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Research paper

Identifying suitable zones for integrated aquifer recharge and flood control in arid Qatar using GIS-based multi-criteria decision-making

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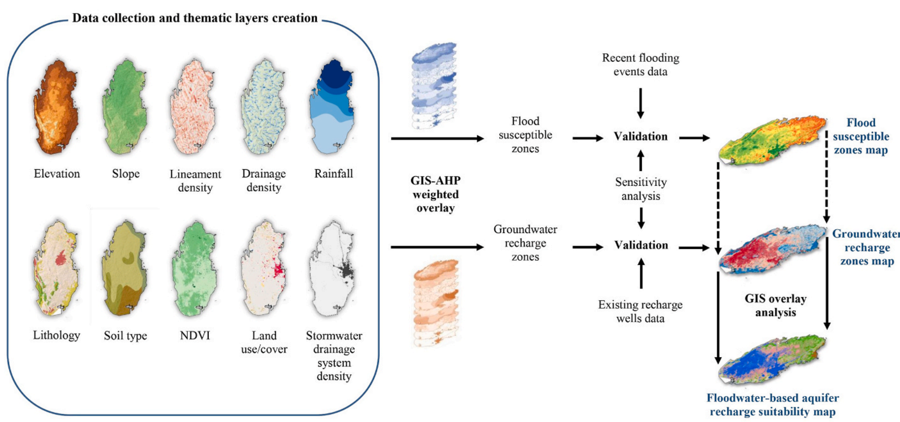
HIGHLIGHTS

- Floodwater can be effectively managed for aquifer recharge, offering dual benefits.
- GIS-MCDM was used to identify flood susceptible areas and potential recharge zones.
- Floodwater-based recharge suitability was mapped using an integrated approach.
- Qatar has significant potential for groundwater recharge using floodwater.
- The approach employed is applicable to similar flood-prone arid regions.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater resources in arid regions play a vital role in meeting water demands; however, they are facing rapid depletion due to unsustainable exploitation practices, exacerbated by climate change. Floods can present a unique opportunity for restoring groundwater levels and mitigating saltwater intrusion into aquifers. The use of properly managed floodwater for aquifer recharge offers a dual advantage by maximizing the potential of floods as a valuable water resource, while minimizing their negative impacts. In this work, we applied a GIS-based Multi-Criteria Decision-Making (MCDM) method, namely the Analytic Hierarchy Process (AHP), to delineate flood susceptible zones and groundwater recharge zones in Qatar, considering several influential topographical, hydrological, environmental, and anthropological criteria. The maps of flood susceptibility and groundwater recharge potential were validated using recent flooding events and existing recharge wells data, respectively. Sensitivity analysis was conducted on both variables to further assess their accuracy. The overlay analysis of the two validated maps suggests that approximately 64% of the Qatar peninsula presents medium to excellent suitability for aquifer recharge using floodwater. The areas best suited for floodwater-based recharge intervention are the northern and coastal regions of the peninsula, while the urban areas and southwestern area are less

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suitable. This study provides decision-makers with spatially explicit information on areas in Qatar that can be targeted for aquifer recharge projects using floodwater as well as recommendations on technical, economic, and regulatory considerations that require additional investigation. The approach employed can be effectively applied in similar flood-prone arid regions and is adaptable to diverse contexts.

1. Introduction

Groundwater is a critical natural resource that assumes a significant role in supporting agriculture, providing potable water supply, and sustaining ecosystems worldwide (United Nations, 2022). Its immense importance makes it a key factor in achieving the objectives outlined in the Sustainable Development Goals (SDGs) (Guppy et al., 2018; Saqr et al., 2021; Velis et al., 2017; Wei et al., 2023). Particularly, groundwater plays a crucial role in arid regions characterized by scarce and unreliable water resources due to limited rainfall and high evaporation rates (Mohamed et al., 2021; Rabeiy et al., 2022). However, the over-exploitation of groundwater resources due to increasing demand and unsustainable practices have led to declining groundwater levels in many regions around the world, thus reducing their socioeconomic and environmental benefits (Bierkens and Wada, 2019; Dangar et al., 2021; Fallatah, 2020; Frappart and Ramillien, 2018; Herbert and Döll, 2019; Scanlon et al., 2023).

As climate extremes intensify (AghaKouchak et al., 2020), there is a growing emphasis on harnessing flood and storm flows to replenish overdrawn aquifers (Dahlke et al., 2018; Fathy et al., 2021; Gangopadhyay et al., 2018; Jacobson, 2019; Yang and Scanlon, 2019). In this context, floods, which are natural disasters with potentially devastating impacts, can present a unique opportunity for restoring groundwater levels and can further help reduce the adverse effects of groundwater depletion such as saltwater intrusion, water quality degradation, and land subsidence (Ashraf et al., 2023; Chinnasamy et al., 2018; Mesbah et al., 2016). Furthermore, the use of properly managed floodwater for aquifer recharge offers a dual advantage of maximizing the potential of floods as a valuable water resource while also minimizing their negative impacts including fatalities and injury, property damage, services disruption, economic losses, and environmental alteration (Antwi-Agyakwa et al., 2023). Moreover, this practice can have a significant contribution to sustaining water and food security and building resilience, notably considering projected droughts resulting from climate change (Langridge and Daniels, 2017; Scanlon et al., 2016). In particular, in arid regions where rainwater harvesting using surface water storage structures is not feasible due to high evaporation rates, floodwater-based recharge can present a win-win solution for sustainable water resource management and flood risk reduction (Escalante et al., 2019; Vanegas-Espinosa et al., 2022).

The process of aquifer recharge by floodwater, recently referred to as Flood-Managed Aquifer Recharge (Flood-MAR), involves intentionally capturing and directing excess surface water during floods to suitable areas where it can be infiltrated into the soil, percolated through sediment and rock, and stored in aquifers for later use (Alam et al., 2020). It is noteworthy that Flood-MAR primarily applies to agricultural areas, while a similar concept in urban settings is termed stormwater managed aquifer recharge (Beganskas and Fisher, 2017). Flood-MAR utilizes the excess water generated during periods of heavy rainfall or flooding, which would otherwise be lost to runoff or cause potential damage.

Groundwater recharge using floodwater can be achieved through a variety of methods, such as spreading basins (Jahangirzadeh and Ghanbarzadeh Lak, 2021), injection wells (Yang and Scanlon, 2019), percolation ponds (Christy and Lakshmanan, 2017), and recharge trenches and pits (Rahman et al., 2013). For example, since 1983, Iran has implemented floodwater spreading in 36 locations as a cost-effective measure to mitigate floods and replenish aquifers and this approach has yielded considerable economic benefits despite requiring a relatively modest investment (Hashemi et al., 2015). Flood-MAR was also recently tested within a preliminary project in the Cornia valley, Italy (Rossetto et al., 2018). In California's Central Valley (USA) as well, there have been recent initiatives aimed at capturing flood flows for recharge and irrigation (Langridge and Van Schmidt, 2020; Scanlon et al., 2023). Pavelic et al. (2021) also highlighted the promising potential of a piloted implementation of Underground Transfer of Floods for Irrigation (UTFI) in an Indo-Gangetic Plain rural community in India, revealing that the approach effectively recharges depleted aquifers with seasonal high flows, enhances groundwater storage, and controls flooding, and indicating its feasibility for larger-scale replication.

Qatar serves as an ideal arid region where there is a pressing need for improved integration of flood and groundwater management systems. The country has been heavily relying on groundwater, its only natural freshwater resource besides occasional minimal rainfall, for agricultural development, which has resulted in depleted aquifers along with groundwater degradation (Al Khoury et al., 2023; Aloui et al., 2023a; Bilal et al., 2021; PSA, 2021). The primary source of aquifer recharge in Qatar is rainfall, with additional contributions coming from urban recharge, mostly concentrated in the Doha area, and agricultural irrigation return flows, distributed sporadically across the country (Al-Muraikhi and Shamrukh, 2017). The existing artificial recharge plans and research developed to overcome these challenges and/or create strategic groundwater reserves have mainly focused on enhancing natural rainfall infiltration (SWS, 2009) and using treated sewage effluent (PSA, 2021) or potentially desalinated water (Jacob et al., 2021; Mohieldeen et al., 2021; Vecchioli, 1976) for aquifer recharge. On the other hand, Qatar falls within the Middle East region which has a long-standing background of destructive floods caused by high seasonal rainfall or major storm occurrences (Mahmoud and Gan, 2018). In recent years, the peninsula has experienced several flash floods of significant impact (Al Mamoon et al., 2015; FloodList, 2015, 2018).

With evident signs of climate change in the region and projections of more intense climate extremes (Zittis et al., 2022), floodwater-based recharge can offer a viable solution to replenish the depleted groundwater resources in Qatar and enhance its water security. Nevertheless, this requires meticulous planning, appropriate design, and efficient management. Particularly, careful decision-making is required to identify suitable areas for aquifer recharge using floodwater. While previous studies have separately proposed zonation maps of groundwater recharge (Baalousha, 2015; Baalousha et al., 2018; Mohieldeen et al., 2021) and flood susceptibility, hazard, and risk (Al Mamoon, 2020; Baalousha et al., 2023; Serdar et al., 2022; MME, 2020) across Qatar, there remains a research gap regarding the spatial assessment of floodwater-based recharge. The spatial suitability for such intervention is nevertheless complex and requires considering the interactive influence of various factors.

Multi-Criteria Decision-Making (MCDM) methods have emerged as useful tools facilitating decision-making in complex situations where multiple deterministic criteria must be considered. Among these methods, the Analytic Hierarchy Process (AHP) allows pairwise comparison of spatial parameters through expert opinion-based weight assignments. It was used in several studies conducted in different climatic and hydrological contexts for delineating groundwater recharge zones (e.g., Abdulkerim et al., 2022; Al-Abadi et al., 2020; Upwanshi et al., 2023; Zghibi et al., 2020) as well as identifying flood susceptible zones (e.g., Abu El-Magd et al., 2019; Mahmoud and Gan, 2018; Souissi et al., 2020; Yilmaz, 2022). MCDM applications have been extensively integrated with Geographic Information System (GIS) and remote sensing (Baghel et al., 2023; Lin et al., 2019), providing a simple and practical tool for spatial assessments before undertaking expensive field explorations (Abdullah et al., 2021; Sallwey et al., 2019).

This study aims to identify suitable sites for groundwater recharge using floodwater across Qatar. We employ an integrated approach, combining Quantum GIS-based MCDM mapping of flood susceptible zones (FSZ) and groundwater recharge zones (GWRZ) based on ten influential criteria, including elevation, slope, lineament density, drainage density, rainfall, lithology, soil types, Normalized Difference Vegetation Index (NDVI), land use/land cover, and stormwater drainage system density. Our investigation is the first to address the use of floodwater for aquifer recharge in the study area and identify suitable implementation sites. The findings provide decision-makers with spatially explicit information for targeted aquifer recharge projects, potentially mitigating groundwater depletion, enhancing water security, and improving flood risk management in the country. Moreover, our integrated and adaptable methodology offers an effective framework for replication in similar regions, empowering further research for sustainable water resource management.

2. Study area

Qatar is a small peninsula of about 11,600 km^2 located in the eastern part of the Arabian Peninsula between latitudes 24° 16′–26° 6′ North and longitudes 50° 27′–51° 24′ East (Fig. 1). It is part of the Gulf Cooperation Council (GCC), situated in a strategic location with the Persian Gulf surrounding it on three sides, while its southern border is shared with Saudi Arabia. The peninsula is primarily composed of flat, sandy desert plains, with some low-lying limestone hills in the southwest. As depicted in Fig. 1, most of the study area has an elevation under 40 m a.s.l.; nevertheless, the elevation can reach up to 94 m a.s.l. in the south. The topography is characterized by land depressions formed through limestone dissolution creating karst features and serving as effective recharge areas (Baalousha, 2015; Sadiq and Nasir, 2002).

