Delineation of the Optimal Groundwater Recharge Zone in Taif Basin, Western Saudi Arabia: Implication for Groundwater Sustainability

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Abstract

The escalating demand of drinking water, coupled with increasing agricultural and industrial needs, has imposed a significant strain on groundwater sources worldwide, which is further exacerbated by the implications of climate change. The current research aims to identify the groundwater potential zones (GPZs) and the optimal sites for artificial recharge in the Wadi Waj watershed, Taif, Saudi Arabia. An integrated approach using remote sensing (RS), GIS, multi-criteria decision analysis (MCDA), and the analytic hierarchy process (AHP) was utilized. Seven hydrological and geological factors have been weighted and analyzed using AHP and GIS-based weight overlay approaches. Five GPZs have been mapped with the range from very high to very low where the very high, high, moderate, low, and very low GPZs were 0.046, 33.5, 31.3, 35.1, and 0.023 percent of the basin, respectively. The high GPZs were found in the downstream region, while the low GPZs were located in the upstream region with impermeable rock and steep slopes. A total of 27 locations have been identified as optimal sites for constructing artificial recharge facilities. These sites are positioned strategically to both catch and encourage the infiltration of rainwater into the ground. The findings were verified with the agricultural farms and wells demonstrating the alignment with moderate to high GPZs. The GPZs were also verified with the groundwater depth data obtained from the global model "GLOBGM v1.0," and the findings showed comparable trends. The findings will support water resources management to enhance regional water security and maintain sustainable groundwater resources.

Keywords Groundwater suitability · Aquifer · Saudi Arabia · Arid region · Water security

1 Introduction

Groundwater is the primary source of water for household and agricultural activities in arid regions with low rainfall and surface water sources. Dependence on groundwater is essential for maintaining communities and facilitating agricultural practices in arid settings [1, 2]. In Saudi Arabia, groundwater satisfied 30.8% and > 83% of domestic and agricultural water demands, respectively [3–5]. The excessive use of groundwater has led to declining water tables and depletion of major aquifers, posing a risk to sustainable water management [6, 7]. Past studies have concluded that the imbalance between groundwater recharge and exploitation rates has led to a depletion of groundwater resources in Saudi Arabia [8]. The depletion has also been accelerated

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due to the loss of a substantial volume of water as surface runoff in the major hydrological basins in the western regions of the country [9]. Ghanim et al. [10] reported that the western region faced severe water scarcity and needed appropriate management of water resources and conservation efforts. It is crucial to implement water conservation measures, promote alternative sources of water, and water recharge into groundwater aquifers to ensure long-term water security [11].

Identification of groundwater potential zones (GPZs) in a region is a critical step for sustainable water resources management. The GPZs are traditionally delineated through applying the field-based techniques using geological, hydrological, and geophysics instruments [12–14]. Those techniques are time-consuming, point-based measurements and are limited in both time and space [10]. In the past years, researchers have enhanced groundwater investigation methods with emerging modeling techniques including logistic regression [14, 15], fuzzy logic [16, 17], artificial neural network (ANN) [18, 19], frequency ratio [20], decision tree model [21], and weights of evidence model[22]. Among these models, the analytic hierarchy process (AHP), which is a multi-criteria decision-making (MCDM) method, is popular due to its simple structure, clarity, efficacy, minimum bias, efficiency, and watershed-influencing considerations.

The AHP model was developed by Thomas L. Saaty for decision-making in the early 1980s [23]. Combining both qualitative and quantitative data, AHP is useful in addressing challenges related to groundwater exploration in areas with limited data. The GPZs can be accurately delineated both spatially and temporally through AHP and Geographic Information Systems (GIS). GIS has been extensively applied to establish GPZs for efficient groundwater monitoring and management [24, 25]. The AHP-derived priority scales were used in the weighted overlay analysis using GIS and produced accurate delineation of GPZs [20]. The GPZs were used to delineate sites for artificial groundwater recharge to conserve water and enhance groundwater storage [12]. The GPZs can assist in long-term production from aquifer systems via artificial recharge, which can benefit sustainable water resources management. The AHP and GIS can be applied to accurately delineate the watershed.

The Wadi Waj is an urban and suburban watershed in the Taif region, which has experienced significant population growth and agricultural and industrial development in the past few decades. The population of Taif increased from 400,000 in 1992 to 580,000 in 2004 with annual growth rate of 3%, and the area is about 440 km^2 of built-up space [26]. These expansion activities have led to increased surface runoff and reduced water retention time, which adversely impacts groundwater recharge. Additionally, urbanization development is likely to be associated with increased water consumption that could potentially stress the groundwater resources and might result in overexploitation and depletion of aquifer levels. Reflecting the need to address these challenges, the current study aims to delineate the GPZs and their vulnerability and define the optimal sites of artificial recharge of groundwater systems in the Taif region using integrated approach. The approach integrates the analytical hierarchy process (AHP), remote sensing (RS), and GIS to construct maps for GPZs and recharge optimal locations.

2 Methodology

2.1 Study Area

The study area is situated in the Taif governorate of western Saudi Arabia, which is within one of the world's large desert belts. It is characterized by high temperatures and from semiarid to extremely arid environments without any permanent streams. However, frequent rainfall events produce runoffs to cause flash floods, which are generally funneled through wadis. Figure 1 depicts the study area in the global coordinate system of latitudes between 21°00′ and 21°30′ north and longitudes between 40°15′ and 40°35′ east. The floods in the study area rarely flow continuously for consecutive days at a time. It rains approximately 268 mm on average each year, and the average temperature ranges from 20 to 39 °C during the summer and from 6 to 29 °C during the winter months. It is nestled within the Sarawat mountain range that runs along Saudi Arabia's western coast, giving it a unique elevated landscape. The city of Taif, surrounded by these mountains towering up to 2800 m, offers breathtaking vistas and lush greenery. With a relief of approximately 15 m per kilometer from southwest to northeast, the topographic elevations in the area under study range from 1,400 m to more than 2,000 m above the mean sea level (MSL). Taif is home to diverse indigenous forests, mostly found in the Sarawat Mountains and the area around Taif City. These woodlands are home to oak, cypress, juniper, and dwarf palm trees. The region's economy, tourism, and wildlife all depend on these woodlands. But because of the numerous human pressures they encounter, it is crucial to conserve them and manage them sustainably [27].

