996) while 4.8 % was reported in the Birjand plain of Iran (Jafari et al., 2019). However, this recharge increases up to 47 % under Managed Aquifer Recharge MAR technologies like ponds and wells as observed in the United Arab Emirates (Sherif et al., 2017). A comparable contribution is evident in Qatar, where recharge wells and irrigation return flow account for approximately 44 % of total groundwater recharge, artificial recharge (31 %), and annual rainfall recharge (25 %)

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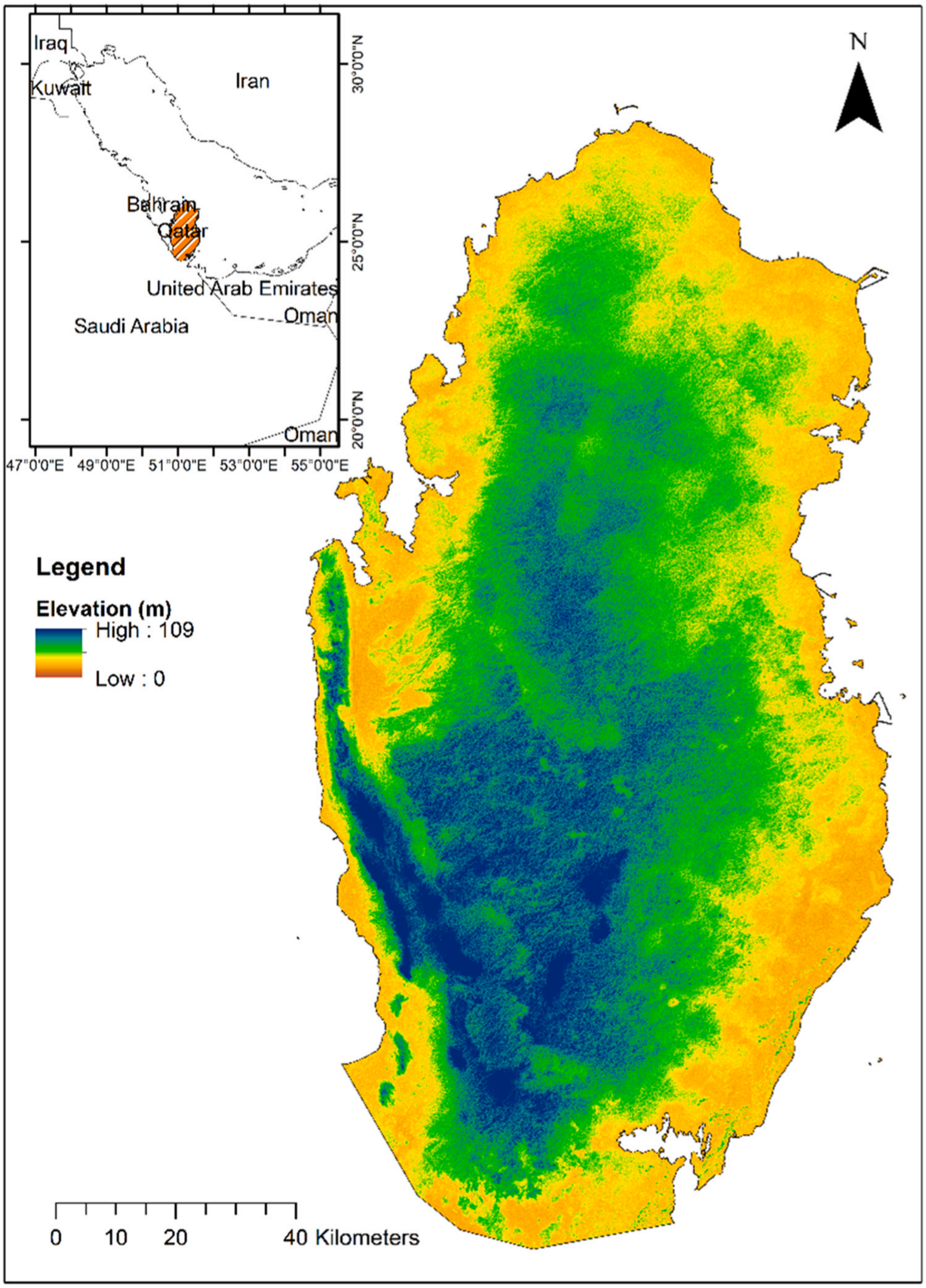

Fig. 1. Study area map with elevation based on digital elevation model 30 m.

(Planning and Statistics Authority, 2019). Agriculture in Qatar faces significant challenges due to its hyper-arid climate, limited arable land, and scarce water resources. The agriculture sector is the largest consumer of groundwater, accounting for 86 %, followed by outflow to the sea (8 %) and municipal and industrial abstraction (7 %) (Planning and Statistics Authority, 2019). Despite artificial recharge efforts, there was a 57–184 million m^3 shortfall in the groundwater budget between 2016-2021 (Planning and Statistics Authority, 2021). The MAR techniques like artificial injection and rainwater harvesting can potentially reduce this annual shortfall and improve groundwater recharge in Qatar (Bilal et al., 2025). The government has planned to construct 380 rainwater harvesting wells in two phases. About 60 wells will be constructed in the first phase and the remaining will be completed in the following years (KAHRAMAA, 2022).

GIS-based multi-criteria has globally been used to identify rainwater harvesting sites. For instance, GIS-based multi-criteria was used to identify suitable locations in Bengal India (Singh et al., 2017). In the Kasungu District, Malawi, a GIS-based Soil Conservation Service Curve Number (SCS-CN) method was used for the identification of suitable RWH sites (Nyirenda et al., 2021). The study revealed that 0.2 % of the area has very high suitable for RWH, 33.5 % high suitablel, 55.9 % moderate suitable, 10.1 % marginal, and 0.3 % not suitable. To verify the model's accuracy, they compared it with existing RWH sites and found that around 81 % of these sites were located in highly and moderately suitable areas, whereas only 13 % were in low suitability areas. Another GIS-based study conducted in Sydney Australia revealed that 9 % of the region is 'very highly suitable' and 25 % is 'highly suitable (Preeti et al., 2022). Similarly, in the Inner Mongolia region 26 % to 30 % of land was identified as highly and moderately suitable for RWH projects (Matomela et al., 2020). Another study showed that

Table 1
Summary of the input criteria, classes and ranking.

Criteria	Range	Classes	Rank order	Weight (%)	Source
Rainfall (mm)	> 60 50–60 40–50 30–40 0–30	1 2 3 4 5	1	24.7	Qatar Meteorology Department (https://qweather.gov.qa/CAA/Index.aspx)
Drainage density	0.22–0.15 0.15–0.10 0.10–0.05 0.05–0.01 < 0.01	1 2 3 4 5	2	17.1	U.S. Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) (https://earthexplorer.usgs.gov/)
Transmissivity (m2/d)	1000–500 500–200 200–100 100–10 < 10	1 2 3 4 5	3	13	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	4	9.5	Ministry of Environment (Schlumberger Water Services, 2009).
Slope (%)	0–5 5–8 8–15 15–30 > 30	1 2 3 4 5	5	6.7	U.S. Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) (https://earthexplorer.usgs.gov/)
LULC	Barren land, Bushes/vegetation, Sand, Sand dunes/beaches, Built-up,	1 2 3 4 5	6	6.1	U.S. Geological Survey (USGS) Landsat–8, level–2. (https://earthexplorer.usgs.gov/)
Depression zones	1–200 200–300 300–400 400–500 > 500	5 4 3 2 1	7	5.6	Delineated from 30 m digital elevation model. (https://earthexplorer.usgs.gov/)
Groundwater salinity (mg/L)	0–1000 1000–2500 2500–4000 4000–5000 > 5000	1 2 3 4 5	8	4.2	Ministry of Environment (Schlumberger Water Services, 2009).
Soil types	Calcaric Regosols, Calcic Yermosols, Gleyic Solonchaks, Lithosols, Orthic Solonchaks,	1 2 3 4 5	9	3.4	Food and Agriculture Organization of the United Nations (FAO-UNESCO)(https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/)
Elevation (m)	12–26 26–41 41–56 0–12 > 56	1 2 3 4 5	10	3.2	U.S. Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) (https://earthexplorer.usgs.gov/)
Distance from farms (m)	1–200 200–300 300–400 400–500 > 500	5 4 3 2 1	11	2.5	Farms were digitized from Google Earth using ArcMap software.
Distance from shoreline (km)	1–5 5–10 10–15 15–20 > 20	5 4 3 2 1	12	2.5	The shoreline was digitized from Google Earth using ArcMap software.
Temperature (°C)	0–10 10–20 20–25 20–30 > 30	1 2 3 4 5	13	1.5	Qatar Meteorology Department (https://qweather.gov.qa/CAA/Index.aspx)

rainwater harvesting (RWH) can significantly contribute to meeting outdoor irrigation demand in Tucson, Arizona USA (Zhong et al., 2022). Currently, most studies use GIS in combination with hydrological models and/or multi-criteria analysis (MCA) for RWH site selection. For instance, RS and a GIS-based SCS-CN method were utilized to evaluate runoff and RWH structure sites, finding that the total rainwater harvesting potential of the study area is 54.49 million m^3, which is sufficient to meet the water demand if harvested and managed effectively (Tiwari et al., 2018). Singh et al. (Singh et al., 2017) utilized a GIS-based multi-criteria decision analysis (MCDA) method, reporting that GIS and multi-criteria methods are time-saving, cost-effective, and highly effective for large-scale water resource planning and management. Wu et al. (Wu et al., 2018) demonstrated the utility of GIS in prioritizing RWH sites in Northeastern Guatemala, estimating that a total volume of 424,070.81 m^3 of water can potentially be harvested from these sites. In arid and semi-arid regions of the Middle East and Africa, GIS-based MCDM has been used by many recent studies to identify suitable locations for groundwater recharge. For instance, MAR site suitability in a karst coastal aquifer was investigated using a new geospatial approach coupled with MCDM in a catchment in Lebanon (Itani et al., 2022). Similarly, about 14 % of the total land area was identified as highly suitable for MAR projects in the State of Qatar (Bilal et al., 2025). In the North-west and Wadi Nisah in the Kingdom of Saudi Arabia about 13.15 % and 18.85 % area was identified for rainwater harvesting using the GIS-based MCDM method (Abd-el-Kader et al., 2023; Seif et al., 2024). Another study in West Bank catchments, Palestine, also used GIS with SCS-CN to estimate runoff volumes, showing that the integration provides an effective tool for runoff estimation. This study prioritizes areas suitable for RWH and RWH structures by incorporating rainfall-runoff modelling, RS, and GIS-based MCDA (Shadeed and Almasri, 2010).

