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Delineating potential sites for artificial groundwater recharge using a mathematical approach to remote sensing and GIS techniques

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ABSTRACT

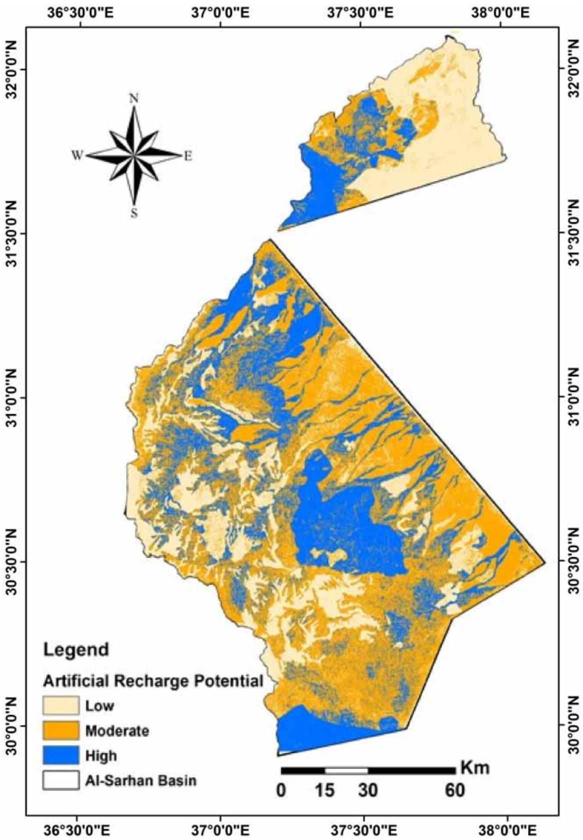
The management of available groundwater resources is vital in arid and semi-arid regions. Artificial recharging should be integrated with groundwater resources to maintain long-term water sustainability. This study applied the cost-effective and time-saving techniques of remote sensing and GIS to delineate the groundwater recharge potential in the Al-Sarhan Basin, located in arid and semiarid regions of Jordan, by following the weighted linear combination method. The results revealed three distinct groundwater potential recharge zones (low, moderate, and high potential zones). High to moderate groundwater recharge potential zones occupied 75% of the Al-Sarhan area with considerable artificial recharge capacity because of the suitable geology, soil texture, drainage density, and flat terrain conditions. The maps produced also depicted that 25% of the Al-Sarhan area possesses low groundwater recharging potential. The model further revealed that 93% of the wells in the study area were located in potential groundwater recharge zones.

Key words: Al-Sarhan Basin, Arid region, artificial recharge, groundwater, remote sensing

HIGHLIGHTS

- Integration of remote sensing and GIS techniques with some environmental factors gave satisfactory results.
- Determines groundwater potential recharge sites.
- Proved efficient in terms of minimizing fieldwork, cost, and time.
- The maps produced are helpful to calculate the percentage of aquifer wells.
- The outcomes are helpful to utilize for developing prospective regulations for implementing realistic recharge projects.

GRAPHICAL ABSTRACT



INTRODUCTION

After glaciers and the ice caps, groundwater is the largest source of freshwater on Earth accounting for nearly 30% of global freshwater supply (Shiklomanov 1993; Senanayake *et al.* 2016). Groundwater is used for several purposes including domestic, agricultural, and industrial applications (Senanayake *et al.* 2016). Groundwater levels are naturally dynamic and depend on the bidirectional flow between surface water and groundwater. Environmental factors such as precipitation rate, evaporation rate, and soil characteristics significantly affect the flow and the availability of freshwater. Excessive withdrawal of groundwater (over-pumping) compared to replenishing from the surface sharply reduces the groundwater levels. This situation degrades the water quality and depletes water levels in aquifers and surrounding water bodies leading to increased drilling and groundwater pumping costs, especially in arid and semiarid areas (Sophocleous 2002; Wada *et al.* 2010; Senanayake *et al.* 2016).

Jordan is among many countries suffering from significant water scarcity (Ibrahim & Koch 2015; Ibrahim *et al.* 2018; Ibrahim & Elhaddad 2021). Agricultural production, unsuitable industrial practices, and high population density have aggravated the water crisis in Jordan (Bajjali 2006). In addition to the water consumption, these factors pollute the available water resources through excessive fertilizers, industrial wastewater, and domestic sewage. The combination of pollution and scarcity puts considerable stress on freshwater resources. Thus, modern methods and new techniques should be employed to tackle this situation. Among the available strategies, groundwater recharge from surface water runoff is an efficient and feasible method for arid and semiarid regions having high evaporation rates and low annual rainfall.

Different methods have been implemented to control declining groundwater sources caused by over-pumping, degradation, or misuse. Artificial groundwater recharge by favouring the flow of surface water into the ground is one of the major water replenishment methods (El-Naqa & Al-Shayeb 2009; Ibrahim 2014; Al-Harahsheh *et al.* 2019; Al-Harahsheh *et al.* 2020). This practice uses natural surface water to increase the amount of groundwater (Bouwer 2002; Bhattacharya 2010; Senanayake *et al.* 2016). Different factors can affect water movement in aquifers including rainfall, drainage density, geology, geomorphology, soil texture, slope, lineament density, and land use/cover of an area (Satpathy & Kanungo 2006; Das & Pardeshi 2018). Each of these factors exerts individual or combined effects during the artificial groundwater recharging process. Therefore, a comprehensive understanding of these factors is crucial for the accurate assessment of the groundwater recharge potential (RP) of an area.

Different methods can be adopted to investigate the potential and distribution of groundwater resources. Remote sensing and GIS techniques have been widely used to determine the spatial distribution of groundwater potential zones through a logistic regression model (Ozdemir 2011), frequency ratio models (Moghaddam *et al.* 2015; Naghibi *et al.* 2015), multi-criteria decision-making models (Mukherjee *et al.* 2012; Kumar *et al.* 2014; Machiwal & Singh 2015; Das *et al.* 2017; Das & Pardeshi 2018; Arulbalaji *et al.* 2019; Haque *et al.* 2020; Khan *et al.* 2020), mathematical models, and other geostatistical and geospatial techniques (Mallick *et al.* 2015; Singh *et al.* 2017; Jasrotia *et al.* 2019; Sarkar *et al.* 2020). Several studies have also explored other groundwater exploration methods such as drilling, geophysical, and geological methods. However, these methods are costly, time-consuming, and require more human resources (Park *et al.* 2017; Arabameri *et al.* 2019). GIS and RS (remote sensing) methods can effectively prepare a groundwater potential map (GPM) and improve the accuracy and speed of groundwater studies (Naghibi & Moradi Dashtpagerdi 2017). Recently, these techniques have become important tools to efficiently analyse spatiotemporal data and predict outcomes of freshwater resources (Ghayoumian *et al.* 2007; Nagarajan & Singh 2009; Subagunasekar & Sashikkumarb 2012; Senanayake *et al.* 2016).