2.2 Data Acquiring Process

Several sources of data were utilized in the current research for the identification of GPZs. The geological and lineament data were obtained from the Saudi Geological Survey (SGS). Rainfall data were derived using the Integrated Multi-satellite Retrievals for GPM (IMERG) algorithm over twenty years from 2001 to 2020. The digital elevation model (DEM) was acquired from the King Abdulaziz City for Science and Technology (KACST) at a resolution of 10 m, which proved
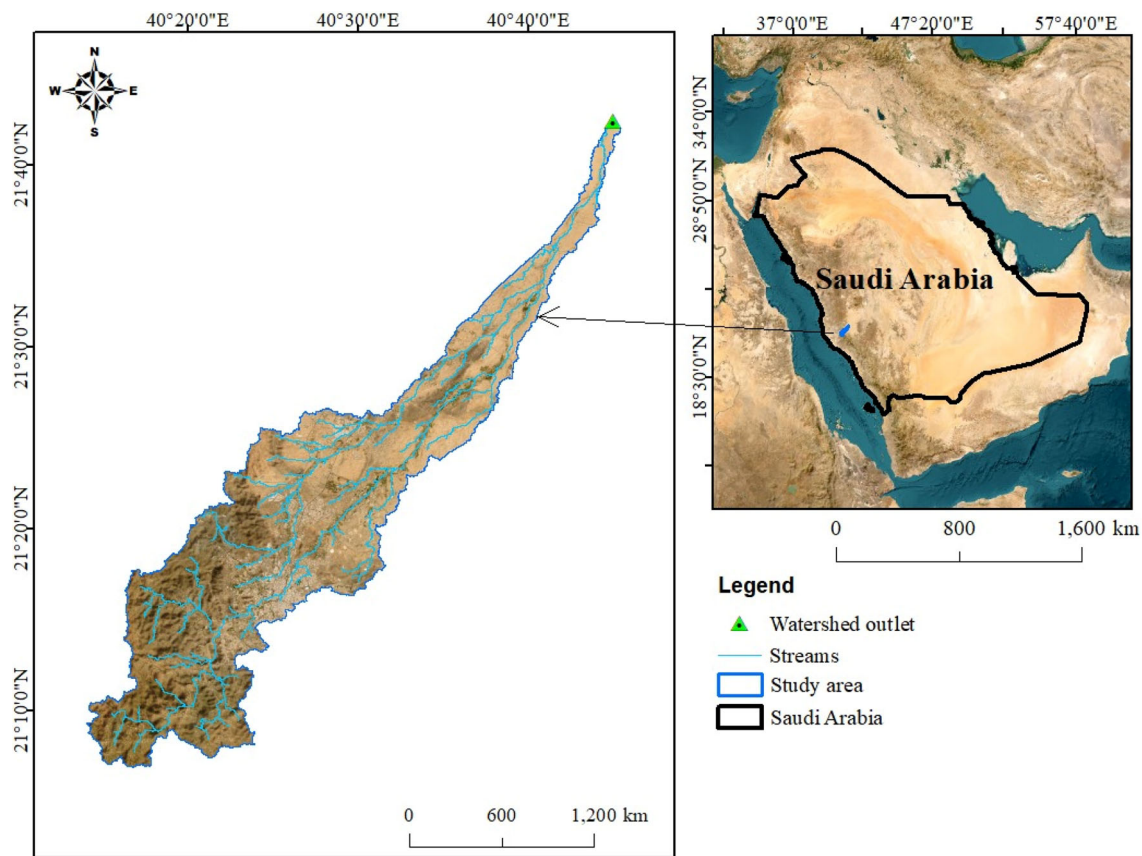
Fig. 1 Map showing the watershed boundary of the studied basin

instrumental in delineating watershed boundaries, assessing drainage density, and slope, and identifying streams. The terrain's slope offers insights into regional geological and geodynamic processes [10]. It gives crucial information about the surface runoff and infiltration rate. For example, steeper slopes cause swift water flow during rainfall, which results in reduced recharge. Drainage network density is a key factor in assessing contamination risk and groundwater availability [28]. The lithology of the study area influences its drainage network, providing insights into infiltration rates. Groundwater zone identification heavily depends on drainage density because of its inverse relationship with permeability. The used formula for drainage density is the total river length divided by the total basin area [29]. High drainage density can lead to reduced water infiltration into the ground, diminishing groundwater resource potential. Conversely, low drainage density suggests decreased runoff and increased infiltration potential, positively impacting groundwater availability. The drainage density map for this study was generated using ArcGIS10.7's from a 30 m DEM.

The land use classification offers significant insight into numerous hydrological processes [12]. It contributes to the understanding of infiltration rates, groundwater–surface water interactions, soil moisture conditions, and the overall water needs of the groundwater system. It is also a fundamental component in assessing the sustainability of water resources and developing proper management strategies. The land use data with a resolution of 100 m were obtained from the Global Land Cover dataset https://lcviewer.vito.be. Water infiltration into the subsurface is quantified based on the soil's textural properties and associated percolation processes throughout the soil matrix. Therefore, the soil type has a direct impact on infiltrated water into the vadose zone and recharges groundwater aquifer. Soil type data at 250 m resolution were obtained from the OpenLandMap database (www.openlandmap.org). The analysis of these data sheds light on the pedological features that influence groundwater recharge patterns. Soil texture and group classifications were utilized to calculate hydraulic conductivity, infiltration potential, and subsurface water transfer rates in the vadose zone. This information enabled the creation of a high-resolution soil type map in ArcGIS 10.7, which delineated zones based on their propensity for groundwater recharge throughout the research region. The resultant soil characterization and geographical distribution allow scientists to evaluate underground processes that influence groundwater occurrence and

renewal. Well locations were obtained from the field visit, literature, and satellite imagery.

Rainfall is the primary source of underground water in this region. A thorough analysis of IMERG rainfall data was conducted. IMERG data have a spatial resolution of $0.1 \times 0.1°$ and a temporal resolution of 30 min and demonstrated good performance for the Makkah watershed located in western Saudi Arabia [30]. The ArcGIS tool was used to generate rainfall maps for the annual rainfall intensity. It showed that the annual precipitation ranges from 97 to 425 mm. For data analysis, a diverse set of spatial analytic tools within the ArcGIS software were used. The analysis for rainfall patterns, geological characteristics, slope analysis, drainage density, land use, identification of lineaments, and soil type assessment was conducted. Rainfall data and generated spatial maps of rainfall distribution were analyzed using the Inverse Distance Weightage (IDW) in ArcGIS 10.7.