The application of these techniques in hyper-arid regions of the Middle East has been limited, where natural recharge is insufficient to meet the annual groundwater demand. To address this knowledge gap and mitigate the annual groundwater recharge deficit, this study aims to develop a suitability map for potential RWH sites to enhance recharge potential. The final map will pinpoint areas suitable for RWH to help improve groundwater availability for agricultural abstraction. The results of this research will aid relevant authorities in effectively planning and implementing water resource management strategies, ensuring a sustainable long-term water supply for irrigation in the State of Qatar.

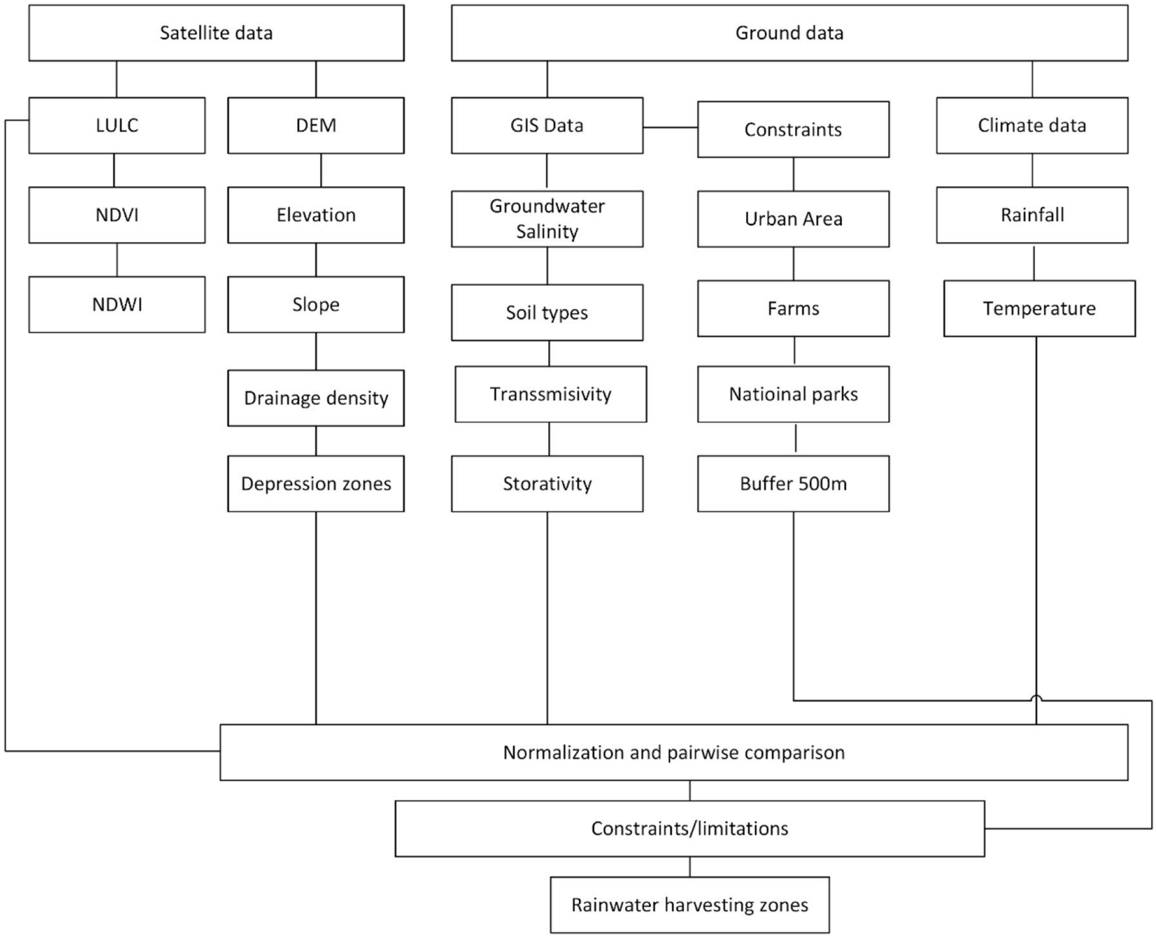

Fig. 2. Flow diagram of the methodology.

Table 2
Pairwise matrix of the selected parameters.

Matrix	GS	RF	TMP	EL	SL	DD	DF	DS	TM	ST	STP	LULC	DPZ
GS	1	0.17	5	3	0.25	0.2	4	1	0.33	0.33	2	0.25	0.5
RF	6	1	6	4	6	3	5	5	4	4	6	6	5
TMP	0.2	0.17	1	0.25	0.2	0.17	0.25	0.25	0.2	0.2	0.25	0.25	0.33
EL	0.33	0.25	4	1	0.25	0.2	2	2	0.2	0.2	2	0.33	0.33
SL	4	0.17	5	4	1	0.33	2	2	0.2	0.5	3	2	1
DD	5	0.33	6	5	3	1	5	5	2	4	4	5	5
DF	0.25	0.2	4	0.5	0.5	0.2	1	2	0.17	0.2	0.33	0.5	0.25
DS	1	0.2	4	0.5	0.5	0.2	0.5	1	0.2	0.2	0.5	0.33	0.33
TM	3	0.25	5	5	5	0.5	6	5	1	2	2	3	4
ST	3	0.25	5	5	2	0.25	5	5	0.5	1	3	3	2
STP	0.5	0.17	4	0.5	0.33	0.25	3	2	0.5	0.33	1	0.33	0.33
LULC	4	0.17	4	3	0.5	0.2	2	3	0.33	0.33	3	1	2
DPZ	2	0.2	3	3	1	0.2	4	3	0.25	0.5	3	0.5	1

GS=Groundwater salinity, RF=Rainfall, TMP=Temperature, EL=Elevation, SL=Slope, DD=Drainage density, DF=Distance from farms, DS=Distance from shoreline, TM=Transmissivity, ST=Storavity, STP=Soil types, LULC=land use and land cover and DP=Depression zones.

2. Methodology

2.1. Study area

Qatar is a small, arid peninsula extending northward from the main Arabian Peninsula. It shares a border with Saudi Arabia and only shares maritime boundaries with the United Arab Emirates to the south (Bilal et al., 2024). The terrain is predominantly flat, ranging from 0 to 109 m above sea level (Fig. 1), characterized by sand dunes, limestones, and salt flats (Al-Marzooqi et al., 2021; Bilal et al., 2025). The climate is hot and humid, with slightly cooler winters. Rainfall is scarce, long-term average about 67 mm annually, and there are no surface water resources. Water supply relies on 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).

2.2. Digital Elevation Model (DEM)

A digital elevation model (DEM) provides a digital representation of the Earth's surface in two dimensions. The NASA Shuttle Radar

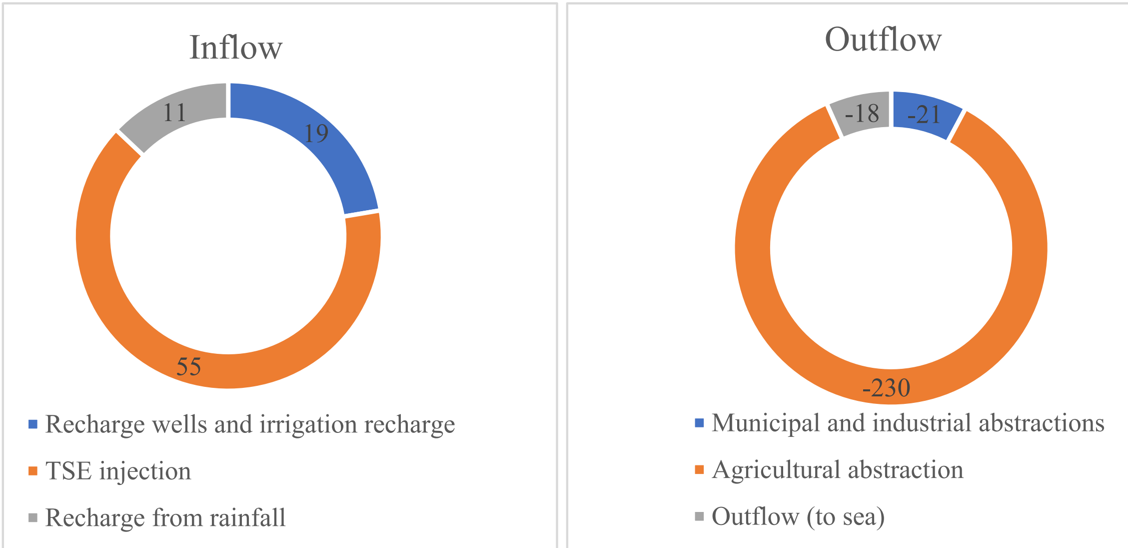

Fig. 3. Water balance of recharge and abstraction during 2021.

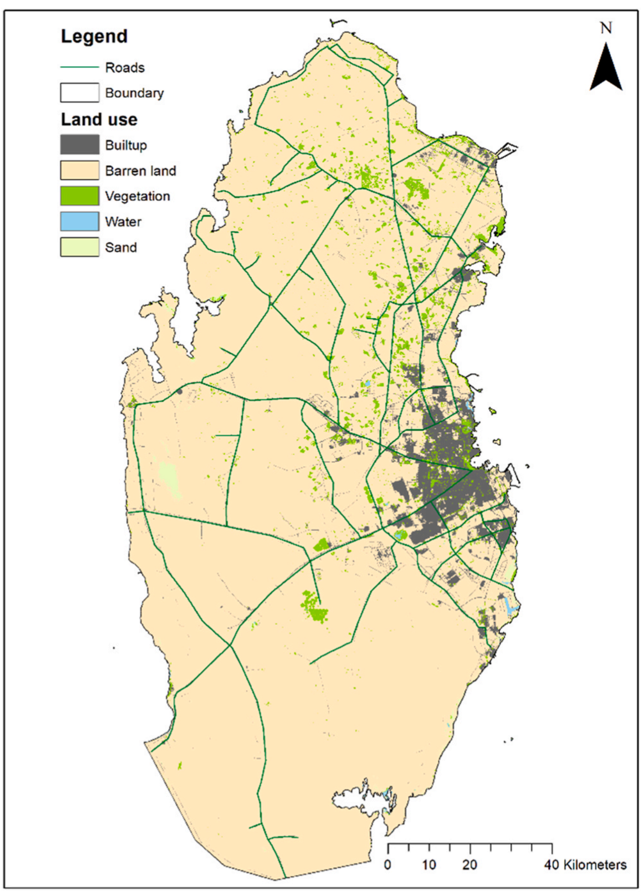

Fig. 4. Land use and land covers in the state of Qatar.