The hydrogeology of Qatar encompasses Pliocene and Eocene geological formations, along with some Quaternary deposits near the coastline. Three main aquifers found in Tertiary deposits can be distinguished (Table 1): Dammam (Eocene), Rus (Eocene), and Umm er Radhuma (Paleocene). The Dammam Formation covers most of Qatar's surface and is predominantly dry with exceptions in low-lying zones and in proximity to the coastline (Baalousha, 2016a). Its thickness ranges from being absent on the Qatar-South Fars Arch (central Qatar) to approximately 40 m along the western coast (Abu-Zeid, 1991). The Rus Formation, underlying the Dammam Formation, serves as the main aquifer, particularly within the country's northern part (Abotalib et al., 2019). In southern Qatar, this layer contains gypsum and anhydrite, resulting in poor groundwater quality. Its thickness ranges from a minimum of 15 m in the Dukhan area, western Qatar, to a maximum of 122 m in the country's southwestern part (Eccleston et al., 1981). The Umm er Radhuma Formation, located at the bottom, extends across the entire region from Saudi Arabia's eastern side, with an approximate

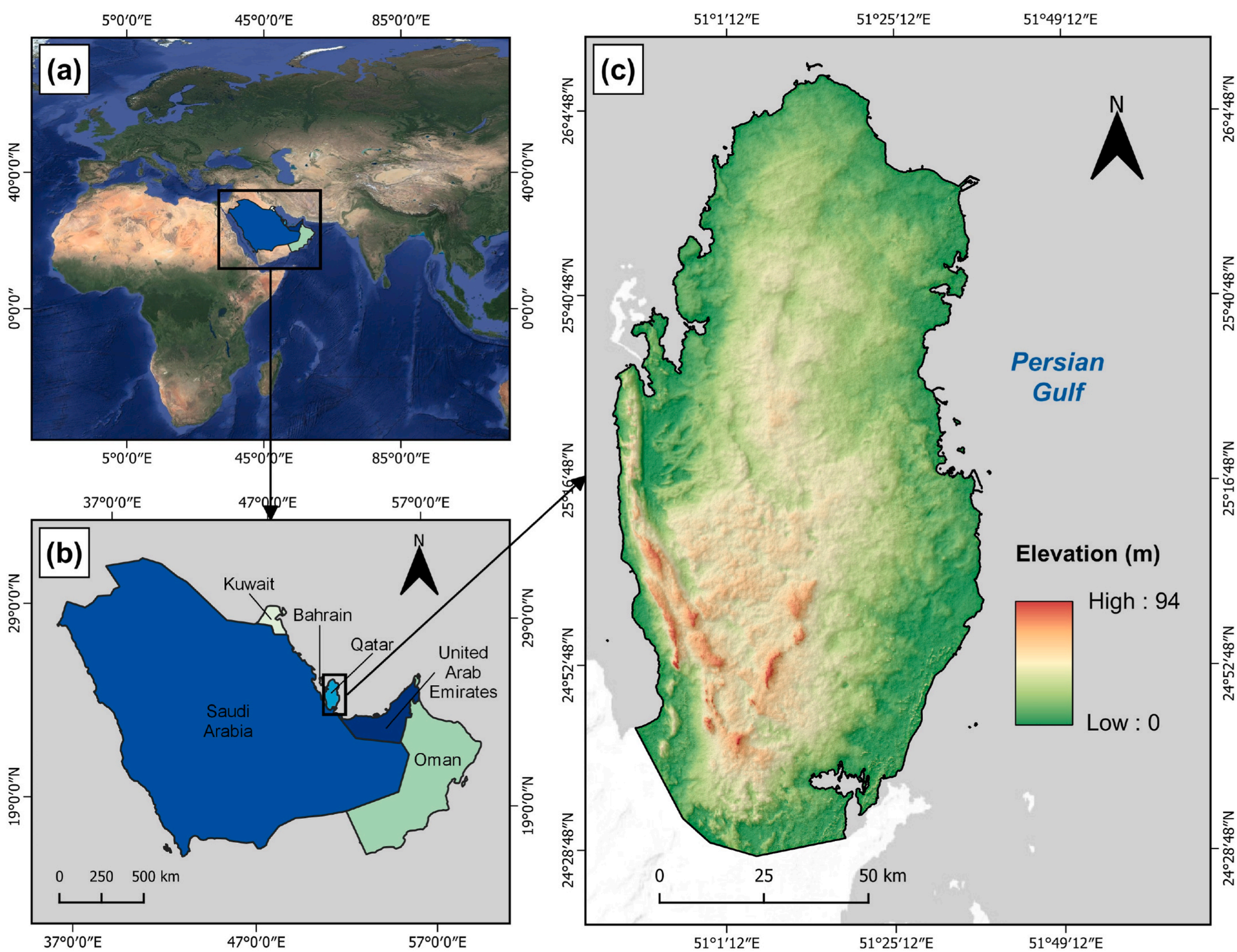

Fig. 1. Location of **(a)** the GCC countries and **(b)** Qatar within the GCC region, and **(c)** elevation of Qatar (based on a 30 m-resolution SRTM digital elevation model).

Table 1
Summary of properties of Qatar's three main aquifers (adapted from Sadooni, 2014).

Aquifer	Age	Formation thickness (m)	Deposits	Groundwater type
Dammam	Eocene	Upper Dammam: 10–65	Dolomitic limestone	Old water (10,000 to 17,000 years)
		Lower Dammam: 12	Fossiliferous chalky limestone with laminated shale	
Rus	Eocene	10–20	Limestone, dolomite, and some marl	Large reserves of freshwater in the carbonate facies
		10–100	Anhydrite with marl	
		10–20	Limestone, dolomite, and some marl	
Umm er Radhuma	Paleocene	300–500	Altering limestones and dolomites	Brackish water

thickness of 300 m (Kimrey, 1985). In the Dukhan field, it thins to about 130 m (Boukhary et al., 2011). Groundwater quality in this layer varies across the eastern Arabian Peninsula but is generally saline in Qatar (Dirks et al., 2018).

The climate in Qatar is hyper-arid, marked by extremely hot summers and mild winters. In summer, scorching temperatures prevail accompanied by strong wind and high humidity rates, especially in coastal areas (MDPS, 2017). Rainfall is mostly concentrated during winter months with an annual average of under 80 mm (Al Mamoon and Rahman, 2017). Despite receiving limited and sporadic precipitation, Qatar is prone to high-volume rainfall runoff during certain rainfall events, leading to significant flooding issues exacerbated by the country's predominantly flat topography and its limited natural drainage systems.

Notably, a severe flash flood occurred in Qatar in 1995 and resulted in human fatalities (Membery, 1997). In 2018, torrential rain caused extensive flooding, with the country experiencing a typical year's total amount of rainfall (84 mm) in a single day (FloodList, 2018). A similar event was also recorded in 2015 (Al Mamoon et al., 2015). The frequency of sudden, heavy rain has been increasing over the past years (Al Mamoon, 2020). This trend is observed in other GCC countries, including recent floods in Saudi Arabia (Ledraa and Al-Ghamdi, 2020), Oman (El Zawahry et al., 2020), and the UAE (Elhakeem, 2017). Projected long-term effects of long-term effects of climate change are expected to exacerbate floods in Qatar (Ajjur and Al-Ghamdi, 2022).

In urban areas of Qatar, recent floods, particularly in poorly drained locations like low-lying areas, underpasses, and roads, caused transportation disruptions, infrastructure damage, and inconvenience for residents and businesses (Serdar and Al-Ghamdi, 2023; Serdar et al., 2022). To mitigate flood impacts, Qatar has implemented a range of infrastructure measures, such as stormwater drainage systems, retention basins, floodwater diversion channels, and a deep injection well system, with the aim of effectively managing excess stormwater runoff (Ashghal, 2021; Jafari and Bernardeau, 2019; Jones and Kelly, 2019). Treatment of stormwater has also been outlined in the plans of the Ministry of Municipality (formerly Ministry of Municipality and Environment) (MME, 2019). However, as noted by Jafari and Bernardeau (2019) and Ajjur and Al-Ghamdi (2022), there is room for improvement in the stormwater drainage system, which currently consists primarily of subsurface chambers and pipes.

Scarce rainfall throughout the year combined with very high evaporation rates of about 2200 mm per year deprive the country from developing surface water resources (Shomar et al., 2014). Currently, Qatar relies on unconventional water resources to fulfill most of its water requirements (Alhaj et al., 2017). As per the latest official statistics, in 2021, the country's water supply relies on seawater desalination (61%), groundwater extraction (23%), the utilization of treated sewage effluent (TSE; 16%), and the recycling of treated industrial water as desalinated water used within the same sector (PSA, 2022). Groundwater, primarily used for agriculture, faces excessive exploitation and saltwater intrusion due to unsustainable irrigation practices and irrigated land expansion (Hussein and Lambert, 2020; Karanisa et al., 2021; Lawler et al., 2023).

The spatial distribution of piezometric heads of Qatar's shallow aquifer in 1958, 1980, 2009, and 2017 is illustrated in Fig. 2. In 1958, the Dammam aquifer, assumed to have been in a steady or pseudo-steady state, had minimal groundwater abstraction (Baalousha, 2016a), with levels ranging from 0 m near the coast to over 13 m a.s.l. in the central region (Fig. 2a). The Dammam aquifer potentiometric map in 1980 (Fig. 2b) demonstrates that the water level reaches a maximum of 6 m a.s.l. in the north and gradually decreases towards the coast. The flow pattern moves from central high-elevation areas towards the sea and shallow regions such as *Sabkhas*. The southern region of Qatar predominantly experiences groundwater mounds which are attributed to vertical groundwater inflow (Alsharhan et al., 2001). The Sabkha Dukhan on Qatar's central western coast exerts a notable influence on the groundwater flow patterns leading to the formation of a regional cone of depression with water flowing from various directions, including the sea. The 2009 potentiometric surface map of Qatar (Fig. 2c), based on a dataset of 1904 water level measurements, revealed that around 90% of the groundwater elevations were under 3.8 m a.s.l., with 77% below 2 m a.s.l. (SWS, 2009). The piezometric map of 2017 (Jacob et al., 2021), also shows the same trend with coastal zones having a weak piezometric gradient, facilitating seawater intrusion (Fig. 2d).

The contour plots show that the significant extraction from the freshwater lens in northern Qatar has led to a decrease in the regional water level, leading to lateral and vertical saline water influxes. This decrease has subsequently led to the influx of saline water, both laterally and vertically. Particularly, groundwater salinization is a prominent issue in Qatar (Aloui et al., 2023a; Mohammed and Darwish, 2017). In 1992, non-saline wells formed only 8% of the nation's total groundwater wells, but by 2012, there were no wells categorized as non-saline, and further in 2014, about 54% of Qatar's wells were classified as moderately saline, 27% as highly saline, 7% as brine, and only 12% were slightly saline (Ahmad and Al-Ghouti, 2020). In 2009, a comprehensive study by the Ministry of Environment (MoE) found that the freshwater lens in northern Qatar had shrunk to about 11% of its size in 1971, as illustrated in Fig. 3 (SWS, 2009). Since 2005, agricultural groundwater extraction has stabilized at around 230 million m^3 per year, due to increased utilization of treated sewage effluent (TSE) for fodder irrigation (Jasim et al., 2016). Furthermore, it is claimed that over 50% of the annual aquifers' additions are attributed to artificial recharge, including recharge wells, TSE injection, and irrigation returns (Al-Muraikhi and Shamrukh, 2017; Ahmad and Al-Ghouti, 2020). Nevertheless, the groundwater abstraction rate in Qatar is about five times higher than the safe yield (57.2 million m^3 per year) (PSA, 2021).