In this study, we used time-saving and cost-effective remote sensing and GIS techniques to delineate groundwater RP zones. Suitable sites were evaluated for their groundwater recharge capacity through knowledge-based variable analysis and hydrogeological analysis of the study area. The integration of remote sensing and GIS techniques with environmental data produced satisfactory results.

Study area

The Wadi Sarhan Basin (Al-Sarhan Basin) lies between Jordan and Saudi Arabia. These areas are classified as arid or semiarid based on the traditional classification of Mediterranean climatic zones (Figure 1). The study area in the basin region within Jordan consists of 15,572 km² whilst the elevation ranges from 1,037 m in the southwest of Jordan to about 555 m along the Jordan–Saudi Arabia border (NRA 1986). The major geological formations of the aquifers are sedimentary and crystalline rocks: basalt, limestone, sandstone, and alluvium with some marl (TWAP 2015). Two fault systems affect the study area (the West-East Siwaqa and Salawan faults and the North–East Sarhan fault).

MATERIAL AND METHODS

Water availability in semiarid areas depends on total annual precipitation, evaporation, rock composition, fluctuations in precipitation and distribution, and physical properties of the soil. Therefore, knowing the groundwater RP index is crucial, especially in semiarid areas, to monitor and identify potential groundwater recharge sites. The calculation of groundwater RP depends on the water table depth, permeability towards the aquifer, soil type, and net recharge equation. All these factors are useful for identifying groundwater RP sites. The methodology used in this study for determining the groundwater RP of the Al-Sarhan Basin is illustrated in Figure 2.

The geological map (1:25,000) of the study area was prepared by the Natural Resources Authority (NRA) under a national geology mapping project containing tectonic lineaments of the area (Barjous 1986). Remote sensing data were used to demarcate other geological lineaments in the study area using satellite image processing techniques. Satellite images were obtained from the Landsat 8 Operational Land Imager (OLI) and thermal infrared sensors (TIRs) from the U.S. Geological Survey (USGS). Finally, a lineament density map was prepared using GIS techniques and a lineament layer (Figure 3(a)).

Geomorphological data from the digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM) of the US National Aeronautics and Space Administration (NASA) did not show any features of a river plane. These data were also used to extract geomorphologies, slopes, and streams networks (Ibrahim *et al.* 2020). The most notable area consists of a low plantation surface with a small mountain that rises gently sloping from the surroundings. The DEM of the study area was further used to create the slope map of the area using the ArcGIS 10.4 software (Figure 3(b)). The DEM data from the USGS showed that about 74% of the study area consists of flat terrain characterized by slopes between 0 and 1-in-6, while 26% of the study area has different terrain characteristics that affect the water runoff.

The drainage network layer was extracted using the hydrology tool in the GIS environment and DEM data from the USGS were used to generate the drainage density map of the study area (Figure 3(c)). A land use/land cover map of the study area

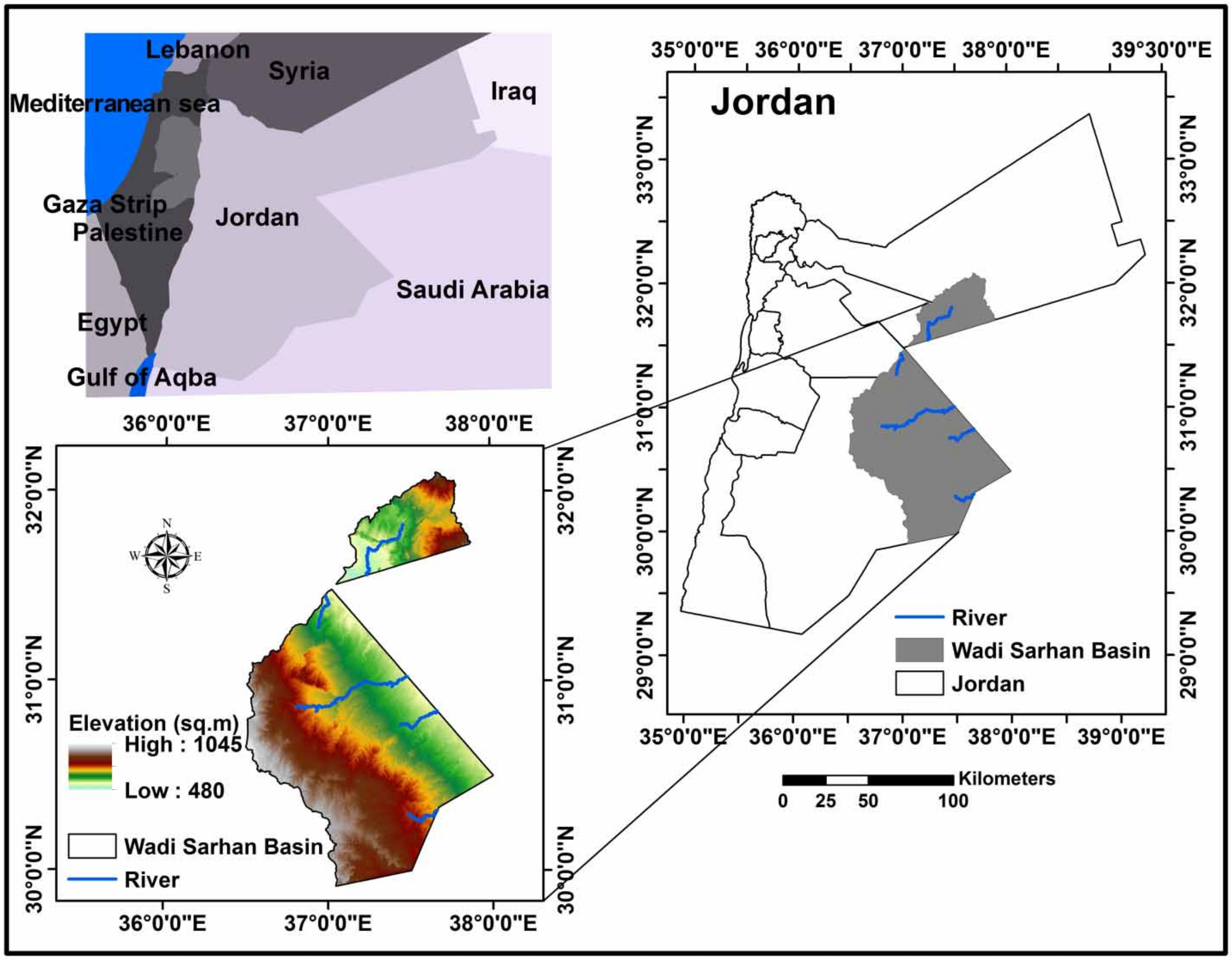


Figure 1 | Location map of the Al-Sarhan Basin (the Wadi Sarhan Basin).