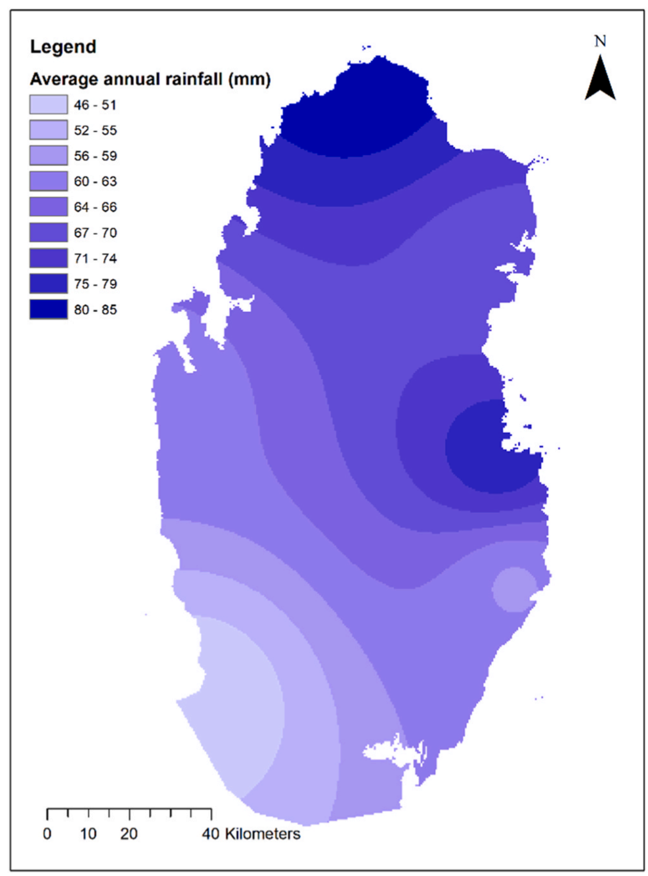

Fig. 5. Annual average total precipitation long-term average 1989–2016.

Topographic Mission (SRTM) utilized interferometric synthetic aperture radar (InSAR) to gather elevation data with a spatial resolution of 30 m. The DEM tiles were obtained from Earth Explorer (https://earthexplorer.usgs.gov/) and processed using ArcMap 10.8 software. The DEM was utilized to extract important topographical features for the study, such as slope, flow direction, depression zones, flow accumulation, and stream order using the hydrology tool in the ArcMap 10.8 (Bilal, 2019).

2.3. Normalized Difference Water Index

The Normalized Difference Water Index (NDWI) is a remote sensing-based index used to detect and monitor water bodies. It enhances the contrast between water and other land cover types in satellite imagery, making it easier to identify and map lakes, rivers, reservoirs, wetlands,

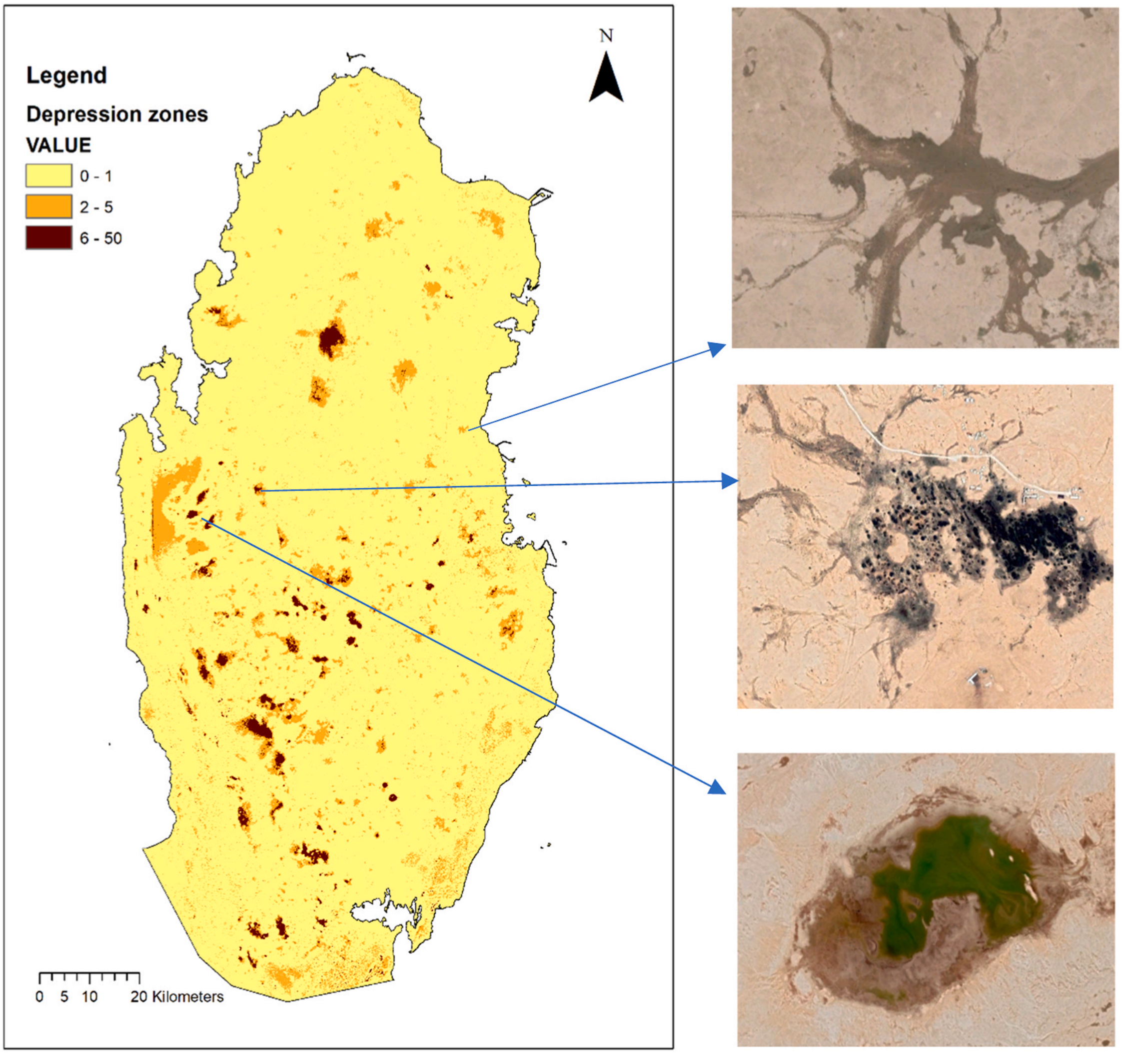

Fig. 6. Map of the depression zones in the study area.

and flooded areas. NDWI is used to identify stagnant water in depression zones. Landsat-8 data of pre and post extreme rainfall of 2018 was downloaded from EarthExplorer (https://earthexplorer.usgs.gov/). The downloaded data was treated in the ArcMap software using the reflectance values of the green and near-infrared (NIR) bands, the NDWI is expressed as:

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

2.4. Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing index for monitoring vegetation health and coverage (Hussain et al., 2025). It enhances the detection of live, green vegetation in satellite imagery by comparing the reflectance values of the near-infrared (NIR) and red bands, as vegetation reflects more NIR light and absorbs more red light. The NDVI is calculated using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (2)$$

NDVI values range from -1 to $+1$, where higher values indicate healthier and denser vegetation, while lower values suggest sparse or no vegetation. NDVI is used to identify natural vegetation growth following rainfall in depression zones. Sentinel-2 data were used to identify pre and post rainfall influence on the natural vegetation.

2.5. Drainage density

Rainwater harvesting (RWH) structures prove effective when capturing runoff at optimal depths, which is dependent on hydrological conditions. Areas with high drainage densities, driven by numerous streams, exhibit significant potential for runoff accumulation. (Adham et al., 2018) utilized DEM data to extract drainage density, employing a standardized reclassification method. Various studies have consistently highlighted that RWH systems are most beneficial in regions characterized by high drainage densities (Wondimu and Jote, 2020).

Drainage density profoundly influences groundwater movement, recharge dynamics, and hydrogeological processes. The amount of runoff lost to infiltration correlates inversely with drainage density; lower densities correspond to reduced potential for RWH (Sayl et al., 2020). Employing DEM data within a GIS framework enables the calculation of drainage density across the study area. This metric quantifies the total stream length per unit catchment area, important for understanding local hydrological patterns.

$$DD = \frac{\sum_{i=}^{n} 1L}{A} \quad (2)$$

where DD is the drainage density, n is the number of streams, L is the stream length (km), and A is the drainage area (km2).

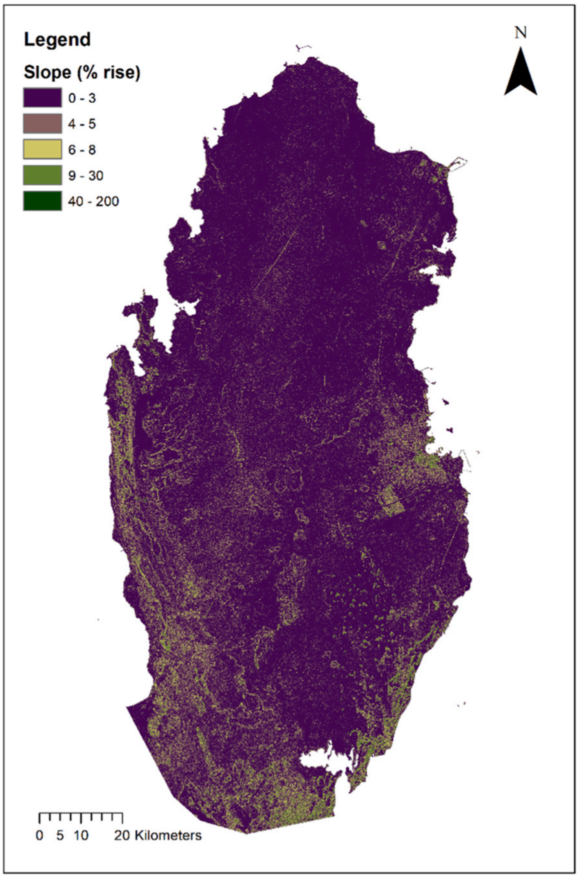

Fig. 7. Terrain slope of the state of Qatar.