3. Materials and methods

This work aims at identifying suitable zones for groundwater recharge using floodwater for an integrated water resource management in Qatar. The methodology we followed is presented in Fig. 4. We first used an expert knowledge-based analysis of influential criteria, namely the AHP, within GIS, to individually map flood susceptible zones (FSZ) and groundwater recharge zones (GWRZ) in the study region. The FSZ are considered as areas where potential floodwater is available as a source for recharge, while the potential GWRZ are identified as areas suitable for implementing recharge structures. We conducted a sensitivity analysis for both AHP applications and validated the two resulting maps. We subsequently overlaid and analyzed the validated maps to

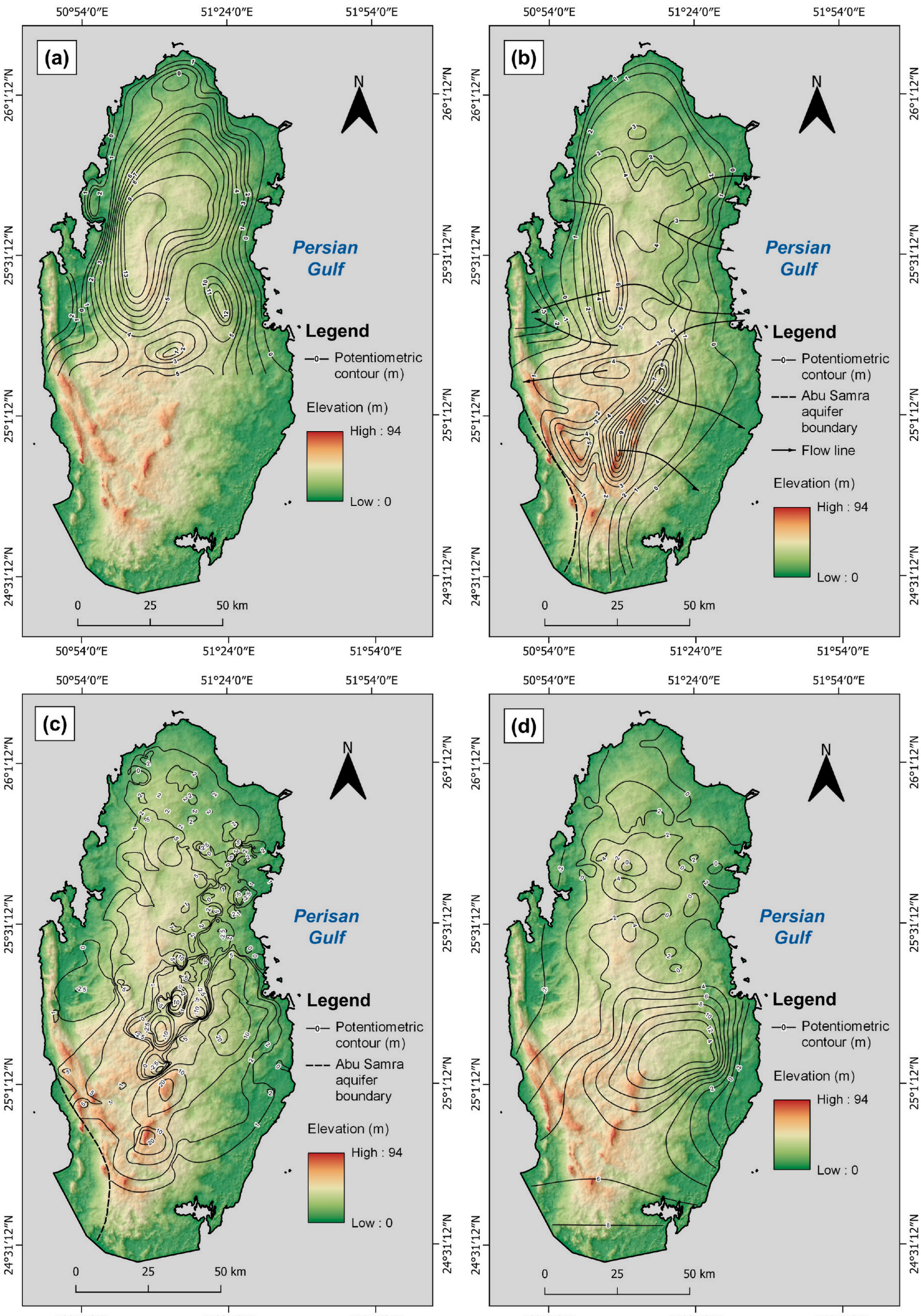

Fig. 2. Evolution of the potentiometric map of Qatar's shallow aquifer: **(a)** 1958 (adapted from Alsharhan et al. (2001)), **(b)** 1980 (adapted from Al-Hajari (1990)), **(c)** 2009 (adapted from SWS (2009)), and **(d)** 2017 (adapted from Jacob et al. (2021)).

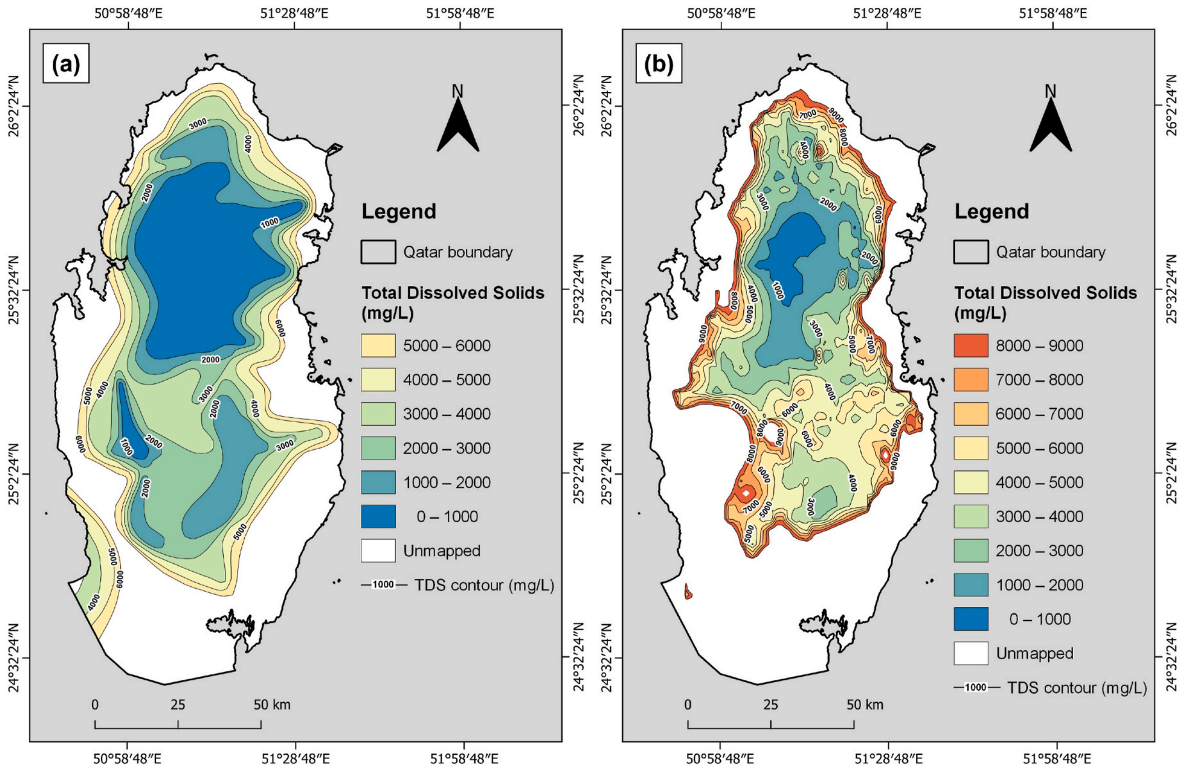

Fig. 3. Distribution of total dissolved solids (TDS) in groundwater (mg/L) across Qatar in **(a)** 1971 and **(b)** 2009 (adapted from SWS (2009)).

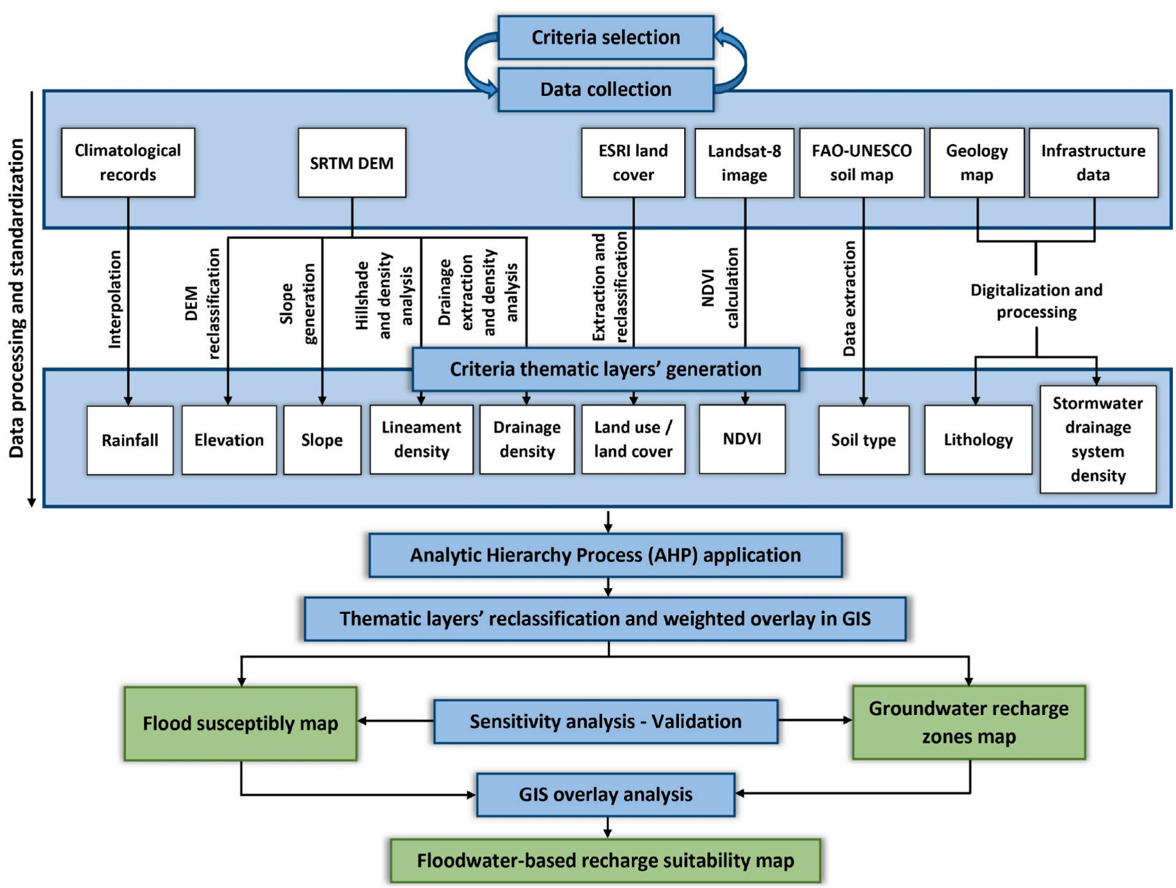

Fig. 4. Research methodology flowchart.

evaluate the spatial suitability of the study area for floodwater-based aquifer recharge. The mapping included criteria layers classification, data standardization, and weighted overlaying using Quantum GIS – QGIS 3.16 (QGIS Development Team, 2022), known for its open-source nature and free access to high-performing algorithms.

3.1. Criteria selection and thematic layers' preparation

Considering the importance of criteria influence on both flood susceptibility and groundwater recharge as well as data availability, we selected a set of ten influential criteria. These include topographical (elevation, slope, and lineament density), hydrological (drainage density and rainfall), environmental (lithology, soil types, and NDVI), and anthropological (land use/land cover and stormwater drainage system density) factors. These factors were selected after conducting a thorough inspection of recent studies focusing on flood susceptibility (Table A1) and groundwater recharge (Table A2) mapping performed in different climatic and hydrological contexts including similar arid regions.

The input data used to prepare the thematic layers was collected from different sources including literature, published maps, and remote sensing information, as summarized in Table 2. To achieve coherence in geospatial analysis and standardize database formatting, we converted all criteria' layers into raster format, employing WGS 84/UTM Zone 39N projection, followed by resampling to a 30 m/30 m resolution.

Table 2
Summary of datasets used for the thematic layers' preparation.

Data	Format	Scale/ Resolution	Source	Derived layer [a]
Digital Elevation Model (DEM)	Raster	30 m/30 m	United States Geological Survey (USGS) Shuttle Radar Topography Mission (SRTM) (https://earthexplorer.usgs.gov/)	EL, SLO, LD, and DD
Surface geology map	Vector	1:395,000	Cavelier (1970), Rivers and Larson (2018), and Seltrust Engineering (1985)	LI
Harmonized world soil database (HWSD)	Raster	1 km/1 km	Food and Agriculture Organization of the United Nations (FAO-UNESCO) (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/)	SL
Average annual rainfall	Table	8 meteorological stations	Public Statistics Authority (PSA) and Schlumberger Water Services (SWS, 2009)	RN
ESRI land cover (2021)	Raster	10 m/10 m	Environmental System Research Institute (ESRI) (https://livingatlas.arcgis.com/landcover/)	LULC
Satellite image (Landsat-8)	Raster	30 m/30 m	United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/)	NDVI
Stormwater drainage system	Vector	–	Serdar et al. (2022)	SWD

[a] **EL**, elevation; **SLO**, slope; **LD**, lineament density; **DD**, drainage density; **LI**, lithology; **SL**, soil type; **RN**, rainfall; **LULC**, land use/land cover; **NDVI**, Normalized Difference Vegetation Index; and **SWD**, stormwater drainage system density.