was built using four satellite images captured by Landsat 8 OLI/TIR from the USGS, where land use and land cover were classified using the maximum likelihood method in the supervised classification technique. About two-thirds of the study area consists of an equally covered limestone desert. A saline transition zone was identified as another land-use class in the area (Figure 3(d)). Generally, GIS technology was used in this study to digitize the hydrologic and geographic information to construct a fundamental database by adjusting appropriate scores of different factors. Finally, a spatial analysis function was used to demonstrate the potential groundwater recharge zones in the study area. The GIS techniques efficiently identified the groundwater.

A lithological map of the study area was prepared by scanning, geo-rectifying, and digitizing the 1:50,000 geology map produced by the NRA, Jordan (Barjous 1986) (Figure 4(a)). Different types of rocks, such as igneous, sedimentary, and metamorphic, were identified in the study area. Limestone, chalky limestone, and chalk marl limestone cover most of the study area. The north-eastern part of the study area is mostly made of basalt rock, whereas the southern part is made of fluvial sandstone, indicating a Kurnub formation. Identifying rock types and their distribution is essential to determine the permeability of the ground. Thus, the permeability of each rock type was used to assign respective weights to rock types in the study area based on the textural properties that allow water to pass through to aquifers. The presence of highly permeable rock types with a large proportion of fractures in an area makes it suitable for groundwater recharging (Krishnamurthy *et al.* 2000).

The soil cover map was provided by the Ministry of Agriculture in Jordan (NSMLUP 1996) (Figure 4(b)). The most prominent soil types in the study area are those with loamy, silty, clay, and clay loam textures. Other soil textures, such as sand

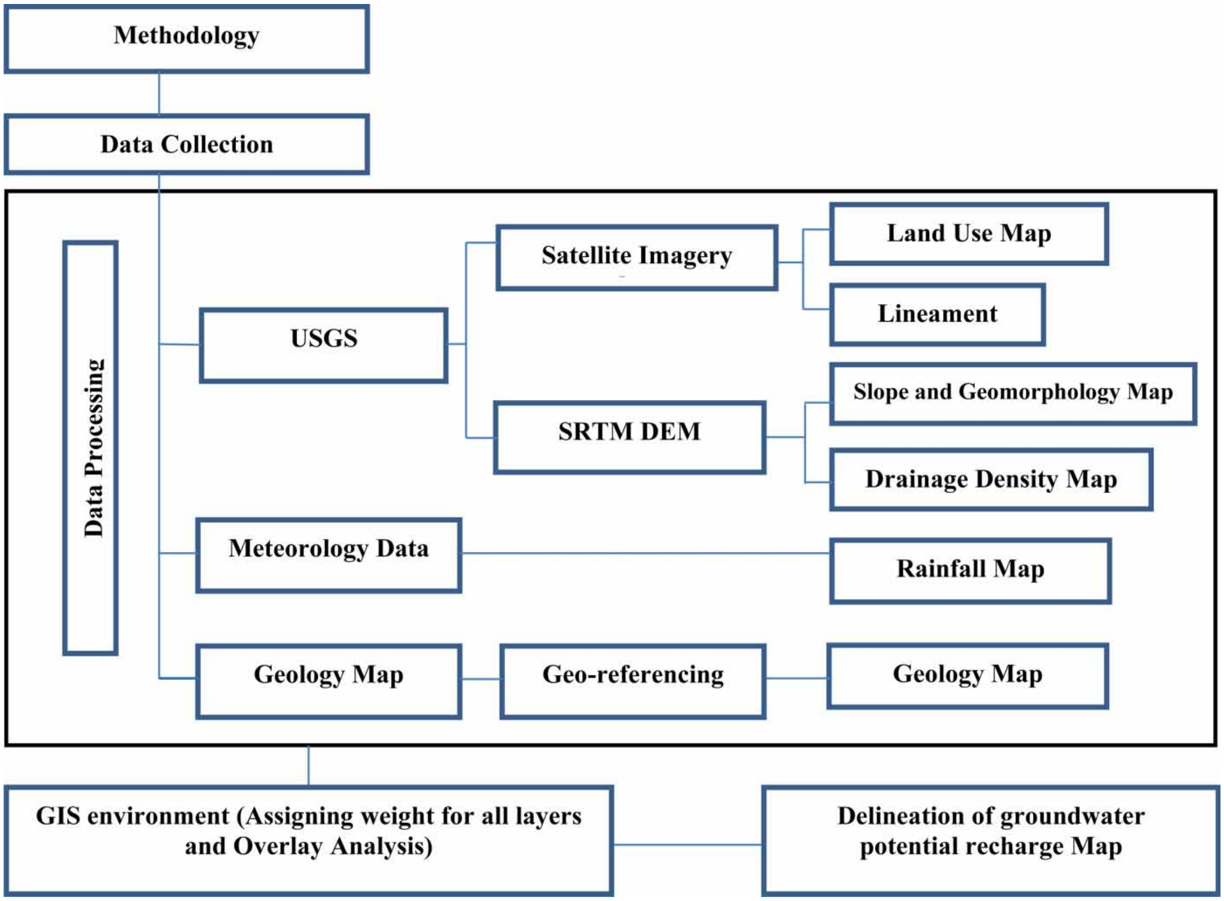


Figure 2 | A schematic summary of the methodology used to delineate the groundwater recharge potential of the Al-Sarhan Basin. USGS: United States Geological Survey; SRTM DEM: Shuttle Radar Topography Mission Digital Elevation Model.

loamy and sandy, are distributed to varying degrees in specific zones across the study area. Knowing soil texture is crucial for understanding the degree of water infiltration in aquifers of the study area. Therefore, weights were assigned to different soil texture types according to their permeability, which is directly related to the infiltration and percolation rates of the aquifers.

The Al-Sarhan Basin stands in the semiarid zone of the Mediterranean climate. Generally, the precipitation in the Al-Sarhan Basin increases during the winter season from the southern to northern parts of the area. Monthly total precipitation data were obtained from the Meteorological Department of Jordan (MDJ) to calculate the average annual rainfall in the Al-Sarhan Basin. Subsequently, the same value of the average annual rainfall (less than 50 mm) was distributed throughout the Al-Sarhan Basin area (TWAP 2015).