2.6. SCS-CN method

The SCS-CN method, originally developed by the United States Department of Agriculture Soil Conservation Service, now known as the Natural Resources Conservation Service (SCS, 1986), is widely utilized for estimating runoff from precipitation events. This method relies on Curve Number (CN) values, which are critical for accurate calculations. The SCS-CN method was applied in this study to compute runoff and evaluate runoff potential across various land covers and hydrological soil groups. The occurrence of runoff is influenced by factors such as rainfall intensity and frequency, land cover type, soil infiltration capacity, and slope. After runoff begins, the SCS-CN method computes potential infiltration rates. CN values, ranging from 0 to 100, are assigned based on Hydrologic Soil Groups (HSGs) and land cover characteristics, incorporating Antecedent Moisture Conditions (AMC). These values vary for different Hydrologic Soil-Cover Complexes (HSCC), and can be obtained from the (NRCS, 2009), which categorizes soils into four main HSGs: A, B, C, and D. Group A exhibits the least runoff potential, while Group D exhibits the highest. In the study area, a substantial portion falls under Group A-HSG, indicating minimal runoff potential. The formula for the SCS-CN method, established by (SCS, 1986) is expressed as follows:

$$S = \frac{54000}{CN} - 254 \tag{3}$$

S is the water retention after a rainfall event while CN is the respective curve number as shown below.

$$CN_{wt} = \frac{n\sum CN_{i}\ {}_{x}A_i}{A_t} \tag{4}$$

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5}$$

Q is the runoff or depth of water. Since there are many hydrological soil groups, curve numbers were weighed with respect to the land cover area.

2.7. Rainwater harvesting potential zones

This study utilized a GIS-based multi-criteria decision analysis (MCDA) modelling approach to standardize various data layers. To identify optimal rainwater harvesting (RWH) sites for groundwater recharge, the thematic layers were prepared using the ArcMap 10.8 software. These thematic layers are: (l) Elevation; (2) Soil types; (3) Drainage density; (4) Distance from agricultural farms to minimize chemical contamination of groundwater; (5) Temperature; (6) Distance from the coastline to reduce rainwater loss into brackish water; (7) Adequate rainfall that can be captured and stored; (8) Storativity; (9) Transmissivity; (10) Groundwater salinity; (11) Slope; (12) Depression zones and (13) land use and land cover (Table 1). In addition, a buffer of 500 m was applied to existing farms, national parks and urban areas for protection. All restricted areas were then combined and a single shapefile was applied to the final suitability map. More details can be found in the flow diagram mentioned in Fig. 2.

The Analytic Hierarchy Process (Saaty, 1977) was employed to rank and prioritize the thematic layers based on expert judgement. These thematic layers were initially prepared and reclassified to a standardized measurement scale. Each raster layer was assigned a specific percentage influence, and the values within each cell were then multiplied by their respective percentage weights to generate an output raster file. Since human judgments are often subjective, minor inconsistencies may arise when comparing multiple criteria. The Consistency Ratio (CR) quantifies how consistent the decision-maker's comparisons are relative to a perfectly consistent matrix. It is calculated using the following formula as:

$$CR = \frac{CI}{RI} \tag{7}$$

where CI is the Consistency Index, defined as:

$$CI = \frac{\lambda\text{max} - n}{n - 1} \tag{8}$$

The λ_{max} is the maximum eigenvalue of the pairwise comparison matrix, while n is the number of criteria. RI is the Random Index, representing the average CI of randomly generated matrices of the same size. A CR value less than or equal to 0.10 (10 %) is generally considered acceptable, indicating that the comparisons are reasonably consistent (Saaty, 1977). Values exceeding this threshold suggest that the judgment matrix may be too inconsistent and should be revised. The CR value of the current study is 9.3 % which is below the acceptable threshold. The following resulting weights (Table 2) are based on the principal eigenvector of the decision matrix.

3. Results and discussion

The total groundwater reserve (comprising total recharge from rainfall, artificial recharge, and irrigation returns) was 85 million m^3 in 2021. In contrast, the groundwater abstraction/loss which includes municipal, industrial, and agricultural withdrawals as well as flow to the sea, was 269 million m^3 this led to about 184 million m^3 in 2021 (Planning and Statistics Authority, 2021). Treated wastewater injection to artificially recharge the aquifer was the dominant inflow (55 million m^3) followed by recharge wells and inflow from irrigation 19 million m^3 and about 11 million m^3 from rainfall recharge. However, the abstraction was higher than the combined recharge. Most of the

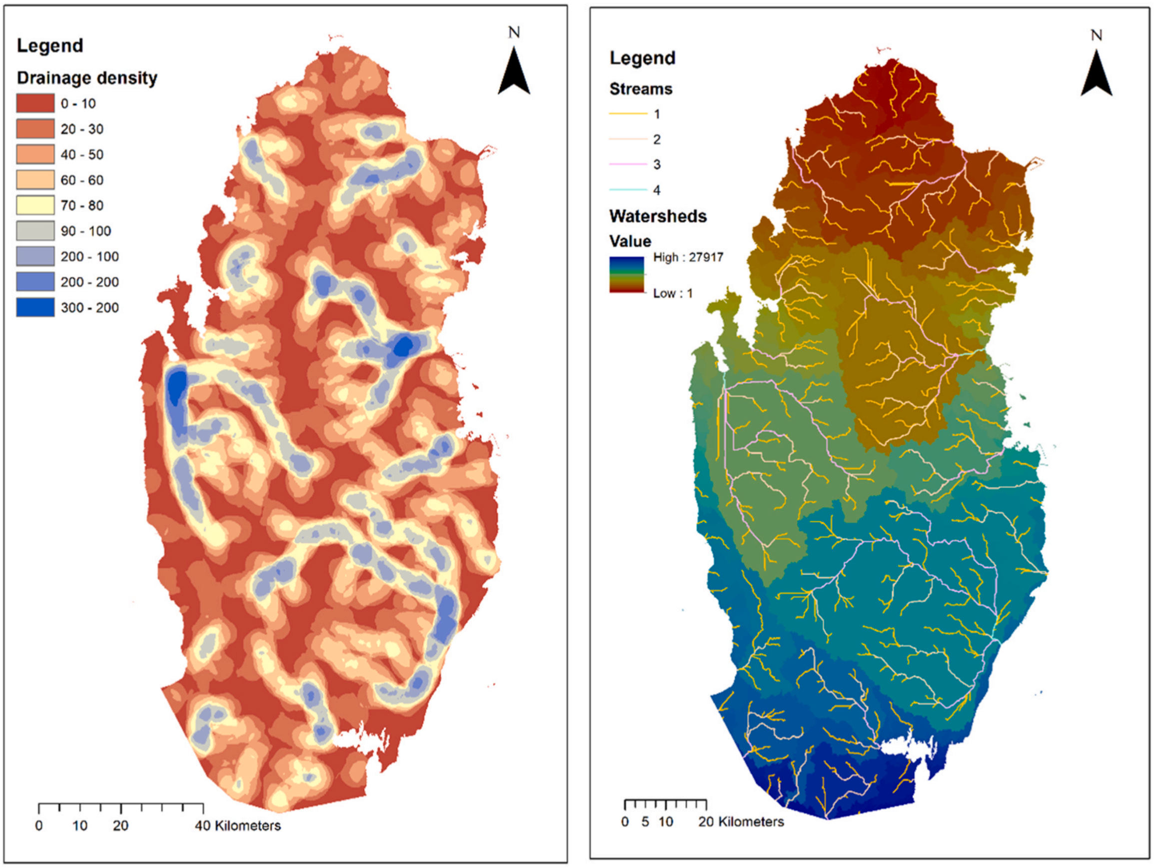

Fig. 8. Reclassified map of drainage density and subbasins with streams.

groundwater abstraction is for agricultural purposes which accounts for 230 million m^3. In addition, about 21 million m^3 was abstracted for municipal purposes and 18 million m^3 was outflow to the Arabian Gulf (Fig. 3).

3.1. Land use and land cover

Land use and land cover play an important role in the hydrological regime of an area. Land use and land cover (LULC) are crucial parameters in surface hydrology and rainwater harvesting due to their significant impact on various hydrological processes. Areas with dense vegetation, such as forests and grasslands, promote higher infiltration rates and reduce surface runoff. This is because plant roots enhance soil structure, allowing more water to percolate into the ground. In contrast, urban areas with impervious surfaces like roads and buildings hinder infiltration, leading to increased surface runoff and potential flooding. The land use and land cover analysis of Landsat-8 imagery indicates that the majority of the land, comprising 89.96 % (12,775.8 km^2), is barren. Built-up areas, including roads, are the second most predominant land use, covering 5.79 % (672.71 km^2) of the land. Vegetation, which includes crops, parks, and natural vegetation, covers approximately 3.33 % of the land. Water bodies account for 0.29 % of the area, while sand and beaches make up 0.61 % of the land as presented in Fig. 4.

3.2. Rainfall

The amount of rainfall directly determines the volume of water that can be harvested. Understanding local rainfall patterns helps in estimating how much water can be collected, which is essential for designing the capacity of rainwater harvesting systems. Rainfall is a primary source of groundwater recharge about 72.2 million m^3 per year is contributed to the groundwater recharge (Planning and Statistics Authority, 2021). Effective rainwater harvesting systems can enhance groundwater levels, especially in Qatar where rainfall is the only freshwater input and contributes significantly to aquifer replenishment. Understanding rainfall patterns helps in designing systems that maximize infiltration and groundwater recharge. Long-term rainfall data indicate that the annual average total precipitation is 67 mm, with slight spatial variation, as shown in Fig. 5. Most of the northern areas and east coast comparatively receive more precipitation as a result agricultural activities are also concentrated in the northeastern areas (Bilal et al., 2025; Bilal, Lahlou, et al., 2025). In contrast southeastern areas are usually dry. In a recent paper a slight decreasing trend in the annual precipitation was observed over Qatar (-0.42 mm/year) (Bilal et al., 2021). Although annual rainfall is erratic and may limit the appeal of rainwater harvesting under normal conditions,the frequency and magnitude of extreme rainfall events has increased in the last decades. For instance, on 20 October 2018, 86 mm of rainfall was recorded at Doha weather station which is more than the annual average rainfall. Similarly, at Fujairah Airport in the UAE an anomalous rainfall event was observed in July 2022 which was twice the long-term annual rainfall of 102 mm (Terry et al., 2023). Furthermore, they reported the recurrence of extreme rainfall events has been reduced from 45 to 25 years. In addition, future projections in Arabian peninsula also showed 1.6–44 % increase in annual rainfall by mid-century using ensembles of from the CMIP6 (Almazroui et al., 2020). A more recent study projected even further enhancement in the magnitude of annual rainfall by 20–40 % by the end of 21st century (Zittis et al., 2022). These variable episodes of rainfall and recent floods events in the capital city Doha further necessitate to capture and store more rainwater.