2.3 Model Development

According to the study's conclusion, GPZ delineation benefits greatly from the combination of AHP and GIS approaches, especially in arid and semiarid regions. This approach is in line with other research that mapped GPZs in arid areas using similar methodologies [31–33]. When creating GPZ maps, it is customary to incorporate theme layers such as geomorphology, geology, soil properties, rainfall, and drainage density data. Our results are consistent with the goals of groundwater research, which aims to address issues in arid areas and maximize resource allocation. This provides information that can be used to plan and manage groundwater resources, especially for agricultural and urban uses. It has real-world promise for things like helping cities manage their water resources sustainably and raising agricultural yield with better irrigation techniques. In this model, the geographic information system (GIS) along with multi-criteria decision analysis (MCDA) and analytic hierarchy process (AHP) techniques was used to convert the geographical data into decisions and the AHP was employed to merge the thematic layers. The impact of each layer on groundwater occurrence was used to assign weights. Layers with more significant effects on groundwater potential received higher weights. The steps used for this research are shown in Fig. 2, which illustrates the workflow.

In this study, factors such as geology, slope, lineament density, land use and land cover, drainage density, soil type, and rainfall were utilized. These factors were carefully chosen based on their relevance to both groundwater recharge and overall groundwater potential. Several studies [34–38] have demonstrated the effectiveness of these factors in accurately estimating groundwater potential zones.

The geology and soil type are critical in understanding the aquifer properties and the storage capacity of the ground, which directly influences groundwater potential. Slope affects the infiltration rate and runoff, thus impacting groundwater recharge and storage. Lineament density is crucial for identifying fracture zones that facilitate groundwater movement. Land use and land cover determine the surface conditions that influence infiltration and recharge rates. Drainage density provides insight into the surface runoff patterns, which inversely affect groundwater recharge. Lastly, rainfall is a primary source of recharge, making it an essential factor in the overall assessment of groundwater potential.

The selection of factors in this study aimed to balance factors influencing both recharge and storage, ensuring comprehensive evaluation of groundwater potential. By integrating these factors through the analytical hierarchy process (AHP), we were able to develop a robust model that reflected the complex interactions affecting groundwater potential, rather than focusing solely on recharge potential. Based on field surveys, stakeholder and expert consultations, and literature reviews, the ranking of parameters was performed. The highest weight was given for geology and the lowest weight for drainage density. Each parameter was further broken down into sub-variables, ranked following the methods recommended by Yammani [39]. In the GIS, a natural break classification method was applied to reclassify subclasses within each layer, assigning them ranks from 1 to 5 [10]. The rank prioritizes the impact of the factor on groundwater development. Table 1 shows the weight of each thematic layer along with a ranking of each factor.

For optimal groundwater recharge zone, a streamlined approach centered on lineaments and streams, which are two crucial features for selecting optimal sites for constructing artificial recharge facilities, was employed. Lineaments indicate subsurface geological features necessary for identifying GPZs, revealing information about groundwater flow and accumulation by identifying the locations of fractures and faults. Streams indicate surface water dynamics and flow direction, essential for understanding the broader hydrological context of an area and identifying areas with higher moisture content, representing potential recharge zones. Stream intersections provide insights into surface water drainage. The lineaments and streams were incorporated into a GIS framework. The GIS generated spatial mappings for lineaments and streams, enabling the identification of areas with high potential for water resources by analyzing the intersection and convergence of these features. GIS was also used to quantify the density, orientation, and distribution of lineaments and streams, aiding in understanding the hydrogeological characteristics of the area and facilitating better assessment for water resource management. Subsequently, various artificial recharge structures such as check dams, farm ponds, and percolation tanks can be implemented [12].

Fig. 2 Research methodology
workflow
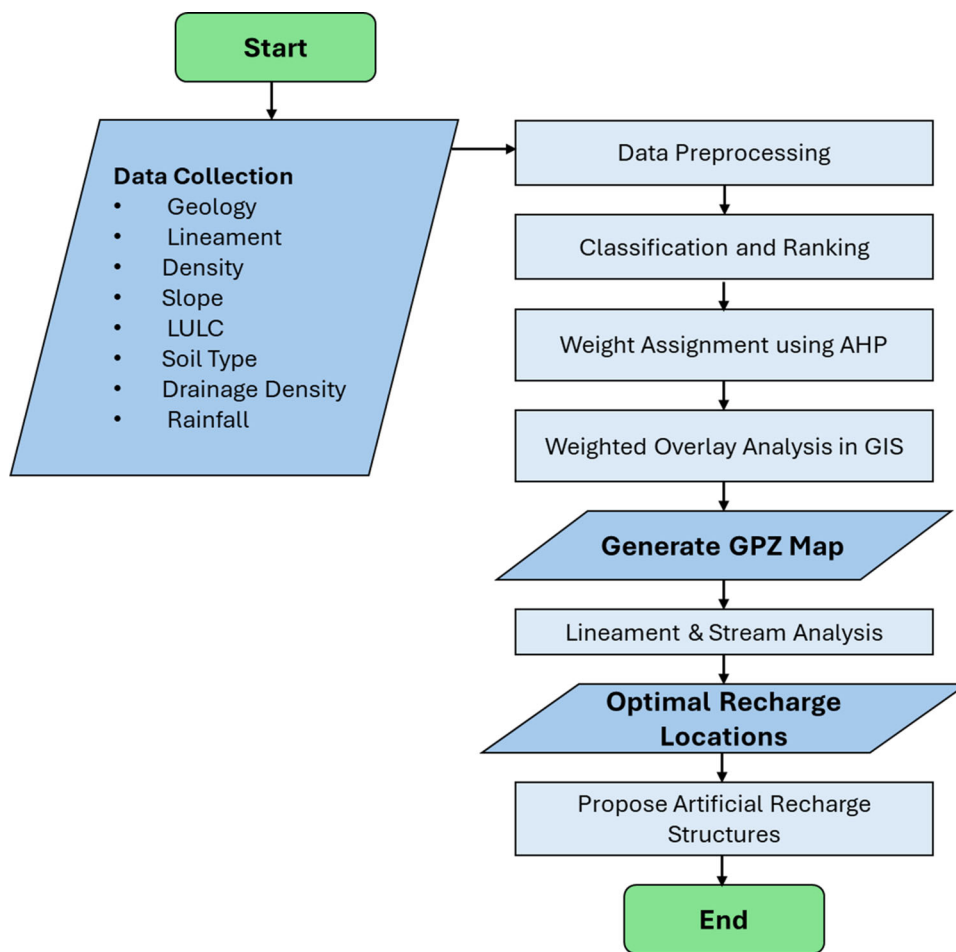
3 Results and Discussion