Finally, all layers, which were used to calculate the groundwater RP index, were converted into the raster format from the vector format. Jordan Transverse Mercator (JTM) projection, created by the Royal Jordan Geographic Center (RJGC), was used to prepare the map. The conversion process was an important part of the linear combination method adopted in this study.

The rating of these variables depends on their importance for determining groundwater RP sites (Table 1). The RP index, given by the equation below, is an indicator of groundwater potential. The RP ratings and weightings were modified to suit the particular conditions of semiarid areas, particularly those of the study area. The RP index was calculated using Equation (1) as follows:

$$RP = RF_w RF_r + LG_w LG_r + GG_w GG_r + SG_w SG_r + LD_w LD_r + DD_w DD_r + LC_w LC_r + SC_w SC_r \quad (1)$$

where *RP* is the groundwater potential recharge index. The subscripts 'w' and 'r' refer to the weight and the rank of an individual parameter, respectively. A weight value, assigned to each parameter, ranged from one to eight based on the direct effect of each parameter on groundwater occurrence. Each parameter was also ranked from one to ten based on the

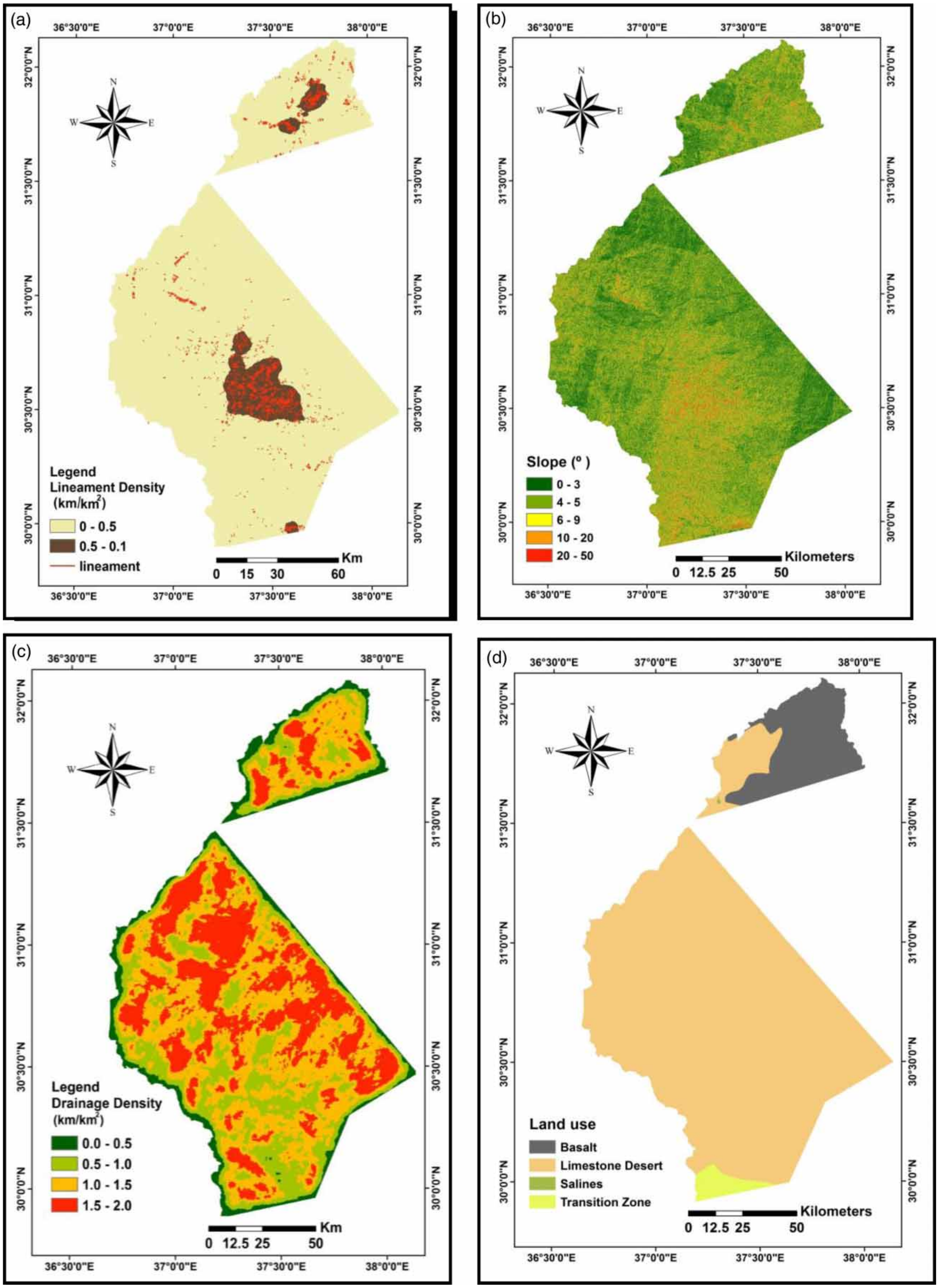


Figure 3 | Maps prepared by GIS techniques: (a) Lineament density map of the Al-Sarhan Basin. (b) Slope map of the Al-Sarhan Basin. (c) Drainage density map of the Al-Sarhan Basin. (d) Land use/land cover map of the Al-Sarhan Basin.