3.3. Depression zones

Depression zones, which are low-lying areas where water naturally

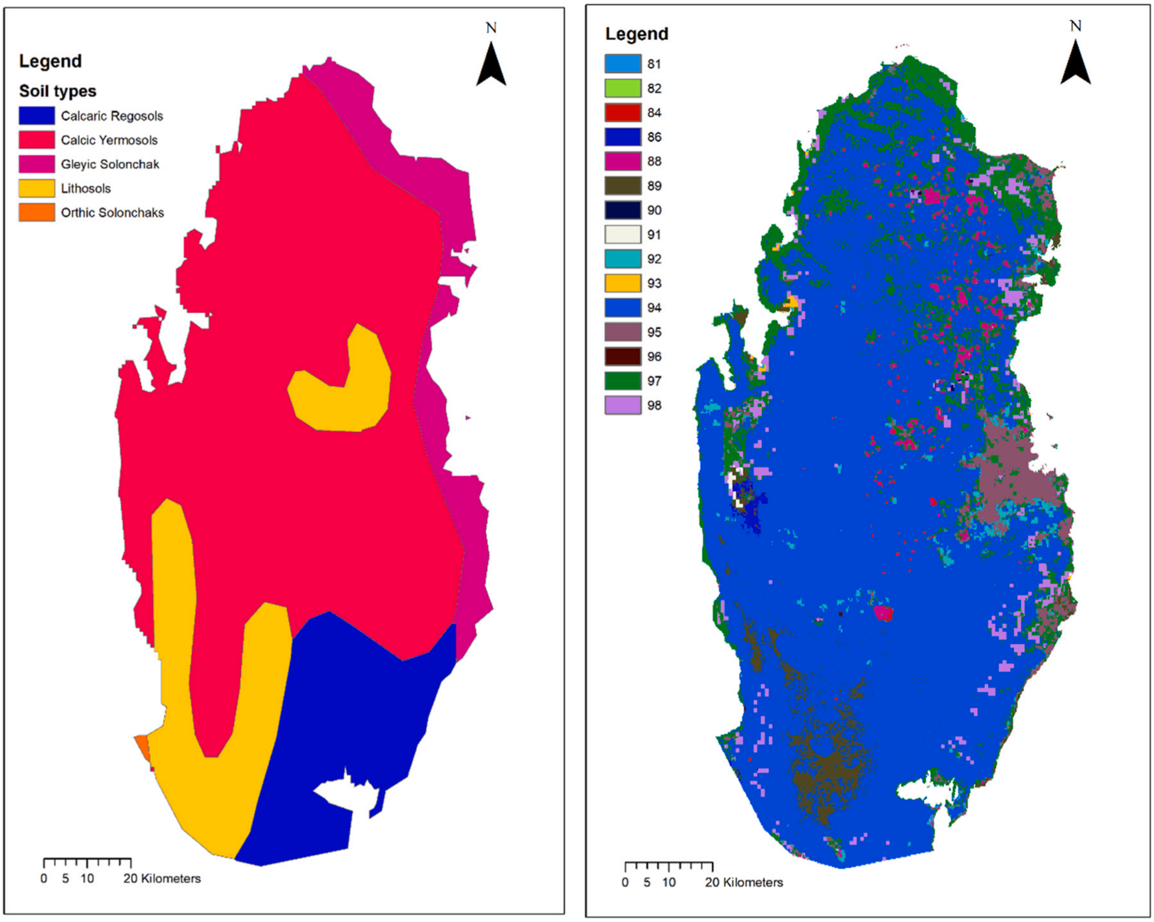

Fig. 9. Soil types and curve number map of the State of Qatar. Source (FAO, 1988).

accumulates, are vital in rainwater harvesting. These zones naturally collect and store water from rainfall and surface runoff. These zones have the potential to retain water for extended periods, making them ideal for storing harvested rainwater. Depression zones are delineated from the DEM using the Raster Calculator in ArcMap 10.8. As shown in Fig. 6 below, majority of the depression zones are concentrated in the south with some major depression zones in the north.

3.4. Slope

Based on the digital elevation model, slopes were categorized into five classes: flat (0–3 %), gentle (3–5 %), moderate (5–8 %), steep (8–30 %), and very steep (>30 %). The majority of areas identified as suitable for rainwater harvesting (RWH) fall within the flat and gentle slope classes.. Moderate slope areas are scattered in small patches across the study area. In contrast, steep and very steep slopes, located mainly in the southeast and southwest, specifically in the dunes regions of the southeast, are considered unsuitable for RWH due to their high slopes (Fig. 7).

3.5. Drainage density

Understanding drainage density helps in identifying areas where water is likely to be concentrated and can be used for recharging groundwater. Areas with moderate drainage density are often ideal for this purpose, as they balance runoff collection and infiltration. Drainage density, defined as the total length of streams and rivers per unit area of land, is a critical parameter in rainwater harvesting studies. The drainage density map was generated using the DEM in the ArcMap software. It was found that the drainage density of the study area is 0.22 km/km^2. The drainage density map was further reclassified and areas with higher density were given more score in the overlay process. As indicated in Fig. 8 important subbasins are situated on east coast in Al Wakrah, Al Shahaniya and Al Khor municipalities. In terms of drainage density these subbasins are contributing significantly to rainwater collection and pouring it into the Arabian Gulf. The pouring points of Al Shahania subbasin is in Zekreet west coast, while Al Wakrah subbasin pouring point is in the sealine area. Another important subbasin is covering areas in Al Khor, Al Daayen, Umm Salal and Al Shahaniya pour water into the sea in Al Daayen.

3.6. Runoff and soil water retention

Runoff and soil water retention are important components in rainwater harvesting analysis. Water retention involves the ability of the soil and landscape to hold water, allowing it to infiltrate and replenish groundwater supplies rather than immediately running off. High water retention means that more water is available for plant use and groundwater recharge. This is influenced by soil texture, organic matter content, vegetation cover, and land management practices. These parameters are largely determined by the hydrogeological characteristics of an area.

In Qatar, the hydrogeology is characterized by geological formations from the Pliocene and Eocene ages, with additional Quaternary deposits near the coastline in the form of salt-flats or Sabkha (Al-Yousef, 2003). The country's geological setup includes three water-bearing layers: the Dam and Dammam Formation, which covers most of Qatar's surface area with a thickness of up to 50 m, typically dry except in low-lying areas and near the coast; the Rus Formation, underlying the Dam and Dammam Formation, serving as the primary aquifer, especially in the

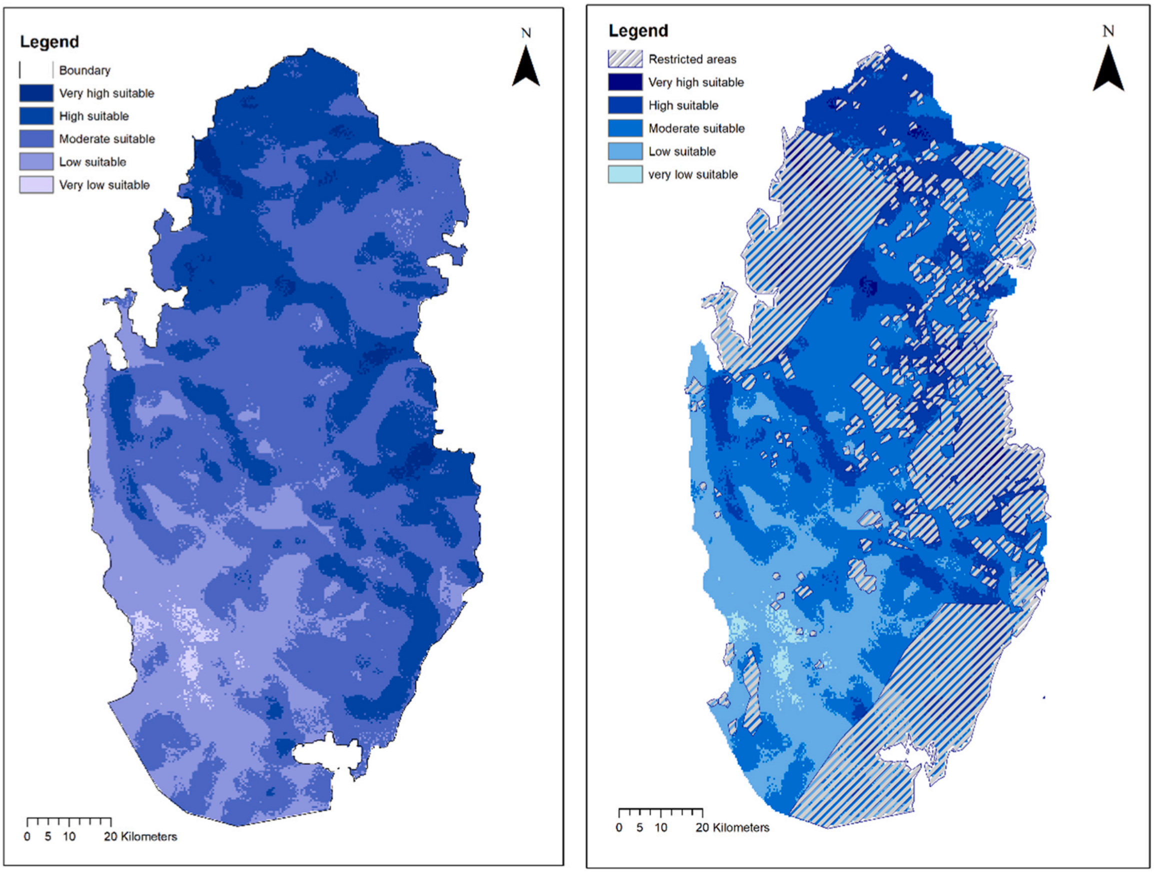

Fig. 10. Suitable sites for rainwater harvesting (left) in the State of Qatar under the influence of legal and environmental restrictions (right).