3.1.1. Elevation (EL)

Elevation has a pivotal role in understanding flood susceptibility and groundwater recharge. Higher elevations exhibit lower flood susceptibility due to superior natural drainage (Abd-el-Kader et al., 2023; Tehrany et al., 2019). Higher elevations generally experience more runoff, while lower elevations favor surface water accumulation and infiltration, enhancing recharge (Maqsoom et al., 2022; Senanayake et al., 2016). The EL data was obtained from the USGS SRTM DEM at a 30 m/30 m resolution.

3.1.2. Slope (SLO)

Rainfall water tends to collect in lower slope areas (Al-Juaidi, 2023). Steeper slopes are therefore less prone to floods, while gentle slopes are vulnerable to riverine flooding or water accumulation from prolonged rainfall. Moreover, steeper slopes lead to increased erosion and runoff reducing infiltration, while gentle slopes promote longer water residence times potentially increasing recharge (Lee et al., 2014; Yeh et al., 2016). SLO gradient information was derived from the DEM in QGIS by estimating the elevation change rate between each cell and its adjacent neighbors.

3.1.3. Lineament density (LD)

By serving as preferential conduits, lineaments such as faults and fractures fundamentally influence water flow dynamics (Lucianetti et al., 2017; Vishnu et al., 2020). Qatar's shallow aquifer is primarily carbonate with secondary porosity (Abotalib et al., 2019), underscoring the importance of incorporating LD. High LD enhances permeability, reducing flood risk and facilitating rapid discharge (Vishnu et al., 2020). It also promotes recharge by increasing subsurface porosity and permeability (Ahmed et al., 2019; Hamdani and Baali, 2019).

The lineaments extraction was based on high-resolution DEM analysis (Saint Jean Patrick Coulibaly et al., 2021). Initially, eight DEM hillshade rasters were generated using distinct illumination angles to highlight terrain features and further processed using filtering techniques. Subsequently, automated lineament extraction was employed to identify linear features. The resultant layer underwent masking to remove manmade features and was further integrated with the Qatar lineaments map developed by El-Kassas and Ashour (1990). Finally, a study area grid was created to count the total lineament length per unit area and prepare the LD map. The lineament density (L_d), which is the total length of lineaments per unit area, was calculated according to equation **(1)** (Magesh et al., 2012):

$$L_d = \sum_{i=1}^{n} L_{li} \Big/ A \tag{1}$$

where, $\sum_{i=1}^{n} L_{li}$ is the total length of lineaments (km), and A is the total surface area (km^2).

3.1.4. Drainage density (DD)

The DD assumes a crucial role in determining runoff distribution and water infiltration level (Andualem and Demeke, 2019). High DD increases flood susceptibility with rapid water accumulation and flow through channels (Ali et al., 2020; Tella and Balogun, 2020). High DD areas have lower groundwater recharge, as water lacks sufficient time for infiltration. Furthermore, lower DD has been associated with permeable soils (Dar et al., 2021). Qatar's drainage system is predominantly endoreic, directing most runoff through *wadis* and overland flow to very short-lived inland water accumulations (SWS, 2009).

The drainage network was generated from the DEM using the Soil and Water Assessment Tool (SWAT), which is an extensively used hydrological model (Aloui et al., 2023b; Arnold et al., 1998). After DEM preprocessing by filling sinks, SWAT calculates flow direction and accumulation for each cell to determine the stream network. A DD map was produced by systematically counting the stream segments' total length within each unit area. Drainage density (D_d) was computed by the division the total length of stream segments by the area of the region (Magesh et al., 2012) as given by equation **(2)**:

$$D_d = \sum_{i=1}^{n} L_{di} \Big/ A \tag{2}$$

where, $\sum_{i=1}^{n} L_{di}$ is the total drainage length (km), and A is the total drainage area (km^2).

3.1.5. Rainfall (RN)

Rainfall, more particularly in desertic regions, constitutes the main natural source of water potentially generating floods and/or recharging aquifers. High rainfall intensities and volumes increase surface runoff, resulting in increased flooding probability (Ramkar and Yadav, 2021; Shahiri Tabarestani and Afzalimehr, 2022). Additionally, high rainfall induces higher recharge, particularly if the water can infiltrate quickly (Arshad et al., 2020; Tolche, 2021). Long-term average rainfall data from eight meteorological stations scattered across Qatar spanning a period of 34 years (1989–2022) was obtained from information published in the Schlumberger Water Services report (SWS, 2009) and by the Planning and Statistics Authority. This dataset was used to generate an RN map employing the Inverse Distance Weighted (IDW) interpolation technique.

3.1.6. Lithology (LI)

Groundwater recharge is significantly influenced by lithology, as it acts as the primary factor governing porosity and permeability (Costache et al., 2020; Tolche, 2021). The characteristics of surface rock profoundly impact the recharge process (Shaban et al., 2006; Yeh et al., 2016). Areas with permeable rocks have higher recharge rates (Achu et al., 2020). LI has a greater influence on recharge due to its gradual, enduring impact, while flood susceptibility is more affected by short-term, variable events (Pradhan et al., 2023). Lithological units were produced from the surface geology map of Qatar (Cavelier, 1970; Seltrust Engineering, 1985).

3.1.7. Soil type (SL)

Soil properties significantly influence infiltration (Edamo et al., 2022; Shekar and Mathew, 2023). Particularly, soil texture is essential for understanding its structure, porosity, adhesion, and consistency (Baghel et al., 2023; Dar et al., 2021). Fine soil texture reduces infiltration and increases runoff, making it flood-prone and less suitable for groundwater recharge (Negese et al., 2022). For instance, clay soils exhibit a higher runoff generation rate following rainfall compared to silty-sandy soils (Ramkar and Yadav, 2021). Data on soil types were extracted from the FAO-UNESCO HWSD. Soil texture was attributed based on FAO soil classification system guidelines (FAO, 1988).

3.1.8. Normalized Difference Vegetation Index (NDVI)

NDVI serves as an indicator for vegetation density and health (Xu et al., 2022). It reflects the extent of vegetation growth, influencing the infiltration and convergence of rainwater across the terrain (Lin et al., 2019). Particularly, it is extensively considered in flood susceptibility assessment (Ali et al., 2020; Khosravi et al., 2019). High NDVI is associated with flood risk reduction and recharge enhancement since vegetation intercepts rainfall, decreases runoff speed, and facilitates infiltration by creating soil macro-pores (Negese et al., 2022; Pradhan et al., 2023). An NDVI map was derived from USGS Landsat 8 imagery (30 m/30 m) processed on Google Earth Engine (GEE). The calculation formula **(3)** for NVDI is as follows (Kanani-Sadat et al., 2019):

$$NDVI = (R_{NIR} - R_R) / (R_{NIR} + R_R) \tag{3}$$

where, R_{NIR} is the reflectance in the near infrared band of satellite imagery, and R_R is the reflectance in the red band.

3.1.9. Land use/land cover (LULC)

Hydrological processes are highly influenced by LULC patterns (Siddik et al., 2022; Talozi et al., 2023). High impervious surfaces increase flood risk and limit recharge by increasing runoff and reducing infiltration (Negese et al., 2022; Pradhan et al., 2023). Conversely, high vegetation cover lowers flood susceptibility and enhances recharge by promoting rainfall infiltration (Tella and Balogun, 2020). We used ESRI's 2021 LULC map pf a resolution of 10 m/10 m. The map was derived from European Space Agency (ESA) Sentinel-2 imagery using artificial intelligence modeling for land classification into nine classes, including bare surface, water, vegetation types, cropland, and built areas. To create the LULC criterion map, we initially extracted the study area's LULC map. Then, we matched and assigned suitable LULC class names to each LULC type, as the original map used numerical codes for classification. Finally, we reclassified the nine classes into five major LULC groups.

3.1.10. Stormwater drainage system density (SWD)

An efficient drainage system aids in eliminating surplus runoff and mitigates water accumulation, particularly in impervious areas (Ajjur and Mogheir, 2020; Lee et al., 2018). Higher SDW indicates a greater potential for water to be efficiently channeled away from the area. Conversely, areas with low SWD have higher flooding risk and higher recharge rates, as surface water can accumulate. Information on stormwater drainage network system, limited to drainage sewer pipes, was acquired from Serdar et al. (2022), based on data from The Public Works Authority "Ashghal". The SWD map was produced by systematically counting the total length of the drainage system segments per unit area.

3.2. GIS-based Analytic Hierarchy Process (AHP)

The AHP is designed to explicitly integrate multiple conflicting criteria in decision-making (Madzík and Falát, 2022). It involves structuring the problem as a hierarchical model using expert knowledge-based pairwise comparisons to assess the relative significance of distinct criteria and sub-criteria incorporated in a judgment matrix (by Saaty, 1980). The AHP has garnered significant attention and recognition as a powerful MCDM tool within the realm of geospatial analysis (Chandio et al., 2013). Several studies employed the AHP for the mapping of flood susceptibility (Table A1) and groundwater recharge (Table A2). The criteria selected were different across the studies depending on the availability of data and researchers' judgement of criteria relevance. These studies verified the accuracy of the AHP using different validation methods and approved the method's ability to generate accurate results. This study utilized GIS-based AHP to map FSZ and GWRZ in Qatar, considering ten influential criteria. This approach transforms geographical data into decision outputs by quantifying qualitative information through pairwise comparison matrices (PCM) (step 1). Subsequently, the factors were assigned weights derived by normalizing the PCM (step 2). To address potential inconsistencies, we calculated the consistency ratio (CR) for the PCM (step 3). Finally, the criteria' layers were assigned their relative weights and overlaid within GIS (step 4).

3.2.1. Pairwise comparison matrix development

The criteria impacting the target variable were initially scored based on their relative significance through pairwise comparisons. The standard 1–9 scale (Fig. A1) developed by Saaty (2008) was used for this purpose; a score of 1 denotes an equivalent influence among the compared criteria, while a score of 9 represents a significantly greater influence of one criterion on the mapped variable in comparison to the other criterion. If a factor "i" is assigned a non-zero value (ranging from 1 to 9) in comparison to a factor "j", then the reciprocal value is attributed to "j" when compared to "i" (ranging from 1 to 1/9).

Subsequently, a PCM was formulated according to Saaty's scores previously derived. The PCM was organized by utilizing the $n\times n$ matrix (A) presented in equation **(4)** as follows:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (4)$$

where, a_{ij} is the relative importance of factor i for the targeted variable compared to factor j, and n is the total number of factors.

Within the established square PCM of order 10, the arrangement of matrix columns was determined by organizing the ten criteria in a descending order of their impact on the mapped variable. The arrangement of PCM columns was determined by organizing the ten criteria in a descending order of their impact on the mapped variable. The diagonal scores are set at 1, as each factor was being compared to itself. The remaining entries in each row are populated using the Saaty's scores in situations where a criterion having greater influence is juxtaposed with one of lesser influence, varying from 2 to 7 for flood susceptibility and from 2 to 9 for groundwater recharge. Conversely, when comparing a less influential criterion to a more influential one, the entries are populated with the reciprocal of the corresponding Saaty's scores, varying from 1/7 to 1/2 for flood susceptibility and from 1/9 to 1/2 for groundwater recharge. This reciprocal relation captures the interplay of influence between the two factors and forms an integral part of the AHP's rigorous analytical framework.

The two PCM for FSZ and GWRZ mapping are respectively outlined in Table A3 and Table A4. The prioritization of criteria within the matrix in Table A3 began with SWD due to its pronounced impact on flood susceptibility. Similarly, LI took precedence as the initial parameter in the matrix in Table A4 due to its heightened influence on recharge potential.

3.2.2. Criteria relative weightage

The PCM were normalized using the eigenvector approach (Saaty, 2003). The normalized PCM elements shown in Table A5 and Table A6 were calculated through the division of element values in Table A3 and Table A4 by their respective total column values. A normalized weight was subsequently computed for each criterion by dividing each sum of row values in the normalized PCM by the total criteria count.

3.2.3. Matrix consistency assessment

The paired criteria evaluation within the AHP can lead to potential inconsistencies. Saaty (1980) introduced the consistency ratio (CR) to quantitatively assess how consistent the criteria weighting is. A judgement matrix is considered near consistent, and the weightage is acceptable if the CR value is less than 0.1 (Saaty, 1980, 2003). *CR* is the ratio established by dividing the consistency index by the random consistency index as indicated by equation **(5)**:

$$CR = CI/RI \quad (5)$$

where, *CI* is the consistency index, and *RI* is the random consistency index. The *CI* was calculated using equation **(6)**:

$$CI = (\lambda_{max} - n) / (n - 1) \quad (6)$$

where, n is the total number of criteria, and λ_{max} is the principal eigenvalue.