3.1 Rainfall Map

Figure 3 provides a detailed representation of the spatial distribution of rainfall in Wadi Waj. The timeframe used for averaging rainfall data in the study area was 20 years. This period was chosen to ensure the comprehensive and stable representation of rainfall patterns, which is essential for accurately interpreting the groundwater potential zones. All GPM data for the years 2001–2020 were downloaded from the NASA website as HDF5 files using the curl command, following the instructions provided on the NASA website. A Python script was then utilized to read these files and extracted precipitation data for locations (GPM stations) within and around the Wadi Wajj Basin. Further analysis was conducted using Python to calculate the yearly precipitation totals for each of these locations. After downloading the data, GIS software was employed to process the rainfall information. The processing involved the use of the inverse distance weighting (IDW) interpolation method, chosen for its effectiveness in creating continuous surface maps from discrete data points. The IDW approach allowed to generate high-resolution rainfall maps that accurately represented the spatial distribution of rainfall across the study area. Areas with darker shading indicate regions of intense annual rainfall exceeding 226.3 mm, whereas the lighter-shaded areas represent regions with minimal annual rainfall, dropping to as low as 129.2 mm. Notably, the highest rainfall events are observed in the central parts of the watershed while the lowest are observed in the upstream of the watershed. The spatial distribution suggests that there will likely be minimal variation in groundwater potential zones due to these rainfall patterns.

3.2 Geology Map

The geology of the region mainly consists of three major rock units including igneous intrusive rock, metamorphic rock, and sedimentary surficial rocks (Fig. 4a). The igneous rocks are dominant in the upper and downstream regions and composed mainly of diorite and gabbro facies in the upstream, granite, and granodiorite in the middle stream, and monzo-granite and syenogranite in the downstream of the study area
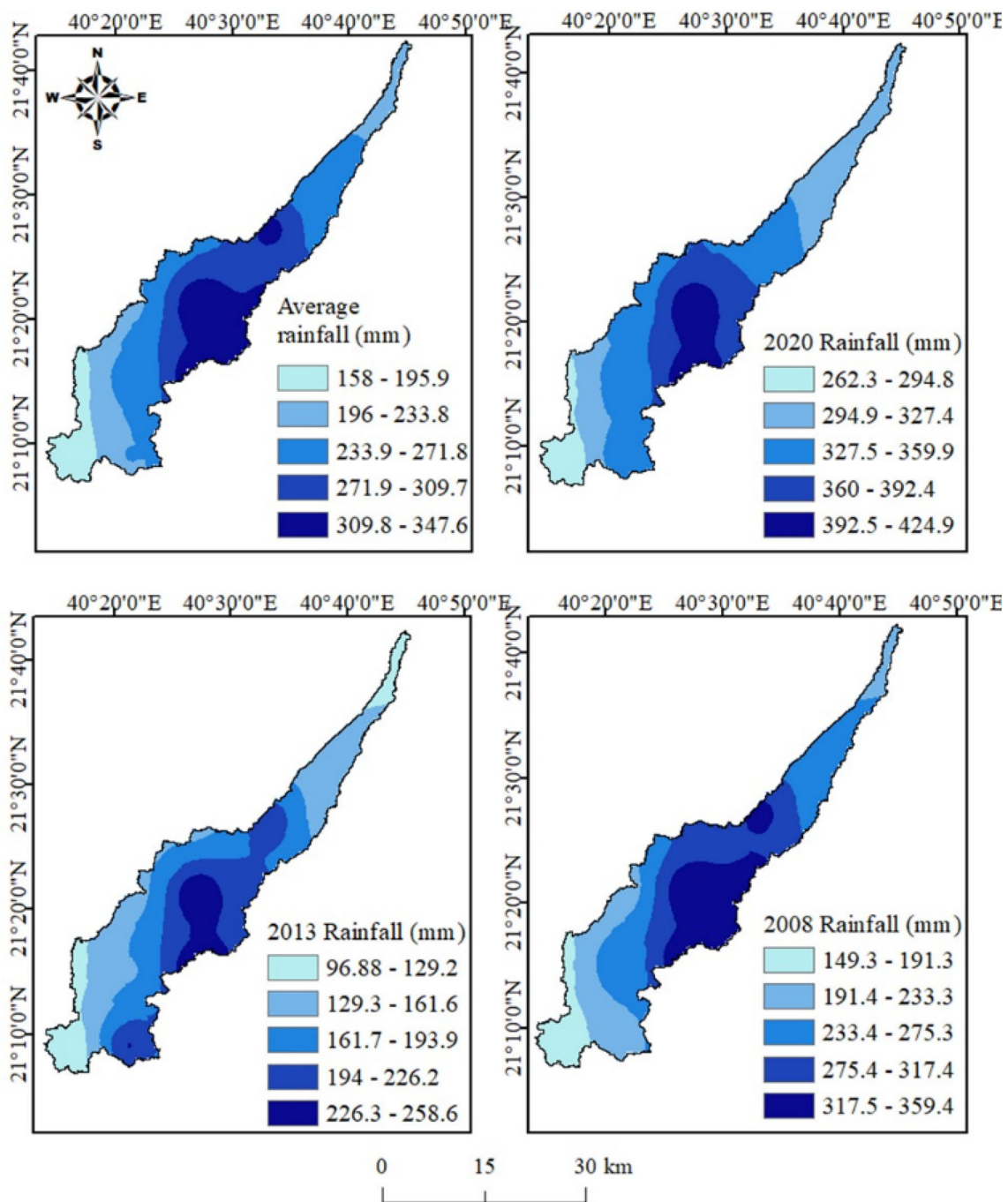
Fig. 3 Rainfall in the study area. **a** Average rainfall over 20 years, **b** rainfall of the year with maximum precipitation(2020), **c** rainfall of the year with minimum precipitation (2013), **d** rainfall of the year with average precipitation (2008)

[40]. The metamorphic rocks are dominant in the middle stream and upper part of downstream with layered facies. The major type of metamorphic rock is the amphibolite schist layers in the downstream region, and undifferentiated metamorphic rock facies in the middle stream and lower upstream regions [40]. The sedimentary deposits are in the form of alluvial deposits of sand, gravel, and silts that occurred in the middle and downstream regions, which have filled the main channel and floodplain of Wadi Waj. The surface geology is divided into three categories: a metamorphic belt, granite sections, and dike intrusions, with Quaternary deposits distributed over the lowlands, which correspond to the conclusions of [41, 42].