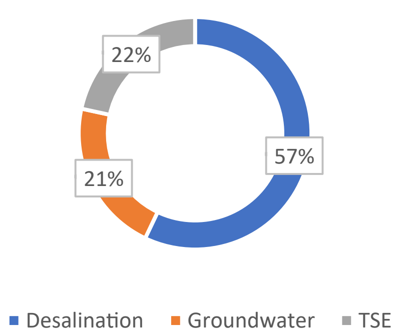

Fig. 11. Total annual freshwater production in 2021. Source: (Planning and Statistics Authority, 2021).

northern part of Qatar, with a thickness ranging from 30 to 90 m and containing gypsum and anhydrite in its southern regions, contributing to poor groundwater quality; and the Umm er Radhuma Formation, the deepest layer with a thickness of around 300 m, stretching from eastern Saudi Arabia across the region, characterized by varying groundwater quality, generally saline in Qatar (Kimrey, 1985). These geological formations host Qatar's two main groundwater resources: the Rus and Umm er Radhuma aquifers. Based on the soil types classification by (FAO, 1970) there are five classes of soil in the State of Qatar. Calcic yermosols is the predominant type of soil which is mostly covering central and northern areas. Lithosols and calcaric regosols are the second and third most common soil types which situated primarily in southeast and west. In addition, gleyic solonchak is spread across the eastern coastlines Fig. 9.

Runoff refers to the portion of rainfall that flows over the ground surface and eventually enters streams, rivers, or other water bodies. In an RWH context, managing runoff is crucial because it determines the amount of water that can be captured and stored for future use. Factors influencing runoff include rainfall intensity, soil type, land slope, vegetation cover, and land use practices. Based on the CN method, the extreme event of 20 October 2018 was selected to estimate the soil water retention and potential runoff/volume of water. According to the Qatar Meteorology Department QMD highest rainfall of 86 mm was observed at the Doha weather station on 20th of October 2018, which has resulted in a record high urban flood. The average daily rainfall from 6 weather stations was 35 mm. The CN method-based results indicated that about 189 million m^3 of water was available, resulting in heavy floods in low-lying areas in Doha city.

3.7. Suitability analysis

For suitability analysis, a ranking scale from 1 to 5 was used to categorize areas into very high suitability, high suitability, moderate suitability, low suitability, and very low suitability areas, as illustrated in Fig. 10. Rankings range from 1, indicating the most appropriate sites, to 5, indicating least suitable sites. The final results show that approximately 142.54 km^2 (1.27 %) of the area is classified as very high suitability, while high suitability areas cover 3050.66 km^2 (27.27 %). Moderately suitable areas dominate the study area, comprising nearly half at 5536.56 km^2 (49.50 %). The remaining areas include 2374.68 km^2 (21.23 %) classified as low suitability and 80.92 km^2 (0.72 %) as very low suitability (Fig. 10). These results are in accordance with the previously conducted studies (Aloui et al., 2024). According to Fig. 10, the most suitable areas are primarily located in the north and central regions along the east coast, while the least suitable areas are in the southwest. This variation can be attributed to factors such as better

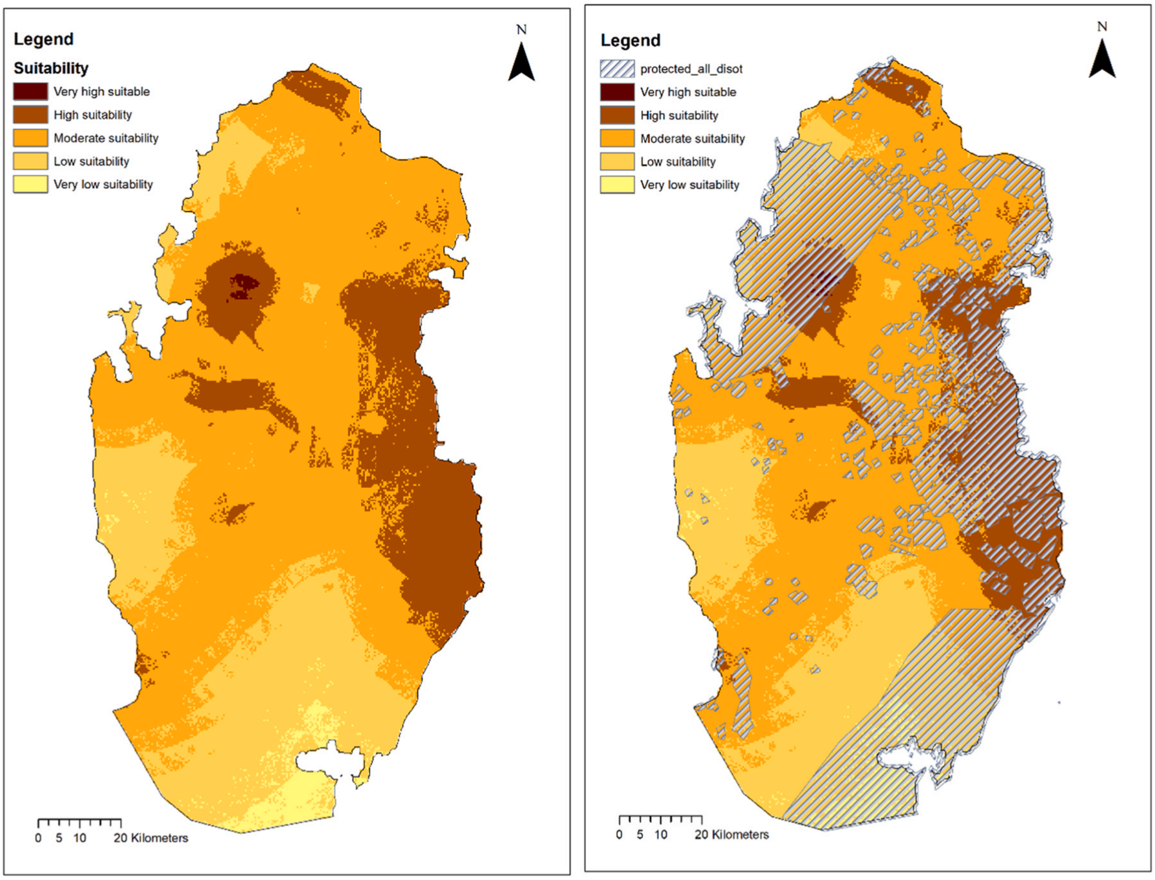

Fig. 12. Land suitability for storing surplus seasonal desalinated water.

soil quality, higher drainage density, less saline groundwater, more precipitation, and relatively flat terrain in the north.

However, after applying the legal and environmental restrictions (national parks, farms and urban areas) to the identified potential suitable area, the resultant areas are reduced significantly. Based on the analysis of the combined restricted area and buffer zone, about 59 % of the available land could be potentially utilized for RWH projects while the remaining 41 % comes under national parks, farms and urban settlements. The very high suitability category of land has been reduced to 21.49 km^2 from 142.54 km^2. The high suitability areas are restricted to 1439.67 km^2 from the initial 3050.56 km2. Similarly, the moderate suitable area is shrunk to 3279.12 km^2 from 2374.38 km^2.

Assuming implementation of engineered rainwater harvesting wells with a recharge efficiency of 40 %, the estimated net recharge volumes from the 'Very High', 'High', and 'Moderate' suitability zones would be approximately 3.25, 43.21, and 60.50 million m^3 /year, respectively. This totals to 107 million m^3 annually, potentially offsetting 58 % of Qatar's 184 million m^3 water deficit (as reported in 2021). These findings demonstrate the substantial potential of RHW infrastructure to enhance groundwater replenishment in priority zones across Qatar.

3.8. Using seasonal surplus desalnated water

The existing rainwater harvesting wells, which work under the force of gravity can also be utilized for storing the seasonal surplus desalinated water. Desalination plants have fixed production regardless of the demand and supply. Since the weather conditions are very harsh and there is a significant variation between the winter and summer weather conditions which consequently affect the demand and supply of freshwater use.

Freshwater is produced mainly from three sources desalination of sea water, groundwater abstraction and the use of treated wastewater. As shown in the Fig. 11 desalination is the prime freshwater production process as about 57 % (669 million m^3) was produced through desalination followed by groundwater abstraction 21 % (250.28 million m^3), and treated wastewater 22 % (253.21 million m^3) (Planning and Statistics Authority, 2021).

To identify suitable locations for storing surplus desalinated water, different criteria are employed as compared to the land suitability for rainwater harvesting. More weightage is given to the areas near the freshwater pipeline networks. Suitability analysis indicates that significant land is available along the east coast with some patches in north east and north as indicated in the Fig. 12 below. However, after applying the restrictions layer the suitable land area is reduced significantly. This is contributed to the fact that most of the freshwater networks are concentrated in the eastern coastal areas of Doha, Lusail, Al khore and Al wakra. Despite the restrictions there is still quite a lot of areas available which can potentially be used to store surplus water. These areas include Al Wakrah, Al Khore, Al Ruwais and Dukhan.