The principal eigenvalue, measuring the extent to which a matrix deviates from consistency, is equivalent to the total of the eigenvalues associated with the considered factors. For a PCM to be near consistent, its principal eigenvalue must be greater than or equal to the factors count (n). The principal eigenvalues obtained for the two PCM were greater than 10 (Table A7). The *RI* value, obtained from the random index scale (Saaty, 1980), was 1.49. The *CI* values for FSZ and GWRZ mapping PCM were 0.07 and 0.04, respectively, confirming the correct establishment of criteria weights.

3.2.4. Weighted overlay

The FSZ and GWRZ were identified based on respectively the FSZ index and the GWRZ index according to equation **(7)**:

$$ZI = \sum_{i=1}^{n} \sum_{j=1}^{m} W_i \times R_j \quad (7)$$

where, *ZI* is the index based on which the zones are mapped (i.e., GWRZ or FSZ), n is the total count of criteria' layers, m is the total count of layer classes, W_i is the weight of criterion layer i, and R_j is the rating of class j of layer i.

After determining the criteria weights, each thematic layer was reclassified into five classes, ensuring comparability across different scales while preserving designated weights. This reclassification aimed to convert susceptibility criteria into five equivalent units: 5, 4, 3, 2, and 1, representing very high to very low susceptibility. Similarly, recharge potential factors were grouped into five categories: 5, 4, 3, 2, and 1, indicating very good to very low recharge potential. Subsequently, the raster calculator tool in QGIS was used to multiply each reclassified layer by its weight, generating FSZ and GWRZ maps.

3.3. Sensitivity analysis and mapping validation

MCDM approaches, including the AHP, are valuable tools for evaluating complex problems involving multiple factors. However, these methods are susceptible to uncertainties, primarily due to data availability and expert opinion for factor selection and weight assignment (Amineh et al., 2017; Azareh et al., 2021). To address this, we conducted a sensitivity analysis, which provides insight into the extent of influence exerted by every factor on the resulting map (Akay, 2021; Gandhi and Patel, 2022). In this study, a Map Removal Sensitivity Analysis (MRSA) was performed on the GWRZ and FSZ indices. MRSA aims to assess input factors sensitivity by systematically removing one or multiple input layers during suitability analysis (Lodwick et al., 1990). We conducted two types of analyses. First, one layer was eliminated at a time to evaluate the outputs sensitivity to the removal of a defined criterion. Second, each ensemble of criteria from the same category was removed one at a time allowing the assessment of the influence of topographical, hydrological, environmental, and anthropological criteria on the final maps. The sensitivity analysis index was computed using equation **(8)**:

$$SI = \left(\left| \frac{ZI}{n} - \frac{ZI'}{n'} \right| \Big/ ZI \right) \times 100 \quad (8)$$

where, *SI* is the sensitivity index in %, *ZI* and ZI' are the indices based on which the zones are mapped for all thematic layers and when one layer or more is removed, n is the total count of thematic layers used for *ZI* computation (*FSZ* or *GWRZ*), and is the count of thematic layers employed for ZI' computation (FSZ' or $GWRZ'$).

The GWRZ map was validated by superposing existing passive recharge wells' locations derived from the Schlumberger Water Services report (SWS, 2009) on it and assessing their zonal correspondence. Due to a lack in flood-related data, inconsistency index assessment and sensitivity analysis were used to verify the FSZ map accuracy.

3.4. Floodwater-based recharge suitability mapping

The floodwater-based recharge suitable zones (FRSZ) map was generated based on an overlay analysis of the validated FSZ and GWRZ maps. The raster pixels of the FSZ map were assigned the values 1, 2, 3, and 4 respectively corresponding to low, medium, high, and very high susceptibility classes. Similarly, the raster pixels of the GWRZ map were assigned the values 1, 2, 3, and 4 with respect to poor, moderate, good, and very good recharge potential classes.

We multiplied the two generated rasters using QGIS's raster calculator tool to obtain a raster with values ranging from 1 to 16 (i.e., 1, 2, 3, 4, 6, 8, 9, 12, and 16), which we reclassified into the following floodwater recharge suitability classes: low (≤4), medium (4–6), high (6–9), very high (9–12), and excellent (>12) as shown in Fig. 5. Further, we identified pixels that simultaneously have the value 2 (medium or moderate) in the FSZ and GWRZ maps. These pixels were afterwards included in the medium class of the FRSZ map (by assigning to them a value of 6 or 8).

4. Results and discussion

4.1. Influential criteria evaluation

In this work, ten influential criteria were selected for mapping FSZ and GWRZ, namely elevation, slope, lineament density, drainage density, rainfall, lithology, soil types, NDVI, land use/land cover, and stormwater drainage system density. The significance of a criterion's contribution to either flood susceptibility or groundwater recharge zonation is indicated by its assigned weight. Greater weight is assigned to the most influential factor. Ten criteria thematic layers have been prepared as shown in Fig. 6 and assigned their relative weights as highlighted in Table 3.

Based on the analysis of the SRTM DEM, our study region's elevation ranges from 0 m to approximately 94 m a.s.l. The EL map was classified into five classes: very low (≤19 m), low (19–38 m), moderate (38–56 m), high (56–75 m), and very high (>75 m) (Fig. 6a). Higher elevations were accorded lower weights for flood susceptibility and higher weights for recharge potential. Gentle slopes dominate Qatar. Gentle slopes dominate our study area. Five main slope gradient classes were identified (Fig. 6b): very low (≤2%), low (2–6%), moderate (6–12%), high (12–18%), and very high (>18%). For both FSZ and GWRZ, higher slope areas were assigned weaker weights. The frequency value in the LD map varies between 0 and over 2 km/km^2. Our study region was categorized into very low (0–0.5 km/km^2), low (0.5–1 km/km^2), moderate (1–1.5 km/km^2), high (1.5–2 km/km^2), and very high (>2 km/km^2) LD classes (Fig. 6c). These classes were weighted according to the logic that groundwater recharge and flood susceptibility are proportional and inversely proportional to LD, respectively.

The DD map is illustrated in Fig. 6d, classified into very low (0–0.5 km/km^2), low (0.5–1 km/km^2), moderate (1–1.5 km/km^2), high (1.5–2 km/km^2), and very high (>2 km/km^2) density classes. DEM analysis has provided a significant understanding of runoff pathways. The RN map is shown in Fig. 6e. The average annual rainfall ranges from about 60 mm in southern Qatar to about 87 mm in its north. The RN layer was classified into very low (≤65 mm/year), low (65–70 mm/year), moderate (70–75 mm/year), high (65–70 mm/year), and very high (>80 mm/year) classes. Extreme rainfall events exhibited comparable spatial distribution (SWS, 2009). For both FSZ and GWRZ mapping, high RN classes were assigned high weights.

Our study region has five lithological classes (Fig. 6f) including the formations Eocene Rus, Eocene Dammam, Miocene Dam, Miocene/Pliocene Hofuf, and Quaternary deposits. Approximately 2% of the study area (mainly located southeastern the peninsula) were excluded from the mapping because of absence of geological (and thus lithological) data in those areas. The Quaternary deposits (mostly sandy sediments) are highly porous and permeable, followed by Rus (limestone and dolomite), Hofuf (continental gravel, sand, and conglomerate), and Dammam (dolomite and limestone). The Rus Formation is more permeable than Dammam Formation, while the Dam Formation (calcareous sediments and gypsum) has the lowest permeability (Baalousha, 2016b). Qatar's soil types (Fig. 6g) are Calcic Yermosols (loamy soils with calcium carbonate accumulation), Calcaric Regosols (loamy-sand texture), Lithosols (loamy soils with shallow hard rock), Gleyic Solonchaks (high moisture content and clayey texture), and a small proportion of Orthic Solonchaks (saline clayey soils) (FAO, 1988; Mahmoud and Gan, 2018). The SL criterion was given low weight due to low data resolution compared to other criteria. Higher-resolution field-based soil data and additional soil attributes can enhance the study (Pradhan et al., 2023). Qatar, being a desertic region, features sparse vegetation covering only small portions of its surface (Rousta et al., 2022). This primarily includes agricultural lands in the northern areas, irrigated grasslands, along with wild plants such as herbaceous plants, shrubs, and some tree species (Yasseen and Al-Thani, 2013). The prepared NDVI layer was classified into five groups (Fig. 6h): very low (≤0), low (0–0.1), moderate (0.1–0.2), high (0.2–0.3), and very high (>0.3). High NDVI classes were assigned lower weights for flood susceptibility and higher weights for recharge potential.

Five main LULC classes can be distinguished for our case study (Fig. 6i): bare ground, built-up area, scrub/shrub, water bodies, and crops. Built-up areas were assigned the highest weight and the weakest weight in FSZ and GWRZ mapping, respectively. Bare ground was

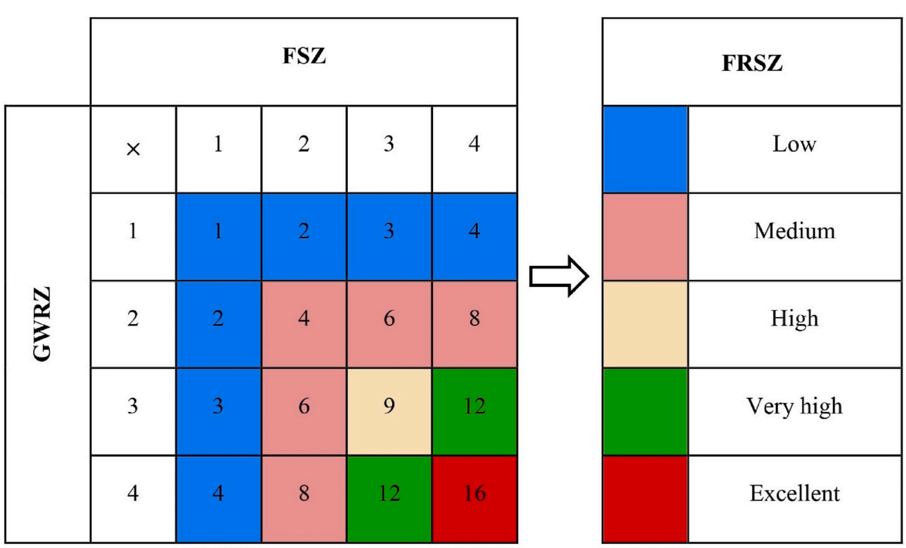

Fig. 5. Computation of floodwater-based recharge zones (FRSZ) based on the multiplication of flood susceptible zones (FSZ) and potential groundwater recharge zones (GWRZ).