The metamorphic band, the area's oldest geological feature, is typified by the amphibolite schist found in Wadi Waj. The geological setting of the area is further complicated by
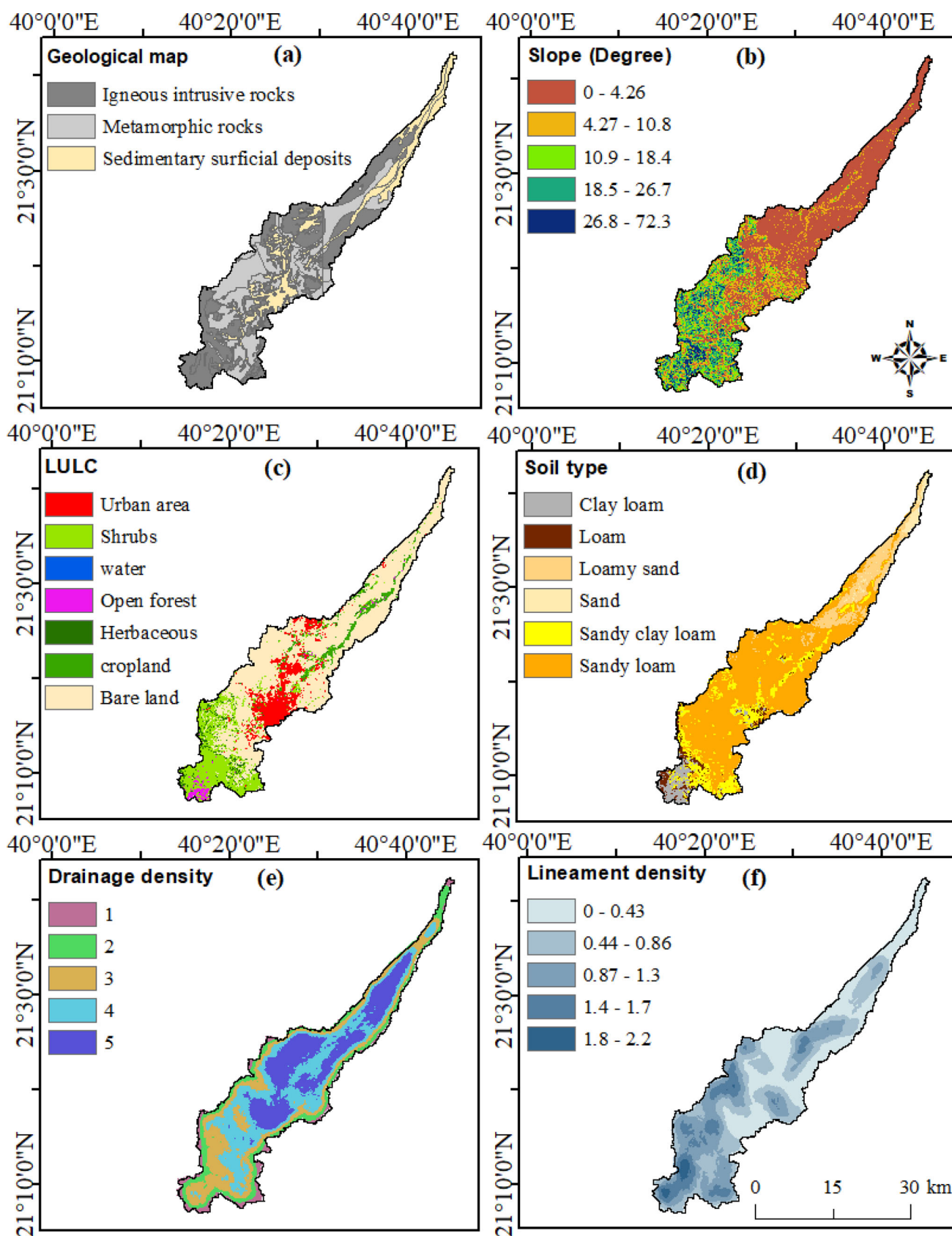
Fig. 4 Thematic layer maps of the Wadi Waj Basin **a** geological map, **b** slope, **c** land use/cover, **d** soil type, **e** drainage density, **f** lineament density

Table 1 Thematic layers weights and ranking of factors

Thematic layer	Factors	Weight (%)	Rank
Geology	Igneous extrusive rocks	39	1
	Sedimentary surficial deposits		5
	Metamorphic rocks		4
Lineament density	0–0.43	19	1
	0.44–0.86		2
	0.87–1.3		3
	1.4–1.7		4
	1.8–2.2		5
Slope	0–4.26	12	5
	4.27–10.8		4
	10.9–18.4		3
	18.5–26.7		2
	26.8–72.3		1
LULC	Urban area	10	1
	Shrubs		3
	Water		3
	Open forest		3
	Herbaceous		3
	Crops		4
	Bare land		1
Soil type	Clay loam	8	1
	Loam		5
	Loamy sand		1
	Sand		5
	Sandy clay loam		3
	Sandy loam		5
Drainage density	1	7	5
	2		4
	3		3
	4		2
	5		1
Rainfall	158–195.9	5	1
	196–233.8		2
	233.9–271.8		3
	271.9–309.7		4
	309.8–347.6		5

the existence of many granitic composition dikes that cut through the old bedrock, indicating a period of great tectonic and magmatic activity [40]. The Wadi Waj itself is a geological mosaic, with sediments varying from coarse to fine-grained, and bedrock depths ranging from a few meters to over 20 m. This geological variety, characterized by the interaction of rock types and structural complexity, has far-reaching consequences for the region's hydrogeological processes and resource management.