3.9. Validation

Historically there were 341 rainwater harvesting wells back in 1980s. Majority of these wells were constructed in the north, a few wells in the central south, while no well was constructed in the southern region. However, a well inventory survey conducted in 1994 stated that 28 wells of 341 were non-operational (KAHRAMAA, 2022). More recently, the government has planned the construction of 380 new rainwater harvesting wells with improved design, as previously installed rainwater harvesting wells were experiencing siltation and structure collapse (KAHRAMAA, 2022). To evaluate the suitability of rainwater harvesting (RWH) sites, we gathered the coordinates of existing RWH structures in

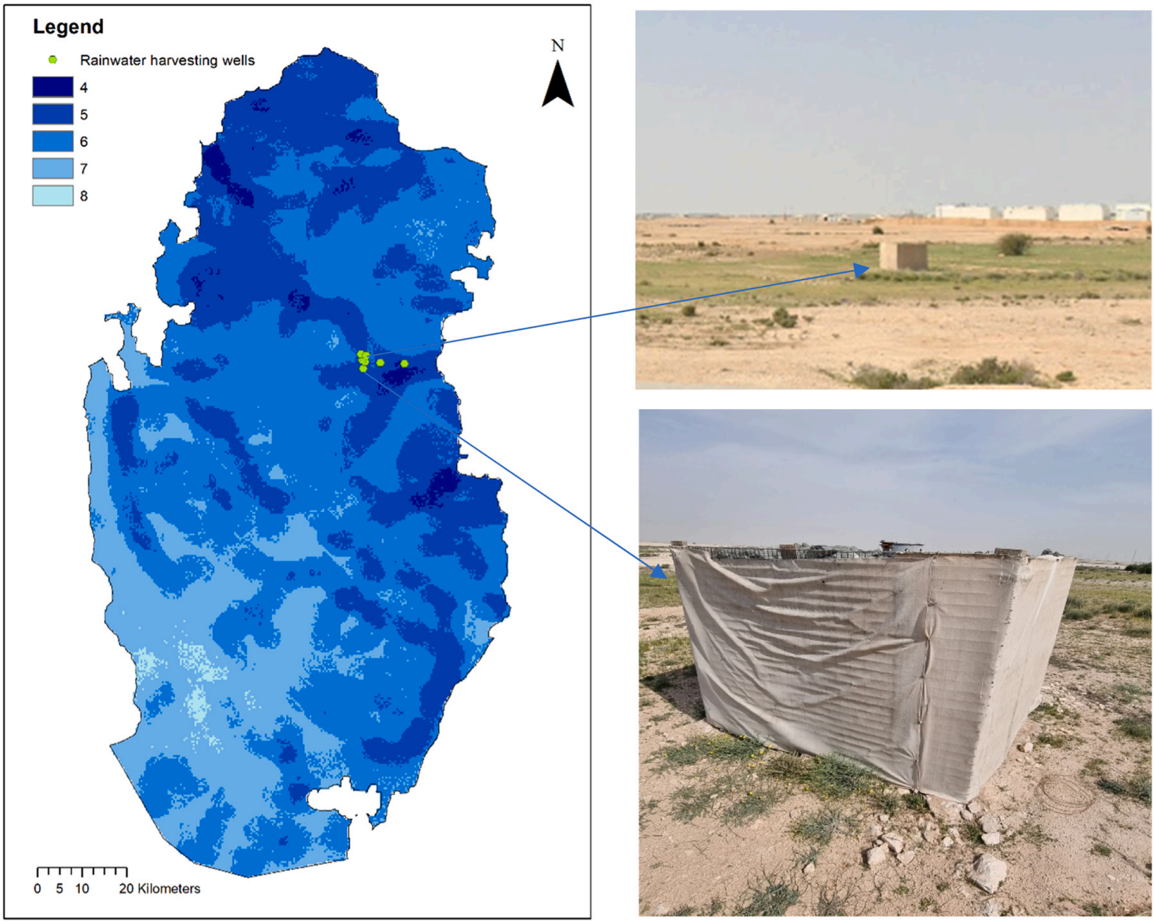

Fig. 13. Comparison of the model results with the existing RWH structures.

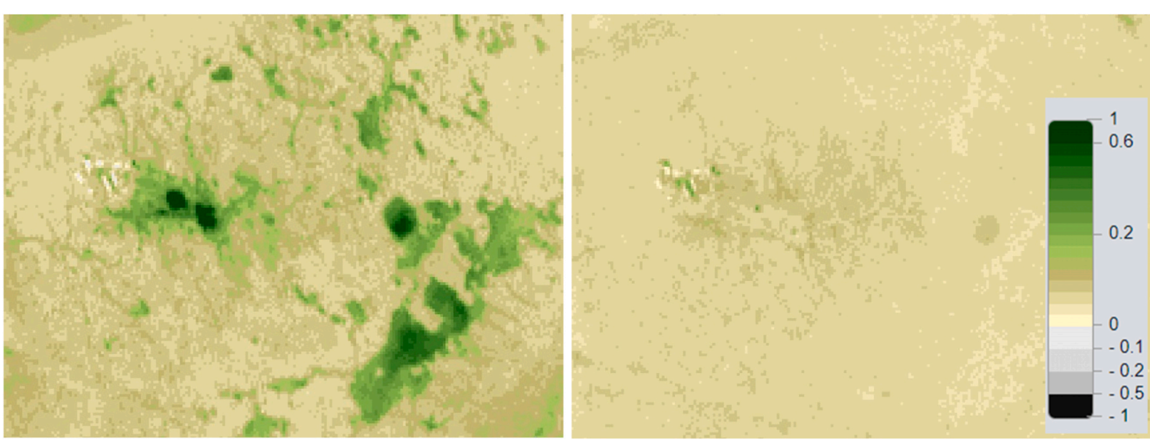

Fig. 14. Comparison of pre (right-07 October 2018) and post (left-26 November 2018) rainfall event on the natural vegetation.

the research area. This point data was subsequently exported and overlaid on the RWH suitability map (Fig. 13). The existing structures fall within very high and high suitable areas as indicated in the Fig. 13 below. Thus, these identified areas can potentially be used to increase the number of rainwater wells in the future.

Rainfall is crucial for the growth of natural vegetation, serving as the primary source of water necessary for plant survival and development. Adequate rainfall ensures that plants receive the moisture needed for photosynthesis, nutrient absorption, and overall metabolic processes. In Qatar erratic or insufficient rainfall leads to stunned vegetation growth and to sparse plant cover. Based on the NDIVI analysis of the pre and post rainfall event in the year 2018, analysis shows that rainfall is vital for the natural vegetation in Qatar. Rainfall water remains for a longer time in the depression zones providing sufficient time for transpiration to take place. As a result the NDVI values or greenness are significantly higher in depression areas than flat areas. Furthermore, the timing and intensity of rainfall are critical, as they influence soil moisture levels and groundwater recharge. Thus, rainwater harvesting sites in depression areas will not only enhance groundwater recharge but also sustain natural vegetation.

Similarly, depression zones play a critical role in storing rainwater. These natural or artificial low-lying areas act as catchment basins,

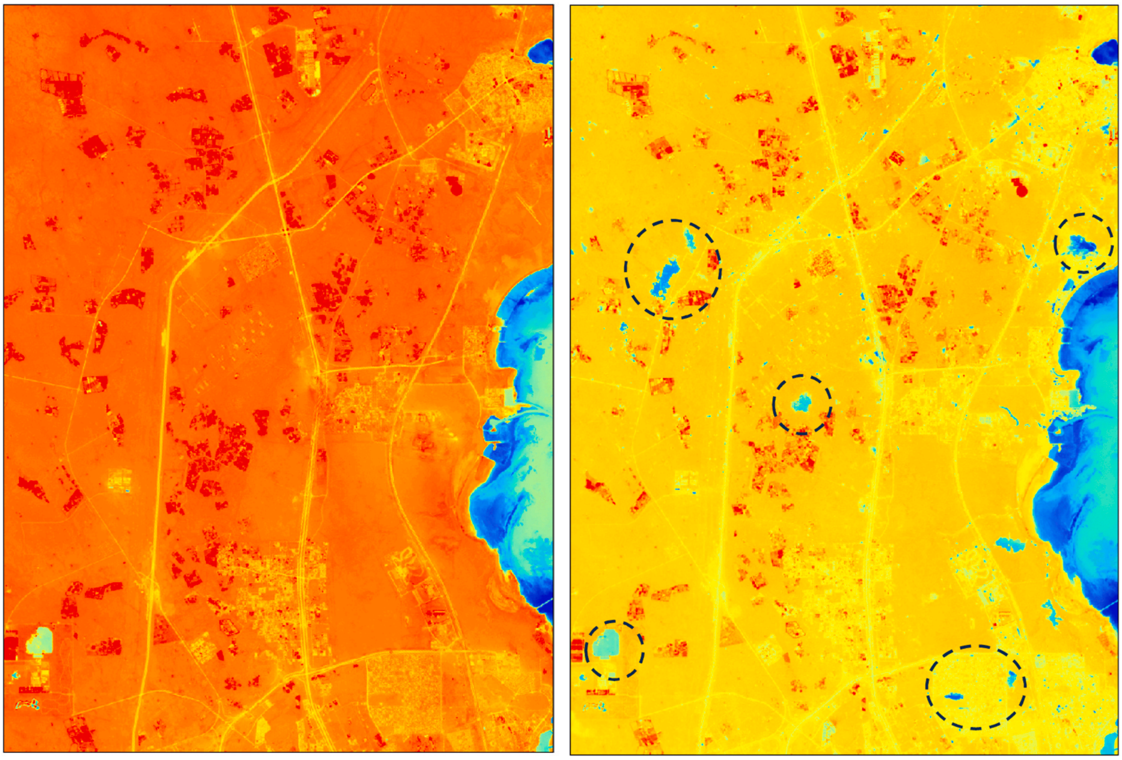

Fig. 15. Normalized Difference Water Index left October 09, Right October 25 201, 2018.

capturing and holding rainwater, which helps mitigate surface runoff and reduce the risk of flooding (Fig. 15). By retaining water, depression zones enhance groundwater recharge, replenishing aquifers and maintaining the water table. Based on the analysis of digital elevation model and Landsat-8 data, it is apparent that low-lying areas hold rainwater and consequently recharge the groundwater. An example is given below using the extreme rainfall event of October 20th 2018. The blue dots represent stagnant water in the depression zones following therainfall event (Fig. 15 right side).

4. Conclusion

Rainwater harvesting (RWH) represents a viable strategy for mitigating water scarcity by enhancing long-term water availability. In this study, a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) was employed to identify optimal sites for RWH, with the objective of reducing the annual freshwater deficit associated with groundwater recharge and abstraction. The results revealed that a significant portion of the State of Qatar, particularly within the eastern and western basins in the northern region, falls within the highly and moderately suitable categories for RWH. Conversely, areas in the southern part of the country were predominantly classified as having low to very low suitability. These lower suitability zones are primarily influenced by factors such as terrain slope, poor soil quality, variable rainfall patterns, suboptimal groundwater quality, and low drainage density. Assuming the deployment of engineered RWH wells with an estimated recharge efficiency of 40 %, the potential net recharge from the 'Very High', 'High', and 'Moderate' suitability zones was calculated at approximately 3.25, 43.21, and 60.50 million m^3 per year, respectively. Collectively, these zones may contribute an estimated 107 million m^3 annually, offsetting approximately 58 % of Qatar's reported 184 million m^3 national water deficit in 2021. These findings underscore the significant potential of targeted RWH infrastructure to enhance and augment groundwater replenishment in strategic areas across Qatar. The outcomes of this study provide valuable insights for policymakers and water resource authorities in formulating sustainable water management strategies. Nevertheless, the implementation of RWH systems should be preceded by further investigations, including the acquisition of updated hydrogeological and physiographic data on groundwater resources and aquifer characteristics.