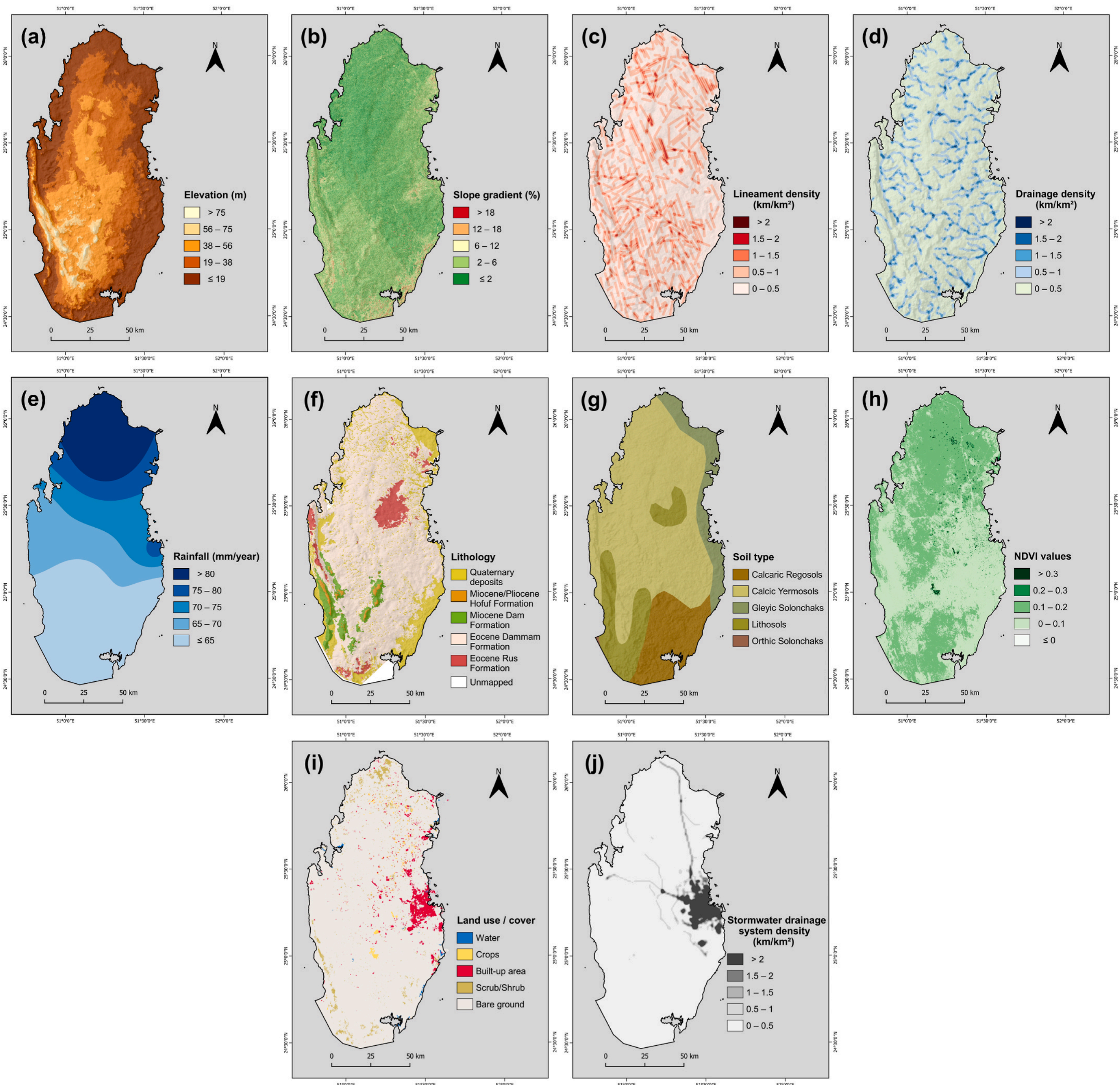

Fig. 6. Thematic input maps for the GIS-AHP mapping of flood susceptibility and groundwater recharge: **(a)** elevation, **(b)** slope gradient, **(c)** lineament density, **(d)** drainage density, **(e)** rainfall, **(f)** lithology, **(g)** soil type, **(h)** NDVI, **(i)** land use/land cover, and **(j)** stormwater drainage system density.

assigned a moderate weight. The crops class was strongly weighted for recharge potential and weakly weighted for flood susceptibility. The SWD factor is mapped in Fig. 6j and categorized into very low (0–0.5), low (0.5–1), moderate (1–1.5), high (1.5–2), and very high (>2) classes. The stormwater drainage system has the greatest influence on flood susceptibility (Ajjur and Mogheir, 2020). Therefore, SWD was attributed the highest weight in FSZ mapping.

4.2. Flood susceptibility map

The flood susceptible zones (FSZ) map of Qatar was established based on the interactive influence of ten influential topographical, hydrological, environmental, and anthropological factors. Stormwater drainage system density emerges as a pivotal element, carrying the highest weight score of 22%, followed by land use/land cover, elevation, slope, lithology, drainage density, rainfall, lineament density, soil type, and NDVI, with weight scores of 19%, 17%, 11%, 9%, 7%, 6%, 4%, 3%, and 2%, respectively. The FSZ was computed by considering the weights and rates assigned to the thematic layers, as outlined in equation **(9)**:

$$FSZ = 0.22 \times SWD + 0.19 \times LULC + 0.17 \times EL + 0.11 \times SLO + 0.09 \times LI + 0.07 \times DD + 0.06 \times RN + 0.04 \times LD + 0.03 \times SL + 0.02 \times NDVI \quad (9)$$

where, *SWD* is stormwater drainage system density, *LULC* is land use/land cover, *EL* is elevation, *SLO* is slope, *LI* is lithology, *DD* is drainage density, *RN* is rainfall, *LD* is lineament density, *SL* is soil type, and *NDVI* is Normalized Difference Vegetation Index.

Table 3
Criteria-assigned ratings and weights for flood susceptibility and groundwater recharge potential using AHP.

Criteria	Class	Area in km^2 (%)	Flood susceptibility				Groundwater recharge potential			
			Rank	Weight	Weighted ranking	Total weight	Rank	Weight	Weighted ranking	Total weight
Elevation (m)	>75	61.96 (0.54)	1	0.17	0.17	2.55	1	0.12	0.12	1.80
	56–75	587.08 (5.05)	2		0.34		2		0.24	
	38–56	2712.11 (23.35)	3		0.51		3		0.36	
	19–38	3419.69 (29.44)	4		0.68		4		0.48	
	≤19	4834.59 (41.62)	5		0.85		5		0.60	
Slope gradient (%)	>18	46.38 (0.40)	1	0.11	0.55	1.65	1	0.15	0.15	2.25
	12–18	132.73 (1.15)	2		0.44		2		0.30	
	6–12	1115.04 (9.63)	3		0.33		3		0.45	
	2–6	6431.52 (55.54)	4		0.22		4		0.60	
	≤2	3853.23 (33.28)	5		0.11		5		0.75	
Lineament density (km/km^2)	>2	1.66 (0.01)	1	0.04	0.04	0.60	5	0.08	0.40	1.20
	1.5–2	75.43 (0.65)	2		0.08		4		0.32	
	1–1.5	645.03 (5.55)	3		0.12		3		0.24	
	0.5–1	4358.89 (37.53)	4		0.16		2		0.16	
	0–0.5	6534.84 (56.26)	5		0.20		1		0.08	
Drainage density (km/km^2)	>2	12.10 (0.10)	5	0.07	0.35	1.05	1	0.03	0.03	0.45
	1.5–2	158.83 (1.37)	4		0.28		2		0.06	
	1–1.5	714.04 (6.15)	3		0.21		3		0.09	
	0.5–1	2306.94 (19.86)	2		0.14		4		0.12	
	0–0.5	8423.81 (72.52)	1		0.07		5		0.15	
Rainfall (mm/year)	>80	2194.92 (18.90)	5	0.06	0.30	0.90	5	0.05	0.25	0.75
	65–70	1117.82 (9.62)	4		0.24		4		0.20	
	70–75	1638.88 (14.11)	3		0.18		3		0.15	
	65–70	2286.20 (19.68)	2		0.12		2		0.10	
	≤65	4378.15 (37.69)	1		0.06		1		0.05	
Lithology	Quaternary deposits	2416.30 (20.80)	1	0.09	0.09	1.35	5	0.30	1.50	4.50
	Miocene/Pliocene Hofuf Formation	64.21 (0.55)	3		0.27		3		0.90	
	Miocene Dam Formation	417.98 (3.60)	5		0.45		1		0.30	
	Eocene Dammam Formation	7956.40 (68.50)	4		0.36		2		0.60	
	Eocene Rus Formation	514.46 (4.43)	2		0.18		4		1.20	
Soil type	Calcaric Regosols	1709.71 (14.72)	1	0.03	0.03	0.45	5	0.02	0.10	0.30
	Calcic Yermosols	7100.68 (61.13)	2		0.06		4		0.08	
	Gleyic Solonchaks	1129.06 (9.72)	5		0.15		1		0.02	
	Lithosols	1668.55 (14.36)	3		0.09		3		0.06	
	Orthic Solonchaks	7.71 (0.07)	4		0.12		2		0.04	
NDVI	>0.3	54.23 (0.47)	1	0.02	0.02	0.30	5	0.02	0.10	0.30
	0.2–0.3	77.18 (0.66)	2		0.04		4		0.08	
	0.1–0.2	5673.95 (48.83)	3		0.06		3		0.06	
	0–0.1	5770.20 (49.67)	4		0.08		2		0.04	
	≤0	42.56 (0.37)	5		0.10		1		0.02	
Land use/land cover	Water	81.42 (0.70)	1	0.19	0.19	2.85	5	0.22	1.10	3.30
	Crops	74.55 (0.64)	2		0.38		4		0.88	
	Built-up area	440.05 (3.77)	5		0.95		1		0.22	
	Scrub/Shrub	340.15 (2.92)	3		0.57		3		0.66	
	Bare ground	10,718.01 (91.97)	4		0.76		2		0.44	
Stormwater drainage system density	>2	414.84 (3.57)	1	0.22	0.22	3.30	1	0.01	0.01	0.15
	1.5–2	89.59 (0.78)	2		0.44		2		0.02	
	1–1.5	174.80 (1.50)	3		0.66		3		0.03	
	0.5–1	383.67 (3.30)	4		0.88		4		0.04	
	0–0.5	10,553.12 (90.85)	5		1.10		5		0.05	

The FSZ map is presented in Fig. 7. The Qatar peninsula has 2172.35 km^2 (18.77% of the total area) of very high FSZ, primarily located in the less developed northern sector alongside urban zones lacking stormwater drainage networks such as the inhabited northern parts of Al Wakrah municipality. In an endeavor by Serdar et al. (2022), a flood susceptibility spatial assessment of Qatar founded on five key criteria also emphasized a robust correlation between flood susceptibility and urban areas. Extensive high FSZ, encompassing 4567.96 km^2 (39.46%), are disseminated across our study area because of the predominantly flat topography of Qatar, limited vegetation coverage, and the absence of drainage systems. Moderate FSZ, spanning an area of 3409.52 km^2 (29.46%), are concentrated in the southern part, encompassing the Dukhan area, Al Rayyan municipality in the central southern zone, and the far southeastern part of Qatar. The low FSZ (10.26% of the study area; 1187.37 km^2) are situated in the Doha metropolitan area benefitting from the presence of stormwater drainage systems, and areas with relatively high elevations and steep slopes.

Lack of information on the storm and flood events in Qatar restrict the country-wise FSZ verification process. Table A9 provides details on past and recent flood events reported for Qatar. The recorded events focused primarily on populated urban areas where the flood risk was assessed rather than the hazard, notably Doha (Jafari and Bernardeau, 2019; Jones and Kelly, 2019). Furthermore, the stormwater drainage system in urban areas was introduced only recently after witnessing the impacts of recent floods (Al Mamoon, 2020).

The FSZ map serves as a fundamental input for floodwater-based recharge suitability mapping. However, its utility extends beyond this application. A FSZ map can guide informed decision-making, risk reduction, and disaster preparedness as highlighted by Al-Juaidi (2023). The recent catastrophic flood in Libya underscores the pressing imperative to enhance readiness in the face of increasingly frequent and severe extreme weather events (Marshall, 2023). This emphasizes the importance of bolstering preventative measures and fortifying emergency response capabilities. By pinpointing high-risk zones and facilitating proactive measures, these maps support resilience and guide land use planning. Several measures can be suggested for flood-prone zones including implementing sustainable drainage systems that mimic natural processes to better manage surface water runoff, encouraging the implementation of green infrastructure to reduce runoff, regulating land use to prevent development in flood susceptible areas, and investing in flood resilient infrastructure.

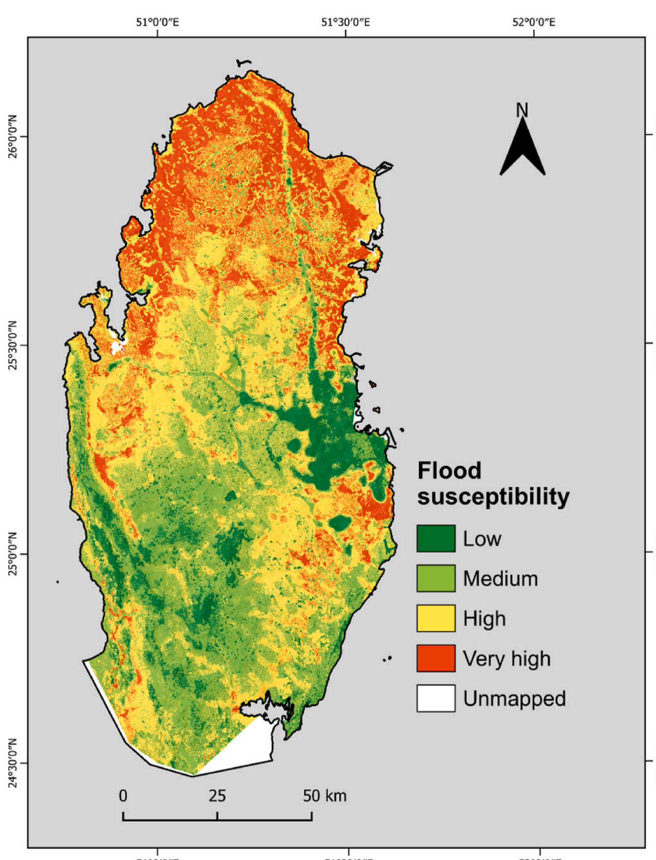

Fig. 7. Flood suitability map of Qatar based on GIS-AHP mapping.