3.3 Soil Type Map

The soil texture of Wadi Waj is primarily sandy loam (Fig. 4d). Loamy sand and sand textures are predominant in the northeastern part (Fig. 4d). These soil textures are characterized by a low runoff potential, high rate of infiltration, and efficient water transmission, exceeding 7.62 mm/hr [43]. These areas hold significant potential as groundwater recharge zones. Conversely, the soil in the southwest area exhibits a clay loam texture, resulting in a high runoff potential, very low infiltration rates, and water transmission of less than 1.27 mm/hr [43]. Additionally, this region features fewer locations of loam texture with moderate infiltration rates and a water transmission rate ranging from 3.81 to 7.62 mm/hr. Table 2 displays the classification of soil types, and this categorization is grounded in the reference provided by the USDA-TR-55.

3.4 Lineament Map

The geological structures (faults and fractures) in the study area that formed a line feature were delineated, and their density is mapped in Fig. 4f. The lineaments have been extracted from the geological map of the study area obtained from Saudi Geological Survey (SGS) (https://ngd.sgs.gov.sa/en) and from digital elevation model (DEM) data obtained from the King Abdulaziz City for Science and Technology (KACST) at a resolution of 10 m. The delineation of lineaments have been conducted within the GIS environment. Lineaments play a significant role in the formation of groundwater flow systems, as they act as storage and pathways for water movement in the subsurface. The presence of high-density lineaments indicates a higher potential for groundwater availability and recharge, while a decrease in their density suggests a lower potential of groundwater resources. Mapping the distribution and density of lineaments is essential for identifying suitable locations for groundwater recharge and management [29, 44]. As shown in Fig. 4f, the lineament density is high in the upstream and midstream regions of the studied basin with denser lineament in the W, SW, and NW parts of the basin. In the downstream region, the lineament density is low compared to the upper

Table 2 Soil type, texture, hydrological properties, and classification based on USDA

	Soil Texture	SCS Group	Water Transmission Rate	Location
	Clay loam	D	0-1.27 mm/hr	West-south, high-slope terrain
	Loam	B	3.81-7.62 mm/hr	Few, scattered
	Loamy sand	A	greater than 7.62 mm/hr	East-north
	Sand	A	greater than 7.62 mm/hr	Very few, East-north
	Sandy clay loam	C	1.27-3.81 mm/hr	Few, scattered
	Sandy loam	A	greater than 7.62 mm/hr	Majority

and midstream regions, with small, localized zones of high-density lineament.

3.5 Slope Map

Wadi Waj terrain has been categorized into five groups based on slope angles. These include nearly flat regions (with slopes less than 4.256°), areas with a slight incline (ranging from 4.257 to 10.78°), locations featuring a gentle slope (spanning 10.79–18.44°), areas characterized by a moderate incline (covering 18.45–26.67°), and zones marked by a steep incline (exceeding 26.68°) [10].

Figure 4b displays the slope map, generated using the spatial analysis tool in ArcGIS 10.7 using 10 m DEM. The developed map illustrates that areas characterized by higher slopes are predominantly concentrated in the center region and extend to the southwestern direction. Such topography is less conducive to groundwater recharge, as surface water has limited time to infiltrate through the soil surface. In contrast, the majority of the terrain, which stretches from the center to the northeast, is merely flat. Owing to the minimal slope, the flat terrains facilitate groundwater recharge.

3.6 Land Use/Cover Map

In the current study, as depicted in Fig. 3c, the Wadi Waj basin has diverse land use/cover categories such as Urban area (11.6%), shrubs (17.9%), water (0.005%), open forest (1.7%), herbaceous (3.2%), cropland (4.3%), and bare land (61.3%). The types of land use were obtained from the Global Land Cover at 100 m resolution via https://lcviewer.vito.be and subsequently adjusted through a comparison with field data and aerial photographs using the ArcGIS 10.7 software. Notably, crops, shrubs, herbaceous, and open forests received high weights owing to their elevated water content. The bare land classes were assigned the same weight as the urban area since most of them are mountain areas (Table 1).

3.7 Drainage Density Map

The drainage density map for the Wadi Waj basin is illustrated in Fig. 4e. The resulting data were used in groundwater potential classification. Lower drainage densities were assigned

Table 3 Potential categories based on geological and hydrological factors

Groundwater potential	Zone	Area (km^2)
Very low	Highland areas	0.33
Low	Highland areas	251.13
Moderate	Midlands and lowlands with high drainage density	224.14
High	Midlands and lowlands with significant infiltration capacity	239.66
Very high	Lowland regions	0.16

significant weights while higher densities were assigned lower weights.

3.8 Groundwater Potential Zones (GPZs)

To achieve a precise assessment of Wadi Waj, all available factors were analyzed, including land use (LU), slope, lineament density, geology, soil properties, rainfall, and drainage density. Figure 4a illustrates the spatial distribution of groundwater potential in Wadi Waj, which was grouped into five distinct categories: very high, high, moderate, low, and very low (Table 3). The categorization is derived from the analysis of geological and hydrological parameters that control the presence and flow of groundwater in the Wadi Waj basin. The zones with very high potential are favorable for the accumulation and extraction of groundwater. Conversely, the areas of low and very low potential have significant limitations that substantially limit the availability of groundwater. The extremely high potential zones are mostly found in the lowland parts of Wadi Waj, where flat terrain, thick alluvium, and low density of drainage make optimal hydrogeological conditions for groundwater storage. The high (33.5%) and moderate (31.3%) potential zones correspond to the midland and lowland settings, respectively, with moderately favorable characteristics. In contrast, the low (35.1%) and very low (0.02%) potential zones are mostly mountainous highland areas underlain by poor permeability igneous rocks and surrounded by steep slopes and drainages

that prevent groundwater accumulation. The slope, geology, soil, and drainage density contributed to these geographical patterns. In general, this comprehensive investigation and mapping of groundwater potential provide insights into developing methods to enhance recharge in areas with high to moderate potential zones. It also identifies regions of limited potential where recharge enhancement may be challenging.