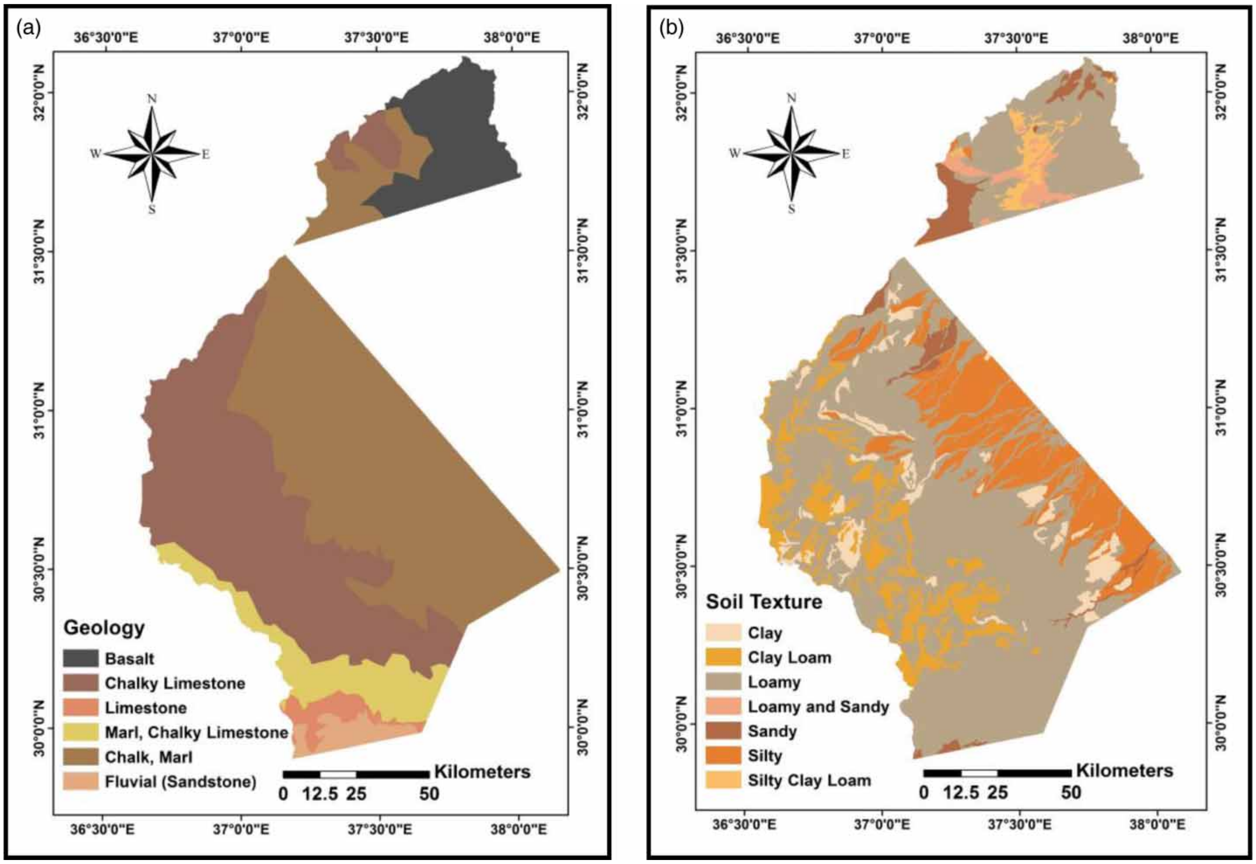


Figure 4 | Maps prepared by GIS techniques: (a) Geological map of the Al-Sarhan Basin. (b) Soil map of the Al-Sarhan Basin.

hydrogeological significance of each class. The weights and ranks assigned to each parameter that influences groundwater potential are presented in Table 1. The factors used in the calculation of the RP index were the rainfall index (RF), lithology index (LG), geomorphology index (GG), slope gradient index (SG), lineament density index (LD), drainage density index (DD), land cover/land use index (LC), and soil cover index (SC). After using the general equation to calculate the RP index (Shahid *et al.* 2000), we validated it by comparing the results with the water table level of wells in the area.

The GIS environment was used to conduct the required operations for the identification of potential groundwater sites within the study area (Table 2). First, LC was generated using the maximum likelihood method under the supervised classification in ERDAS IMAGINE software, which was imported to ArcGIS and then reclassified based on Table 1. LC values varied from 12 to 42 after reclassification (Figure 5(a)). Second, GG and SG were extracted from SRTM DEM. Table 1 was used to classify pixel values of geomorphology and slope. A single GG value of 28 indicated a flat land with a plantation surface, while SG values varied between 5 and 40 (Figure 5(b)). Third, maps for LG, RF, and SC were edited by accounting for the ratings described in Table 1 (the outputs of editing were converted from vector format into raster format). LG values varied between 16 and 48 after reclassification (Figure 5(c)). A single RF value of 4 indicated annual precipitation of less than 600 mm, whereas SC values varied between 12 and 48 (Figure 5(d)). Finally, LD and DD were calculated using the line density function tool in the GIS environment and considering the classification described in Table 1.

LD values varied between 6 and 24 after reclassification (Figure 6(a)), whereas DD values varied between 5 and 15 (Figure 6(b)).

RESULTS AND DISCUSSION

The resulting map of groundwater potential recharging indicates artificial recharging capacity and was divided into three classification zones: high (RP 172–227), moderate (RP 154–171), and low (RP 103–153) (Figure 7). The map depicts that

Table 1 | Ratings and weights for the parameters of the potential recharge index calculated as previously described (Shahid *et al.* 2000; Jaiswal *et al.* 2003; Kumar *et al.* 2007; Sarup *et al.* 2011; Yeh *et al.* 2014; Senanayake *et al.* 2016; Arulbalaji *et al.* 2019) with modifications

Parameter	Description	Rank	Weight
Soil texture			
	Non-shrinking and non-aggregated	1	6
	Clay, clay loam, muck	2	
	Silty, silty loam	4	
	Loam, loamy sandy	6	
	Sand	8	
	Gravel	9	
Geology			
	Basalt, massive shale, metamorphic, igneous	2	8
	Weathered metamorphic and igneous, massive rock with less fractures	3	
	Massive sandstone, massive limestone, shale sequences, marl limestone, chalky, carbonate rock	5	
	Fluvial (quartzite and quartz rich), alluvium (sand/silt/clay)	6	
	Karst limestone	8	
Slope (°)			
	>15	1	5
	15–10	3	
	10–5	4	
	5–2	6	
	2–1	8	
	<1	9	
Drainage density (km/km^2)			
	0–0.5	1	5
	0.5–1.0	2	
	1.0–2.0	3	
	2.0–3.0	5	
	3.0–5.0	6	
	5.0–7.0	8	
Rainfall (mm)			
	<600	1	4
	600–700	2	
	700–900	3	
	>900	5	
Lineament density (km/km^2)			
	0–0.5	1	6
	0.5–1.0	4	
	1.0–3.0	6	
Land use/land cover			
	Rock, built up	2	6
	Forest, grassland, pastures	3	
	Agriculture, cultivated land	5	
	Lakes, marshy land,	7	
	Sand	8	
Geomorphology			
	Flatlands, planation surface	4	7
	River plans	7	

Table 2 | Criteria-assigned ratings and weights of each parameter in the investigated area according to Senanayake *et al.* (2016); Shahid *et al.* (2000); Jaiswal *et al.* (2003); Kumar *et al.* (2007); Sarup *et al.* (2011); Yeh *et al.* (2014)