Flood susceptibility is intricately linked to spatial as well as temporal dimensions (Azareh et al., 2021; Khosravi et al., 2019). The absence of temporal evaluation in this study is attributable to data limitations and the aim of spatially analyzing flood susceptibility. Furthermore, a significant number of the considered factors (EL, SLO, LD, DD, LI, and SL) exhibit temporal constancy or undergo changes only over extended intervals. Nevertheless, using real-time datasets for some factors (RN, NDVI, LULC, and SWD) demonstrating noteworthy short-term changes can reduce uncertainties. Additionally, incorporating supplementary elements that exert influence on flooding and display temporal variability, such as groundwater levels and soil moisture data, holds merit. Moreover, since this approach lacks insights into flood depth or velocity, it is advisable that future research integrates hydraulic modeling for improved accuracy and comprehensiveness.

4.3. Groundwater recharge zones map

The groundwater recharge zones (GWRZ) map of Qatar was established considering the combined impact of ten governing criteria. Lithology emerges as a pivotal element, being assigned the highest weight score (30%), followed by land use/land cover, slope, elevation, lineament density, rainfall, drainage density, soil type, NDVI, and stormwater drainage system density with weight scores of 22%, 15%, 12%, 8%, 5%, 3%, 2%, 2%, and 1%, respectively. The delineation of GWRZ involved the assessment of rates and weights attributed to the criteria layers, as described in equation **(10)**:

$$GWRZ = 0.30 \times LI + 0.22 \times LULC + 0.15 \times SLO + 0.12 \times EL + 0.08 \times LD + 0.05 \times RN + 0.03 \times DD + 0.02 \times SL + 0.02 \times NDVI + 0.01 \times SWD \quad (10)$$

where, *LI* is lithology, *LULC* is land use/land cover, *SLO* is slope, *EL* is elevation, *LD* is lineament density, *RN* is rainfall, *DD* is drainage density, *SL* is soil type, *NDVI* is Normalized Difference Vegetation Index, and *SWD* is stormwater drainage system density.

The GWRZ map is shown in Fig. 8a. Approximately 20.02% of the study area (2317.09 km^2) qualifies as very good GWRZ, positioned within the depressions dotting Qatar's landscape especially to the north, the Rus Formation outcroppings especially when combined with high lineament density, and permeable soils particularly along coasts. Comprising roughly 18.51% of the land extent (2142.75 km^2), the good GWRZ are concentrated in northern Qatar with favorable lithology, slopes, rainfall, and vegetation cover conditions. This finding aligns with Mohieldeen et al. (2021)'s results. The authors proposed a plan for large-scale artificial aquifer recharge by freshwater in Qatar. The identified recharge regions in their study were located northern of the country where they judged climate and geologic layers as most favorable for both recharging and storing rainfall. In this study, moderate GWRZ, constitute 36.50% of the study area (4224.61 km^2). Poor GWRZ span roughly 22.92% of the study area (2653.08 km^2). These zones with reduced groundwater recharge potential are dominant in urban areas characterized by impervious surfaces alongside with the country's southern part where elevation reaches its highest values, steeper slopes are experienced, coupled with relatively limited rainfall.

In Qatar, there are 313 documented recharge wells in total, which are gravity-based and passive in nature, with no active injection involved (Al-Muraikhi and Shamrukh, 2017; SWS, 2009). Among these,

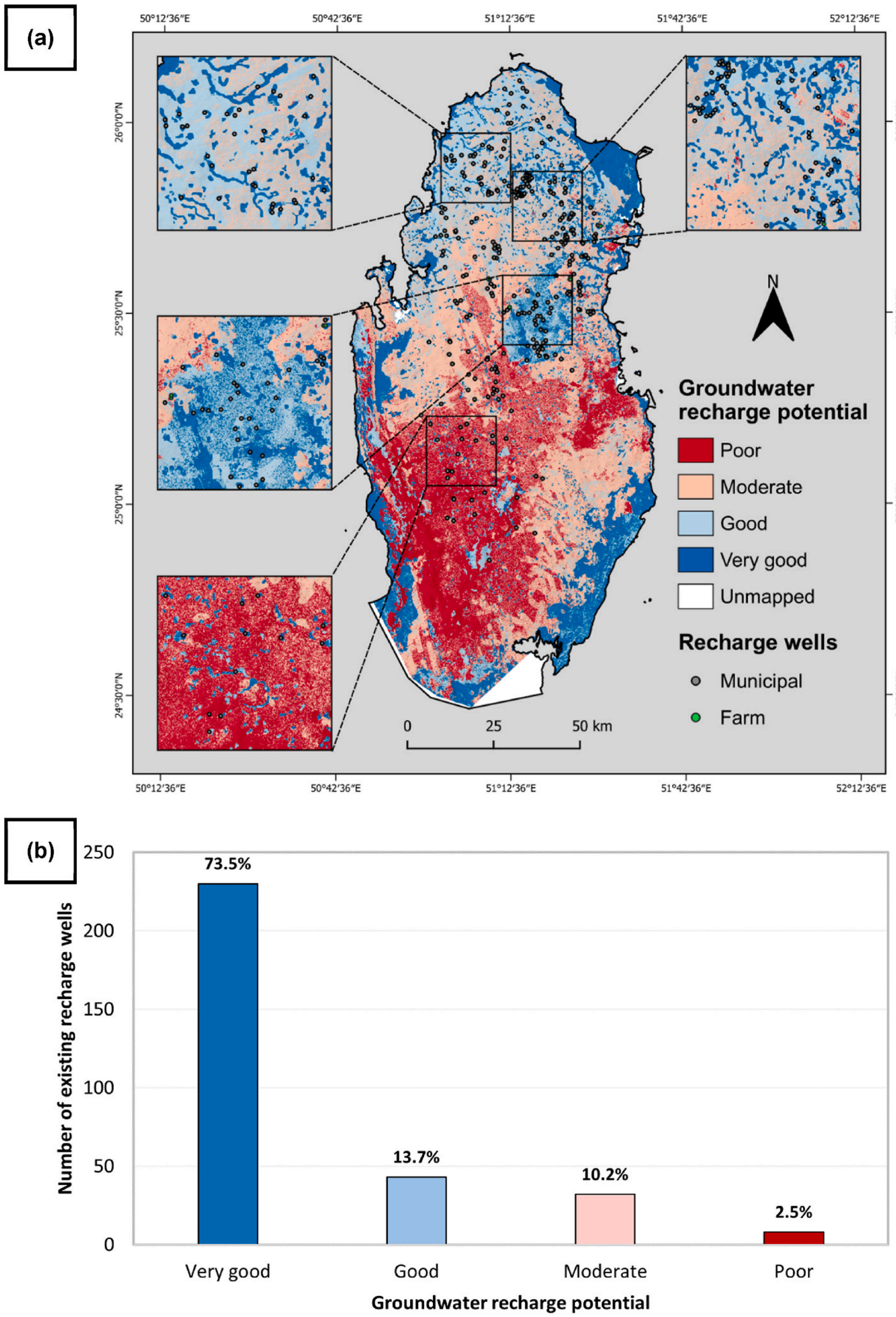

Fig. 8. (a) Potential groundwater recharge zones of Qatar based on GIS-AHP mapping validated using existing recharge wells' locations, and **(b)** distribution of the existing recharge wells according to their location within the different delineated recharge zones.

166 wells are situated within depressions and 147 wells are positioned outside depressions, such as *wadis*' trajectories. Most of these wells lie in Qatar's northern region, attributed to greater rainfall frequency and lower groundwater salinity. The locations of these wells were derived from the Schlumberger Water Services report (SWS, 2009) and used to validate the GWRZ map (Fig. 8a). As illustrated by Figs. 8b and 230 (73.5%), 43 (13.7%), 32 (10.2%), and 8 (2.5%) of the existing recharge wells fall within the very good, good, moderate, and poor GWRZ, respectively.

While the developed GWRZ map primarily serves as a basis for mapping recharge suitability using floodwater, its applicability extends beyond this scope. Qatar has been developing experimental MAR projects to investigate the potential of the technique (Ajjur and Baalousha, 2021; Al-Muraikhi and Shamrukh, 2017). This map can effectively assist planners and decision-makers in identifying suitable areas for various artificial recharge forms, notably using reclaimed wastewater and desalinated water. Previous recharge zones identifications in Qatar were mainly based on depressions' delineation, geology, and climate (Baalousha, 2015; Mohieldeen et al., 2021; SWS, 2009), whereas our work integrates several additional factors. Furthermore, the identified favorable zones can be protected areas and/or serve as the location for additional passive wells, particularly in low-lying depressions, to enhance natural rainfall infiltration and mitigate seawater intrusion as recommended by SWS (2009). Therefore, the GWRZ map forms a strategic asset for sustainable groundwater management, optimized land use planning, and holistic development, fostering water resilience in Qatar. Incorporating additional criteria related to groundwater recharge, such as geomorphology, groundwater depth or level, aquifer transmissivity, and groundwater quality can further enhance our results (Khan et al., 2020; Ravichandran et al., 2022).

4.4. Sensitivity analysis results

We conducted a sensitivity analysis to assess the final maps sensitivity to the various factors. The statistics of MRSA for individual layer removal are presented in Table 4. Sequentially removing individual layers did not reveal a substantial variation in the FSZ and GWRZ indices, as the criteria variation indices consistently exhibited values that were in proximity to one another. However, the removal of SWD and LULC from FSZ computation resulted in relatively high SI_{MV} values (2.06% and 1.72%). Similarly, relatively high SI_{MV} values were generated when removing LI (1.92%) and SLO (1.42%) from GWRZ computation. These results can be explained by the significant theoretical weights assigned to SWD (22%) and LULC (19%) in FSZ mapping, and LI (30%) and SLO (15%) in GWRZ mapping.

The second analysis revealed a bias in the resulting mapping outputs based on the criteria category. The MRSA statistics for the removal of maps ensembles are reported in Table 5. Both GWRZ and FSZ were sensitive to removing topographical layers with respective SI_{MV} of 3.83% and 2.52% as these criteria were assigned high theoretical weights. Furthermore, the FSZ index showed high sensitivity to removing anthropological factors (SIMV of 4.31%), mainly due to significant weights assigned to SWD (22%) and LULC (19%). On the other hand, the GWRZ index displayed greater sensitivity to environmental criteria removal as indicated by an SI_{MV} value of 2.42%. This aligns with the influence of geological composition on groundwater recharge, reflected by the high weight attributed to LI (30%) in the GWRZ mapping. Minimal sensitivities were observed when excluding hydrological criteria for both FSZ (SI_{MV} of 0.40%) and GWRZ (SI_{MV} of 0.47%), considering Qatar's limited rainfall and surface water.

4.5. Suitable zones for aquifer recharge using floodwater

Groundwater recharge using floodwater is a nature-based solution aimed at enhancing water supply reliability and improving groundwater resources. The value of GIS and remote sensing methods in assessing the spatial suitability for recharge using floodwater has been underscored by several researchers. Alesheikh et al. (2008) proposed a GIS-integrated approach to locate flood-spreading sites in the Samal sub-basin (Iran) considering factors pertaining to earth sciences and hydrology. Mahmoud and Alazba (2016) applied a GIS-based methodology for mapping flood management and artificial recharge in Al-Riyadh region, Saudi Arabia. Nohegar et al. (2016) applied a GIS-based network process analysis (ANP), incorporating nine factors, to delineate flood-prone zones and propose structures for flood spreading. Similarly, Naghibi et al. (2020) employed three models to map suitability in Iran's Mashhad plain watershed, exemplifying artificial recharge technique suitability in arid regions. Lentini et al. (2022) introduced a GIS-based method for stormwater flooding mitigation using drainage systems and aquifer recharge in Rome, emphasizing hydrogeological influences.

In this study, the overlay of FSZ and GWRZ maps resulted in the floodwater-based groundwater recharge suitability map of Qatar (Fig. 9). Although only constituting 1.34% (154.74 km^2) of the study area, the excellent FRSZ represent prime locations floodwater-based groundwater recharge, encompassing both the very high FSZ and GWRZ. Predominantly situated in the northeastern coastal region, they are accompanied by scattered small sites. Notably, most of these optimal sites are near industrial zones, necessitating judicious consideration for recharge initiatives. The very high FRSZ, encompassing 20.58% (2382.34 km^2) of Qatar's surface, are concentrated in the north, including regions like Al Ruwais, Al'Arish, Al Zubara, and Ras Eshairij. This aligns with most groundwater extraction locations and declining groundwater levels (Fig. 2). Additionally, the very high FRSZ comprises scattered sites like Umm Wadi near Dukhan and coastal areas such as Abu Samra and Shaqra'. Covering approximately 15.90% (1840.05 km^2) of total region, the high FRSZ are dispersed throughout the landscape. The medium FRSZ, encompassing around 26.14% (3025.68 km^2) of the study area, assume significant importance. The low FRSZ (3934.51 km^2; 33.99%) are prevalent in urban areas such as Doha, and the southern regions.