The results of Fig. 5a also indicate that fault-bounded depressions and wadis have the highest groundwater accumulation, primarily in the midland region. Due to the existence of inferred faults, the water table is elevated, giving high potential for groundwater. The existing locations of the wells in Wadi Waj were compared to the GPZs map. This method was employed in earlier studies to verify the accuracy of the developed GPZs map [10]. The regional variability shown in earlier research for the Arabian-Nubian Shield region is consistent with the distribution of GPZs in Wadi Waj [45–47]. According to Hassaballa & Salih. [38], the GPZ map is considered accurate when around 50% of the existing well locations are located within "moderate" or "high," zones. This suggests that the selected thematic layers and their assigned weights yield appropriate results. As a result, it was found that wells in the watershed were located in a zone with moderate to high potential. This indicates that the zones of moderate and high potential contain 83.3% of the already available wells. Since there are only a certain number of existing wells, the farms' locations inside the watershed were identified. These farms were also situated in zones with moderate and high potential.

To improve the comprehension of groundwater dynamics, data from the "GLOBGM v1.0: a parallel implementation of a 30 arcsec PCR-GLOBWB-MODFLOW global-scale groundwater model" [48] were combined and examined (Fig. 5b). The comparison demonstrated significant agreement between the groundwater potential maps produced by the proposed techniques and the GLOBGM v1.0 model in terms of trends and patterns. Similar trends with the past study using different techniques support the validity of the proposed technique. Predictions based on RS, GIS, MCDA, and AHP in projecting groundwater potential zones can be considered dependable.

Given the lack of precise groundwater depth data, it was not possible to directly compare the findings with the GLOBGM v1.0 model quantitatively. However, based on the existing knowledge of hydrogeology in the research region, there may be potential differences. More precisely, the groundwater depths projected by the model in the areas upstream are in line with the observed well levels and the known geological formations that limit infiltration. The difference emphasizes the significance of incorporating local knowledge and data into global-scale models. Although worldwide models provide significant insights, their accuracy for regions can be improved by integrating localized data and expert knowledge, resulting in a more accurate and reliable assessment of hydrological processes.

3.9 Optimal Groundwater Recharge Zone

The optimal locations for artificial recharge facilities were identified based on the intersections between streams and lineaments. These locations were chosen due to their high potential for effectively recharging the aquifer, as the intersection points often indicate zones of increased permeability and groundwater flow. This method ensures that recharge efforts are concentrated in areas where they are most likely to enhance groundwater storage.

Regarding the location of water demand relative to these recharge sites, the study basin features distinct zones of residential and agricultural activities. Residential areas are predominantly situated in the middle parts of the basin, while agricultural activities are more common in the downstream zones. Despite the differences in the sizes of the basins, the overall water demand across these zones does not vary significantly, ensuring that recharging aquifers in the selected locations are likely to benefit both residential and agricultural needs.

Moreover, by focusing on the intersections of streams and lineaments, we ensure that the recharge facilities are placed in strategic locations that can maximize the efficiency of groundwater replenishment. This approach not only addresses the immediate recharge potential but also considers the long-term sustainability of water resources within the basin.

Figure 6 depicts the resulting optimal sites for constructing artificial recharge facilities. This streamlined approach demonstrates a practical and effective strategy for leveraging GIS in addressing environmental and resource management challenges. There are a total of 27 recharge locations located in the middle, downstream, and upstream regions. In order to replenish groundwater supplies, these sites are positioned strategically to both catch and encourage the infiltration of water into the ground.

The headwaters and slopes of the upstream mountain area serve as crucial recharge zones due to their high elevation, steep gradients, and dense forest cover. Because of their high precipitation levels and quick drainage, these regions are perfect for retaining and allowing water to seep into underground aquifers. Furthermore, these mountainous regions' porous geological formations enable effective recharge, ensuring a sustained supply of groundwater to places downstream.

Even while agricultural and urban development may make it difficult to recharge in some areas of the middle area, there are still places in this zone with vital recharge potential. Infiltration and recharging can be facilitated by riparian zones beside streams, undeveloped natural spaces, and agricultural lands managed sustainably. Furthermore, by imitating natural
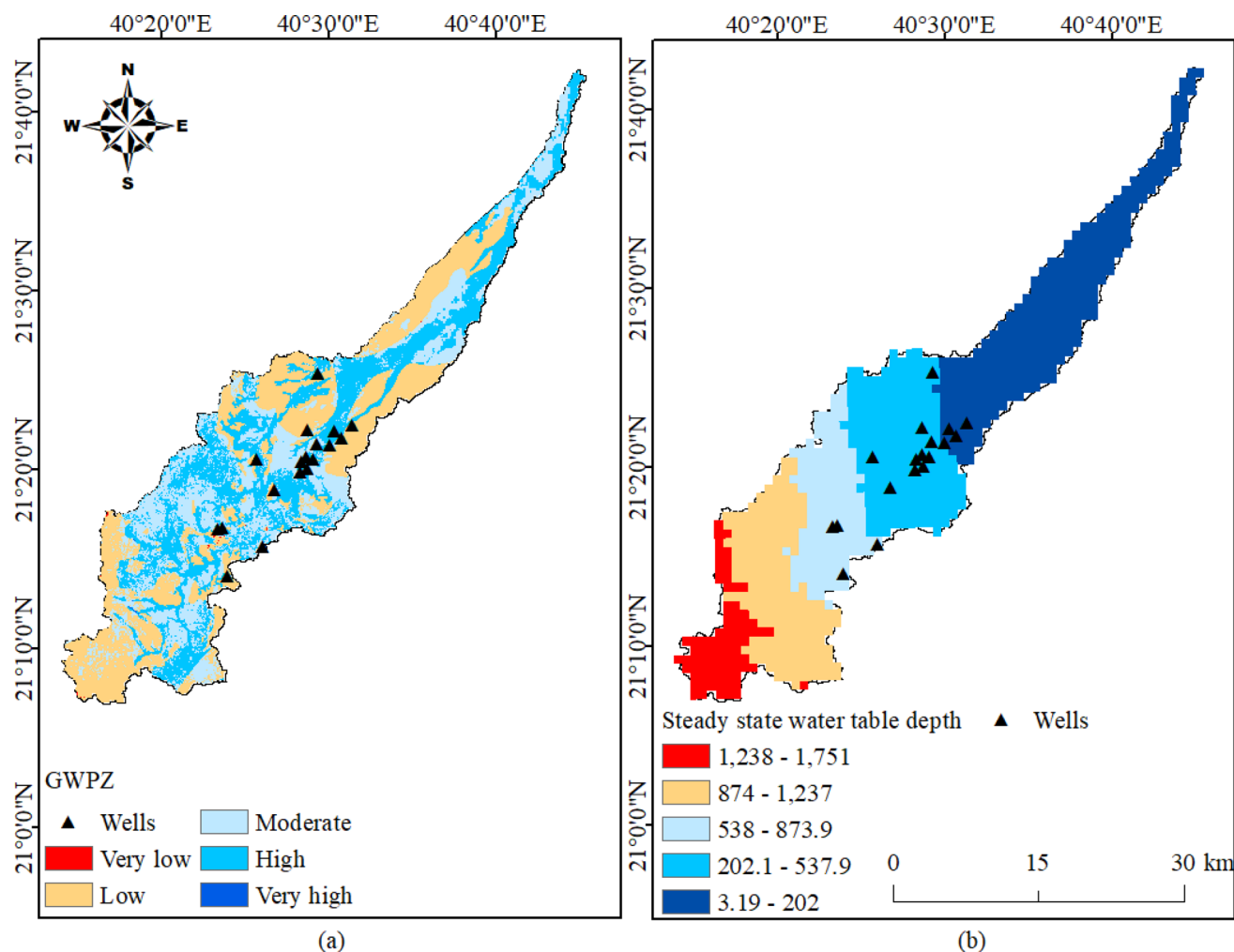
Fig. 5 GPZs distribution in Wadi Waj along with the well points. Steady-state water table depth for the study area