Class	Description	Rank	Weight	r x w
Soil texture				
	Clay, Clay Loam, Muck	2	6	12
	Silty, Silty Loam	4		24
	Loam, loamy sandy	6		36
	Sand	8		48
Geology				
	Basalt, massive shale, metamorphic, igneous	2	8	16
	Massive sandstone, massive limestone, shale sequences, marl limestone, chalky, carbonate rock	5		40
	Fluvial (quartzite and quartz rich), Alluvium (sand/silt/clay)	6		48
Slope (°)				
	>15	1	5	5
	15–10	3		15
	10–5	4		20
	5–2	6		30
	2–1	8		40
Drainage density (km/km^2)				
	0–0.5	1	5	5
	0.5–1.0	2		10
	1.0–2.0	3		15
Rainfall (mm)				
	>600	1	4	4
Lineament density (km/km^2)				
	0–0.5	1	6	6
	0.5–1.0	4		24
Land use/land cover				
	Rock, built up	2	6	12
	Lakes, marshy land	7		42
Geomorphology				
	Flatlands, plantation surface	4	7	28

25% of the Al-Sarhan area consists of zones with low groundwater recharging potential, whereas 48% of the area possesses moderate potential for artificial recharging. The statistical data revealed that 27% of the total area can be categorized as a high potential artificial recharging area. The Al-Sarhan area has a considerable artificial recharging capacity mainly because of the suitable geology, soil texture, drainage density, and flat terrain. The observation that the southern part of the study area has a high recharging potential might be due to the existence of fluvial sandstone, high infiltration rates triggered by lineaments, and a high drainage density. Figure 8 shows the potential groundwater recharge zones in the Al-Sarhan Basin.

The model was validated using data from 82 groundwater wells located in the study area. Six of these wells were located in the low zone, 17 in the moderate zone, and 59 in the high zone (Table 3). The model revealed that 93% of the wells in the study area were located in potential groundwater recharge zones (moderate/high zones).

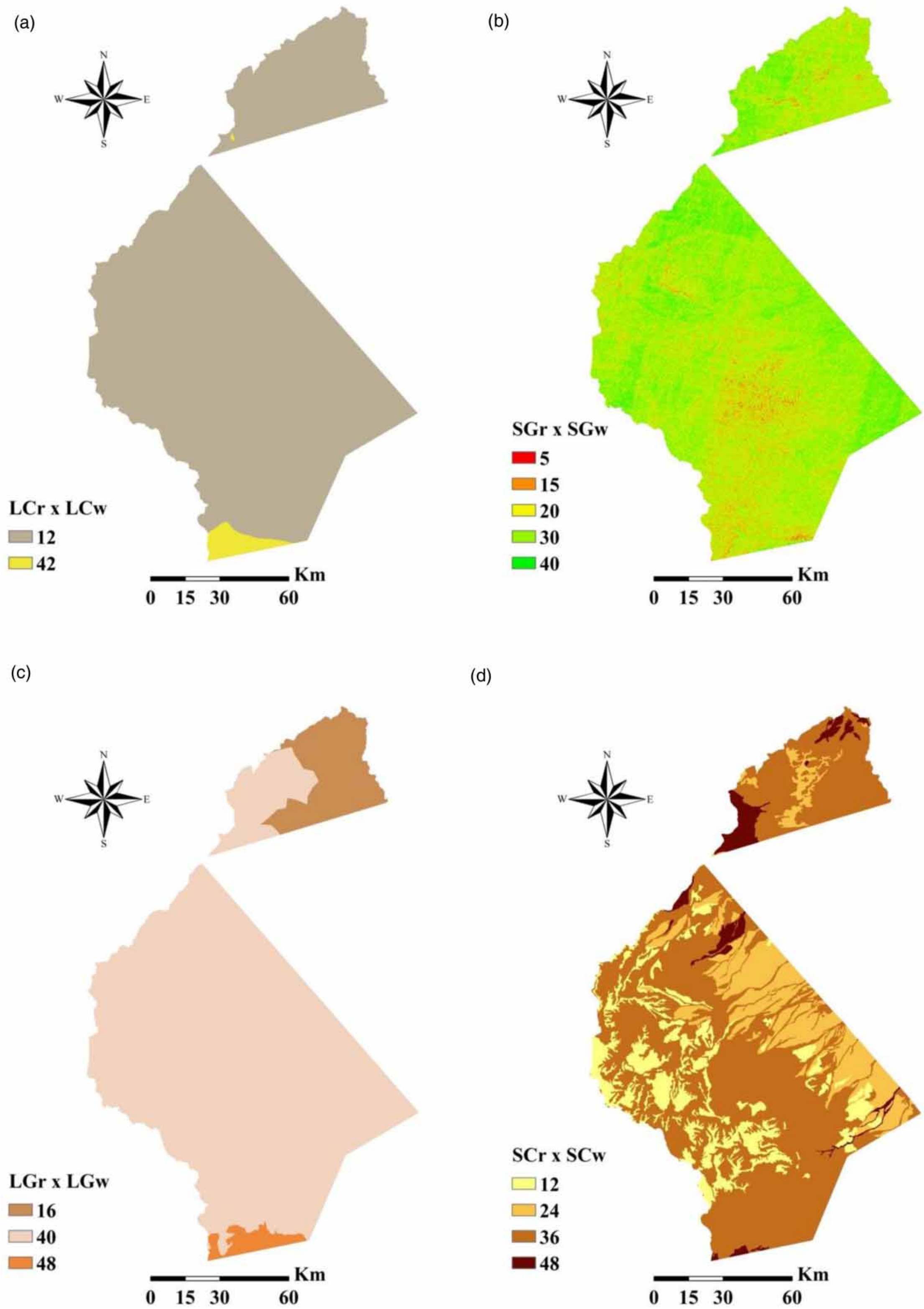


Figure 5 | GIS analysis of land cover/land use index (LC), slope gradient index (SG), lithology index (LG), and soil cover index (SC). Ratings (r) were multiplied by a weight (w) and then summated. (a) LCr × LCw; (b) SGr × SGw; (c) LGr × LGw; (d) SC × SCw.