The methodology employed in our study offers valuable insights into identifying suitable sites for integrated aquifer recharge and flood control in Qatar. However, several limitations exist in our approach. Firstly, the lack of a universally agreed-upon set of factors for such studies introduces uncertainty and subjectivity into the analysis. Establishing standardized protocols or contextual guidelines for conducting similar studies could help mitigate this issue and improve the consistency and comparability of future research efforts. Secondly, while our study considers ten influential criteria for mapping FSZ and GWRZ, it is important to recognize that additional factors and better data resolution could further refine the analysis. Furthermore, one of the notable limitations of our method is the absence of the temporal dimension in the analysis. Incorporating temporal aspects could enhance the accuracy and reliability of our predictions. Moreover, the lack of comprehensive validation data poses a challenge in assessing the accuracy of our methodology.

The robustness of the FRSZ map can be further fortified through validation via fieldwork, integration of more influential factors, and higher-quality data (Itani et al., 2022; Marwaha et al., 2021). Exploring diverse mapping techniques could optimize our modeling efforts (Naghibi et al., 2020). The integration of real-world floodwater quantities is recommended. Additional research is also needed to delve into climate projections and weather forecasting. Integrating our results with numerical modeling will allow simulating groundwater level fluctuations under different recharge scenarios (Javadi et al., 2021; Perzan et al., 2023). Furthermore, proper monitoring of groundwater levels and quality is also crucial to assess the lasting effects of flash floods on groundwater recharge rates (Tariq et al., 2023). Future research can focus on local-scale, high-resolution suitability analysis, building upon these preliminary results.

4.6. Recommended considerations

This study's core objective is to identify suitable zones for potential floodwater-based groundwater recharge in Qatar. While benefiting from flood events to replenish groundwater resources holds promise for integrated water management, its successful implementation demands

Table 4
Results of single map removal sensitivity analysis.

Removed criteria [a]	Sensitivity analysis index (SI; %)							
	Minimum		Maximum		Mean variation index (SI_{MV})		Standard deviation (Sd)	
	FS [b]	GR [c]	FS	GR	FS	GR	FS	GR
EL	0.00	0.00	3.14	2.42	0.96	0.83	0.44	0.39
SLO	0.00	0.00	1.69	3.23	0.30	1.42	0.17	0.49
LD	0.46	0.00	1.01	0.91	0.93	0.63	0.08	0.21
DD	0.00	0.34	0.94	1.04	0.82	0.95	0.14	0.08
RN	0.01	0.00	0.96	0.98	0.66	0.62	0.26	0.28
LI	0.00	0.08	0.88	5.50	0.26	1.92	0.31	0.95
SL	0.36	0.29	1.03	1.06	0.90	0.81	0.09	0.10
NDVI	0.61	0.59	1.06	1.06	0.90	0.91	0.04	0.05
LULC	0.00	0.00	2.83	3.29	1.72	0.68	0.26	0.32
SWD	0.00	0.70	3.86	1.09	2.06	0.92	0.47	0.04

[a] **EL**, elevation; **SLO**, slope; **LD**, lineament density; **DD**, drainage density; **RN**, rainfall; **LI**, lithology; **SL**, soil type; and **NDVI**, Normalized Difference Vegetation Index; **LULC**, land use/land cover; and **SWD**, stormwater drainage system density.
[b] **FS**, flood susceptibility.
[c] **GR**, groundwater recharge potential.

Table 5
Results of map ensemble removal sensitivity analysis.

Removed criteria ensemble [a]	Sensitivity analysis index (SI; %)							
	Minimum		Maximum		Mean variation index (SI_{MV})		Standard deviation (Sd)	
	FS [b]	GR [c]	FS	GR	FS	GR	FS	GR
Topographical (**EL**; **SLO**; **LD**)	0.13	0.43	5.61	5.79	2.52	3.83	0.44	0.66
Hydrological (**DD**; **RN**)	0.00	0.00	0.77	0.91	0.40	0.47	0.24	0.26
Environmental (**LI**; **SL**; **NDVI**)	0.00	0.59	1.61	5.94	0.37	2.42	0.16	0.89
Anthropological (**LULC**; **SWD**)	0.57	0.00	6.93	3.54	4.31	0.87	0.53	0.36

[a] **EL**, elevation; **SLO**, slope; **LD**, lineament density; **DD**, drainage density; **RN**, rainfall; **LI**, lithology; **SL**, soil type; and **NDVI**, Normalized Difference Vegetation Index; **LULC**, land use/land cover; and **SWD**, stormwater drainage system density.
[b] **FS**, flood susceptibility.
[c] **GR**, groundwater recharge potential.

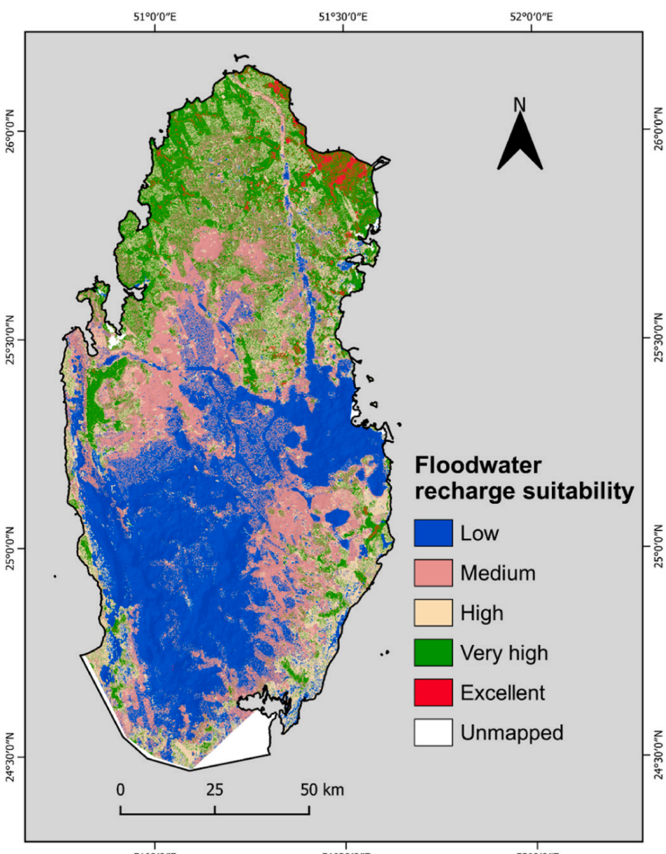

Fig. 9. Floodwater-based groundwater recharge suitability map of Qatar.

meticulous planning, stakeholder coordination, and technical insights (Jacobson, 2019; Pavelic et al., 2021). The water quality, land use compatibility, environmental impacts, and socioeconomic aspects must be addressed.

The technical considerations comprise selecting optimal recharge methods, ensuring water quality, and conducting field trials. In arid regions like Qatar, methods minimizing evaporation losses, such as injection wells and galleries, may be preferred. Recharge by injection can rapidly yield positive results as highlighted by Ríos et al. (2023). However, managing water quality during injection is crucial. Although a significant amount of water may be lost to evaporation, spreading basins are less technically complex and involve less concern regarding surface water quality as it relies on the soil's natural infiltration capacity. Alternatively, recharge trenches can be effective in arid regions because they allow quick water infiltration.

When considering floodwater-based artificial recharge, regular comprehensive water quality monitoring before and after injection is necessary (Pavelic et al., 2021). Floodwater injection can lead to substantial microbial contamination of drinking well water (Masciopinto et al., 2019). The recharge water quality is crucial for depth techniques as variations in control parameters may lead to intricate contamination issues. In-depth understanding of the recharge water composition is essential to prevent adverse physicochemical interactions, clogging, or bacterial growth in injection wells (Ríos et al., 2023). Additional data concerning water usage can enhance the quality analysis (Hayat et al., 2021). Biophysical and ecological indicators also must be monitored, particularly involving periodic inspections for vegetation health (Kaarakka et al., 2019). The occurrence of root zone waterlogging can lead to diminished aeration, decreased bacterial activity, and heightened susceptibility of plants to diseases (Alam et al., 2020). An additional important technical consideration is conducting on-site field trials to validate model outcomes and assess the practical viability of different recharge methods. Previously, Streetly and Kotoub (1998) described a hydrogeological investigation aiming at assessing the feasibility of large-scale recharge plans which included field testing and the modeling of two aquifers, namely Rus and Umm er Radhuma, at four sites. The MoE also conducted injection testing across Qatar to gather information on the performance of recharge wells and to obtain hydraulic data necessary for supporting studies on aquifer recharge (SWS, 2009). Such initiatives are highly recommended.

An in-depth examination of costs related to infrastructure, transportation, storage, treatment, and facilities is necessary. This assessment should be made in relation to potential advantages, such as flood mitigation, water supply resilience, and subsidence control (Vanegas-Espinosa et al., 2022; Yang and Scanlon, 2019). Furthermore, funding mechanisms must be explored to support the implementation of recharge projects. The long-term economic viability of these projects must be assessed by considering potential return on investment, benefits duration, and changing hydrological conditions' financial impact. Collaboration with regulatory bodies to adapt or create regulations, tailored guidelines for floodwater-based groundwater recharge methods, and clear legal frameworks promoting stakeholder engagement and alignment with water management policies, land use strategies, and ecosystem management objectives are essential (Jacobson, 2019). In conclusion, the successful implementation of floodwater-based groundwater recharge in Qatar necessitates a holistic approach that integrates meticulous technical planning, economic viability assessments, and robust regulatory frameworks.

5. Conclusions

In this study, we have identified zones within Qatar where strategic management interventions can transform water hazards, specifically floodwaters, into valuable groundwater resources. Recognizing the intricate interplay of various factors driving both flooding and groundwater recharge, we applied a geospatially integrated Analytic Hierarchy Process (AHP) framework to proceed. This framework, driven by ten influential criteria, allowed us to map flood susceptibility, delineate groundwater recharge zones, and ultimately assess the spatial suitability of floodwater-based recharge in Qatar. To ensure the robustness of our approach, we conducted consistency tests, sensitivity analyses, and leveraged information from recent flood events, as well as existing recharge well data. The study, encompassing about 98% of the entire country's surface, yielded the following outcomes.

1. The identification of flood-prone areas within Qatar was accomplished, providing a framework for prioritizing strategic flood control measures and reducing flood-risk. About 18.8%, 39.5%, 29.5%, and 10.3% of the study area respectively present very high, high, moderate, and poor flood susceptibility.
2. The delineation of zones across Qatar suitable for effective aquifer recharge was achieved, with approximately 20%, 18.5%, 36.5%, and 23% of the study area presenting very high, high, moderate, and poor recharge potential, respectively.
3. The findings emphasize Qatar's substantial potential to harness floodwater for groundwater recharge and provide a delineation of suitable sites for floodwater-based recharge across the country. Approximately 1.3%, 20.6%, 15.9%, 26.1%, and 34% of the Qatar peninsula respectively present excellent, very high, high, medium, and poor suitability for aquifer recharge using floodwater.
4. The study effectively demonstrated the cost-effective and efficient use of GIS-Multi-Criteria Decision-Making (MCDM) for geospatial suitability mapping.

Our approach provides valuable insights into identifying suitable sites for integrated aquifer recharge and flood control in Qatar. The methodology's adaptability lends itself to replication in analogous regions facing comparable challenges. Moving forward, research efforts should prioritize expanding criteria considerations, incorporating temporal dynamics, validating and continuously updating and refining mapping outputs, and enhancing methodology robustness to improve decision support in water resource management and risk reduction initiatives. Additionally, careful technical planning, economic assessments, and strong regulatory frameworks are crucial for ensuring the successful and sustainable implementation of the proposed solution.

CRediT authorship contribution statement

Sarra Aloui: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft. **Adel Zghibi:** Conceptualization, Data curation, Methodology, Supervision, Validation, Writing – review & editing. **Annamaria Mazzoni:** Methodology, Supervision, Visualization, Writing – review & editing. **Adel Elomri:** Conceptualization, Funding acquisition, Project administration, Resources, Validation, Writing – review & editing. **Tareq Al-Ansari:** Resources, Supervision, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2024.101137.

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