hydrological processes, the installation of green infrastructure strategies in metropolitan areas, such as rain gardens, retention ponds, and permeable pavements, can accelerate recharge rates.

Even while it might not receive as much direct recharge as the middle and upstream zones, the downstream area is nevertheless very important for replenishing groundwater. In the downstream region, riparian zones, floodplains, and wetlands act as organic flood barriers and store surplus surface water during rainy seasons, which helps replenish groundwater supplies. In order to sustain groundwater levels and the populations downstream who depend on groundwater for a variety of uses, it is imperative that these ecosystems be preserved and restored.

It is possible to develop targeted management strategies and conservation efforts to increase recharge rates and guarantee the long-term sustainability of water resources in the study area by identifying and ranking the most important recharge locations in each zone according to their hydrological significance and potential contributions to groundwater replenishment.

For groundwater recharge, strategic locations were recommended based on zones of optimal interaction of surface and groundwater via overly analysis of lineament and stream. Furthermore, it is recommended to construct recharge structures like check dams, percolation tanks, or farm ponds at those sites to enhance groundwater infiltration and address the water shortage in water-scarce regions. The research also provides a framework for long-term groundwater management for arid settings by defining priority zones and recharge facilities.

In summary, recharge sites are essential for attaining sustainable water management and groundwater conservation because they maintain ecosystems, replenish aquifers, reduce water shortages, control flooding, enhance water quality, and guarantee long-term water security. Together, communities, stakeholders, and politicians can prioritize the upkeep and
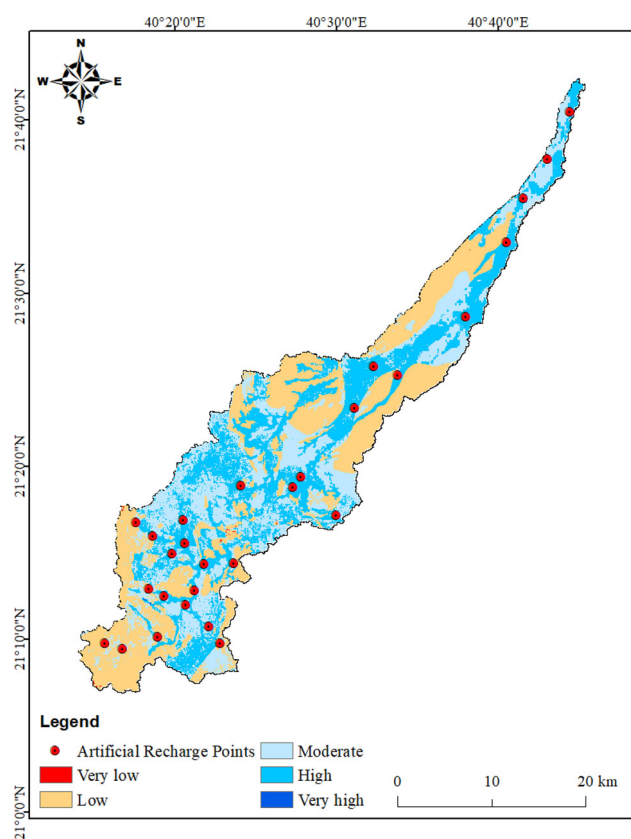
Fig. 6 Optimal sites selection for groundwater recharge

suitable sites for groundwater recharge were identified and mapped based on the lineament and stream analysis. The limitations of the study are connected to the lack of appropriate data on aquifer thickness, variations in groundwater depth, recharge rate, hydraulic conductivity, proximity to rivers, and water usage for agriculture and domestic purposes. Further, anthropogenic activities including groundwater extraction were not included, which could have a significant impact on water availability and recharge rates. The complex and heterogeneous geology of Wadi Waj introduces variability in groundwater availability, posing challenges in identifying consistent patterns. Despite these constraints, the study sheds light on improving irrigation systems, enhancing agricultural productivity, and aiding sustainable water management. Upon availability of the essential data, the study can be updated in the future.

development of these sites in order to protect this priceless resource for present and future generations.

4 Conclusions

The research primarily aimed to identify and classify potential groundwater zones (GPZs) and delineate the optical locations for groundwater recharge within the Wadi Waj watershed, Taif region a vast mountainous region in Western Saudi Arabia. The map classified the Wadi Waj basin into five distinct GPZs: very high, high, moderate, low, and very low. The highland areas predominantly contained zones with very low and low GPZs, while midland and lowland regions with high drainage density exhibited moderate and high potential zones. Factors such as igneous rocks, high drainage density, and steep slopes played crucial roles in the formation of low and very low potential zones. The findings indicate that 35.15% of the basin is categorized as very low to low potential zones, 31.3% is the moderate potential zone, 33.5% in the high potential zone (primarily covering the northern and eastern parts), and only 0.023% in the very high GPZs, mainly situated in the central regions of the study area. The accuracy of the map was verified by aligning it with the locations of existing wells and irrigated farms. The

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