CRediT authorship contribution statement

Rajabi Mohammad Mahdi: Formal analysis. **Chefi Triki:** Conceptualization. **Slim Zekri:** Formal analysis, Conceptualization. **Al-Maktoumi Ali:** Writing – review & editing, Formal analysis. **Hazrat Bilal:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Rajesh Govindan:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Abd-el-Kader, M.M., El-Feky, A.M., Saber, M., AlHarbi, M.M., Alataway, A., Alfaisal, F. M., 2023. Designating appropriate areas for flood mitigation and rainwater harvesting in arid region using a GIS-based multi-criteria decision analysis. Water Resour. Manag. 37 (3), 1083–1108. https://doi.org/10.1007/s11269-022-03416-6.

Adham, A., Sayl, K.N., Abed, R., Abdeladhim, M.A., Wesseling, J.G., Riksen, M., Fleskens, L., Karim, U., Ritsema, C.J., 2018. A GIS-based approach for identifying potential sites for harvesting rainwater in the Western Desert of Iraq. Int. Soil Water Conserv. Res. 6 (4), 297–304. https://doi.org/10.1016/j.iswcr.2018.07.003.

Al-Marzooqi, M., Bilal, H., Govindan, R., Kanikicharla, K.K., Al-Ansari, T., 2021. Impact of the urban heat island effect on the climate of the State of Qatar. Int. J. Glob. Warm. 24 (3–4), 400–419.

Almazroui, M., Saeed, S., Saeed, F., Islam, M.N., Ismail, M., 2020. Projections of precipitation and temperature over the South Asian countries in CMIP6. Earth Syst. Environ. 4, 297–320.

Aloui, S., Zghibi, A., Mazzoni, A., Elomri, A., Al-Ansari, T., 2024. Identifying suitable zones for integrated aquifer recharge and flood control in arid Qatar using GIS-based multi-criteria decision-making. Groundw. Sustain. Dev. 25, 101137. https://doi.org/10.1016/j.gsd.2024.101137.

Al-Yousef, M. (2003). Mineralogy, geochemistry and origin of Quaternary sabkhas in the Qatar Peninsula, Arabian Gulf.

Bazuhair, A.S., Wood, W.W., 1996. Chloride mass-balance method for estimating ground water recharge in arid areas: examples from western Saudi Arabia. Journal of Hydrology 186 (1–4), 153–159.

Bilal, H., 2019. Recent snow cover variation in the Upper Indus Basin of Gilgit Baltistan, Hindukush Karakoram Himalaya, 16, 296–308.

Bilal, H., Govindan, R., Al-Ansari, T., 2021. Investigation of groundwater depletion in the state of qatar and its implication to energy water and food nexus. Water (Switz.) 13 (18). https://doi.org/10.3390/w13182464.

Bilal, H., Govindan, R., Zekri, S., Al, A., Mohammad, M., Rajabi, M., Triki, C., 2025. Identification of potential managed aquifer recharge sites in hyper - arid environment using GIS and analytical hierarchy process. Appl. Water Sci. 2017. https://doi.org/10.1007/s13201-025-02431-3.

Bilal, H., Lahlou, F.Z., Al-Ansari, T., 2025. Land suitability assessment and self-sufficiency evaluation for fodder crop production in a hyper arid environment coupling GIS-based multi-criteria decision making and optimization. Ecol. Model. 501 (December 2024), 111021. https://doi.org/10.1016/j.ecolmodel.2025.111021.

Bilal, H., Okonkwo, E.C., Al-Ansari, T., 2024. A pathway to 25% reduction in greenhouse gas emission by 2030 using GIS-Based multi-criteria decision making for renewables, date palm (Phoenix dactylifera), and carbon credits: a case for Qatar. Front. Energy Res. 12 (February), 1–19. https://doi.org/10.3389/fenrg.2024.1272993.

Boretti, A., Rosa, L., 2019. Reassessing the projections of the world water development report. NPJ Clean. Water 2 (1), 15.

Chiew, F.H.S., Young, W.J., Cai, W., Teng, J., 2011. Current drought and future hydroclimate projections in southeast Australia and implications for water resources management. Stoch. Environ. Res. Risk Assess. 25, 601–612.

FAO. (1970). *FAO-Unesco Soil Map of the World.* Unesco.

FAO (1988). Soils map of the world: revised legend. Food and Agriculture Organization of the United Nations, Rome. 119 p.

Hussain, F.S., Bilal, H., Al-Ansari, T., 2025. Quantifying the role of mangroves in carbon sequestration in Qatar's mangrove forests. Ecological Informatics 103332.

Itani, N., Harik, G., Alameddine, I., El-Fadel, M., 2022. Managed aquifer recharge in karstic systems:Site suitability mapping by coupling multi-criteria decision analysis with remote sensing and hydrologic modeling. J. Environ. Manag. 322 (August), 116162. https://doi.org/10.1016/j.jenvman.2022.116162.

Jafari, H., Sudegi, A., Bagheri, R., 2019. Contribution of rainfall and agricultural returns to groundwater recharge in arid areas. Journal of Hydrology 575, 1230–1238.

KAHRAMAA, 2022, Qatar General Electricity and Water Corporation, Outstanding Achievements and Qualitative Transformation in KAHRAMAA During the Three Years of Blockade, Accessed on 12/02/2024, ⟨https://www.km.qa/MediaCenter/pages/NewsDetails.aspx?ItemID=354⟩.

Kimrey, J.O., 1985. Proposed Artificial Recharge Studies in Northern Qatar. US Geological Survey.

Matomela, N., Li, T., Ikhumhen, H.O., 2020. Siting of Rainwater Harvesting Potential Sites in Arid or Semi-arid Watersheds Using GIS-based Techniques. Environ. Process. 7, 631–652. https://doi.org/10.1007/s40710-020-00434-7.

NRCS, U. (2009). Chapter 7–Hydrologic soil groups in: NRCS–National engineering handbook (NEH), Part 630–hydrology. *USDA NRCS, Ashington, DC*, 1–7.

Nyirenda, F., Mhizha, A., Gumindoga, W., Shumba, A., 2021. A gis-based approach for identifying suitable sites for rainwater harvesting technologies in kasungu district, malawi. Water SA 47 (3), 347–355. https://doi.org/10.17159/wsa/2021.v47.i3.11863.

Planning and Statistics Authority, 2019. Planning and Statistical Authority Qatar, Annual Water Statistics 2019. PSA.

Planning and Statistics Authority. (2021). *Water Statistics In the state of Qatar 2021*.

Preeti, P., Shendryk, Y., Rahman, A., 2022. Identification of suitable sites using GIS for rainwater harvesting structures to meet irrigation demand. Water (Switz.) 14 (21), 1–17. https://doi.org/10.3390/w14213480.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15 (3), 234–281. https://doi.org/10.1016/0022-2496(77)90033-5.

Sayl, K., Adham, A., Ritsema, C.J., 2020. A GIS-based multicriteria analysis in modeling optimum sites for rainwater harvesting. Hydrology 7 (3). https://doi.org/10.3390/HYDROLOGY7030051.

Schlumberger Water Services. (2009). Studying & Developing the Natural & Artificial Recharge of The Groundwater Aquifer in The State of Qatar. Department of Agriculture and Water Research (DAWR) and Ministry of ….

SCS. (1986). Urban hydrology for small watersheds, technical release no. 55 (TR-55). *US Department of Agriculture, US Government Printing Office, Washington, DC*.

Seif, A.K., Masria, A., Ghareeb, M., Saleh, A.A., Soliman, K., Ammar, A.I., 2024. Identifying managed aquifer recharge and rain water harvesting sites and structures for storing non-conventional water using GIS-based multi-criteria decision analysis approach. Appl. Water Sci. 14 (8), 1–20. https://doi.org/10.1007/s13201-024-02246-8.

Shadeed, S., Almasri, M., 2010. Application of GIS-based SCS-CN method in West Bank catchments. Palest. Water Sci. Eng. 3 (1), 1–13.

Sherif, M., Ebraheem, A., Shetty, A., 2017. Groundwater recharge from dams in United Arab Emirates. In: World Environmental and Water Resources Congress 2017, pp. 139–146.

Singh, L.K., Jha, M.K., Chowdary, V.M., 2017. Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply. J. Clean. Prod. 142, 1436–1456. https://doi.org/10.1016/j.jclepro.2016.11.163.

Terry, J.P., Al Ruheili, A., Almarzooqi, M.A., Almheiri, R.Y., Alshehhi, A.K., 2023. The rain deluge and flash floods of summer 2022 in the United Arab Emirates: Causes, analysis and perspectives on flood-risk reduction. J. Arid Environ. 215, 105013.

Tiwari, K., Goyal, R., Sarkar, A., 2018. GIS-based methodology for identification of suitable locations for rainwater harvesting structures. Water Resour. Manag. 32 (5), 1811–1825. https://doi.org/10.1007/s11269-018-1905-9.

Wondimu, G.H., Jote, D.S., 2020. Selection of rainwater harvesting sites by using remote sensing and GIS techniques: a case study of Dawa Sub Basin Southern Ethiopia. Am. J. Mod. Energy 6 (4), 84–94.

Wu, R.-S., Molina, G.L.L., Hussain, F., 2018. Optimal sites identification for rainwater harvesting in northeastern Guatemala by analytical hierarchy process. Water Resour. Manag. 32, 4139–4153.

Zhong, Q., Tong, D., Crosson, C., Zhang, Y., 2022. A GIS-based approach to assessing the capacity of rainwater harvesting for addressing outdoor irrigation. Landscape and Urban Planning 223, 104416.

Zittis, G., Almazroui, M., Alpert, P., Ciais, P., Cramer, W., Dahdal, Y., Fnais, M., Francis, D., Hadjinicolaou, P., Howari, F., 2022. Climate change and weather extremes in the Eastern Mediterranean and Middle East. Rev. Geophys. 60 (3) e2021RG000762.