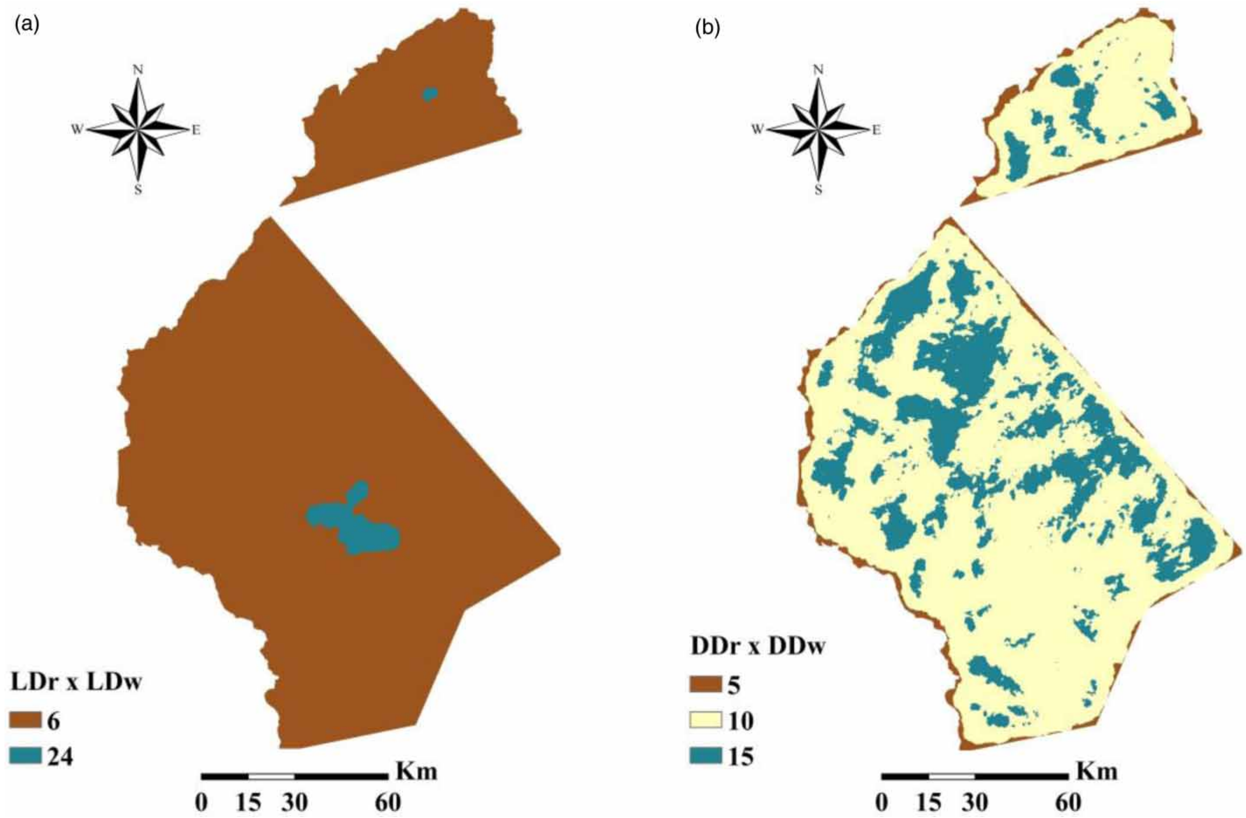


Figure 6 | GIS analysis of lineament density index (LD) and drainage density index (DD). Ratings (r) were multiplied by a weight (w) and then summated. (a) LDr × LDw; and (b) DDr × DDw.

The direction of groundwater flow in the southern part of Jordan, according to the static water level in the monitored wells, indicates the natural recharging potential throughout the study area (Figure 9). To enhance the existing groundwater resources in the Al-Sarhan area, artificial recharging strategies, such as trenches, check dams, percolation pits, recharge basins, land flooding, and recharge wells, could be built in ridges and furrows (CGWB 2007). However, recharging wells is more likely to be successful because of the high evapotranspiration rate in the Al-Sarhan area.

The use of data with increased accuracy and spatial resolution can further improve the results of the approach followed in this study. Moreover, this method can be applied to the whole territory of Jordan after adjusting parameters, ranks, and weights. The method can also be extended to other arid and semiarid regions, with appropriate modifications, to identify potential groundwater recharging zones. *In situ* field verification of the existing terrain conditions (land use/land cover and drainage systems) is useful to identify the most suitable artificial recharging strategy for replenishing groundwater in a study area. Overall, this technique provides valuable information for choosing and implementing suitable groundwater management activities.

Different studies around the globe have used geospatial tools to delineate potential zones for artificial groundwater recharge in arid and semiarid areas. Jothiprakash *et al.* (2003) and Krishnamurthy *et al.* (2000) applied these methodologies for identifying artificially rechargeable zones. The accuracy of the final results significantly depends on the thematic layers and resultant weighting factors used in the study. Magesh *et al.* (2012) and Manikandan *et al.* (2014) used the multi-influencing factor (MIF) technique to identify the zones with groundwater recharging potential. Kumar *et al.* (2007), Krishnamurthy *et al.* (2000), and Prasad *et al.* (2008) also used geospatial technologies to delineate the zones with groundwater potential in hard rock terrains with variable geological settings. Several researchers have performed the integration of influential factor layers using the weighted overlay method on a GIS platform to delineate zones with artificial recharging potential. Shaban *et al.* (2006), Yeh *et al.* (2009), and Shashikkumar & Metilda (2012) applied a similar approach to identify artificial recharging sites in hard rock terrain.

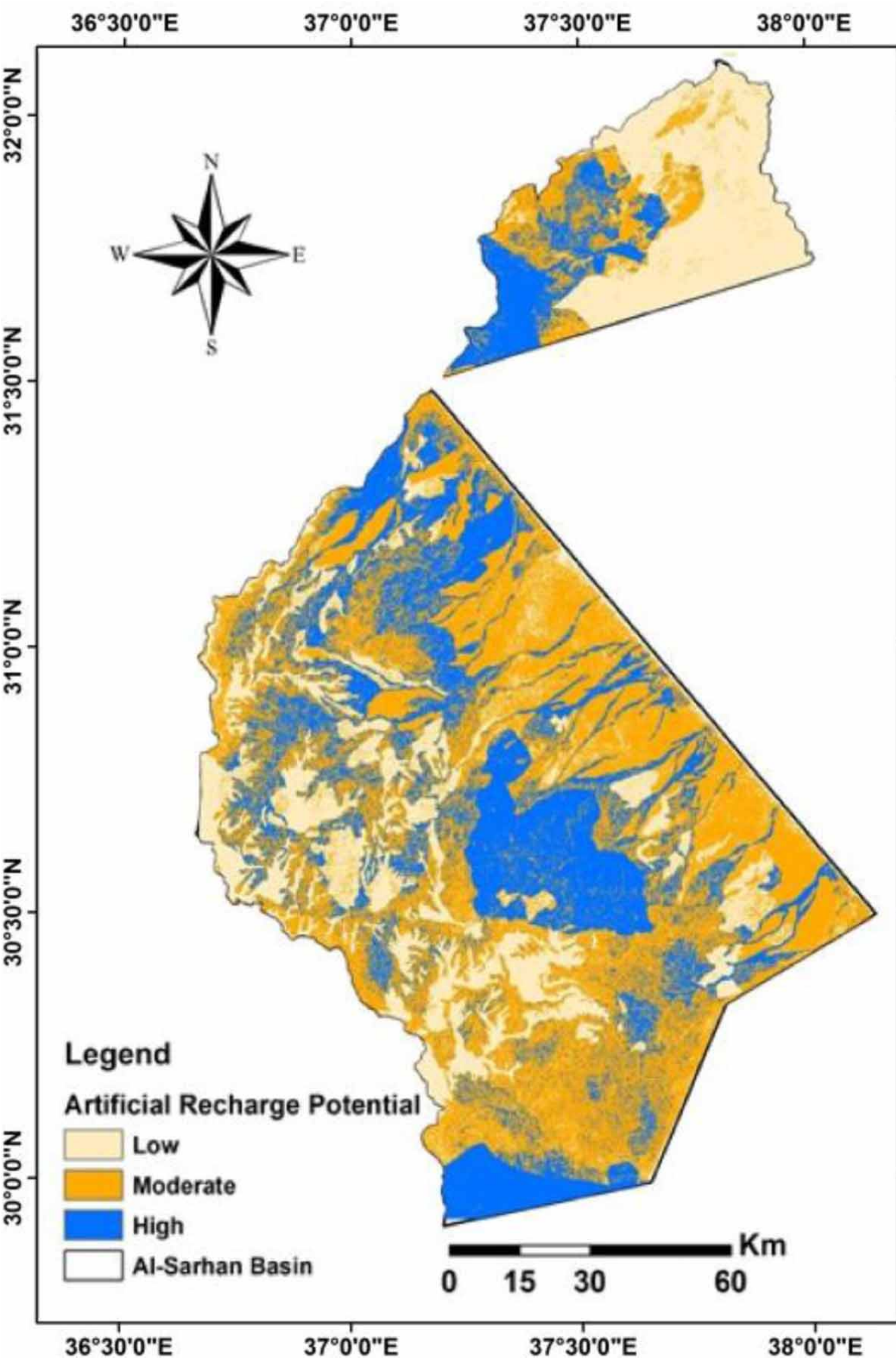


Figure 7 | Groundwater recharge potential zones in the Al-Sarhan Basin.

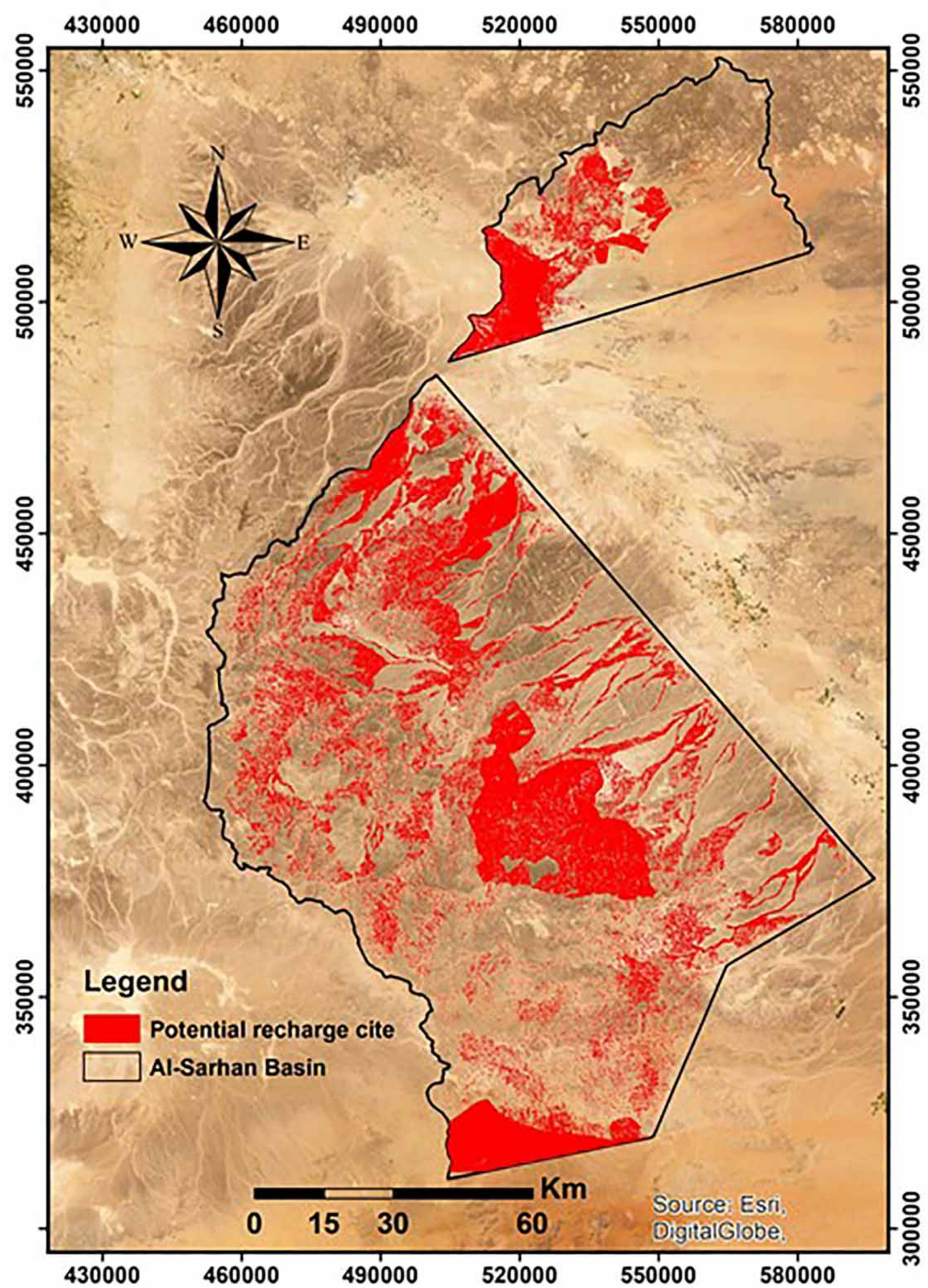


Figure 8 | Spatial distribution of potential groundwater recharge zones.

Table 3 | Zones with artificial recharging potential and groundwater wells in each zone

Recharge potential zone	Area (km^2)	Relative area (%)	Number of wells	% of wells
Low	3,921	25	6	7
Moderate	7,484	48	17	21
High	4,167	27	59	72
Total	15,572	100	82	100

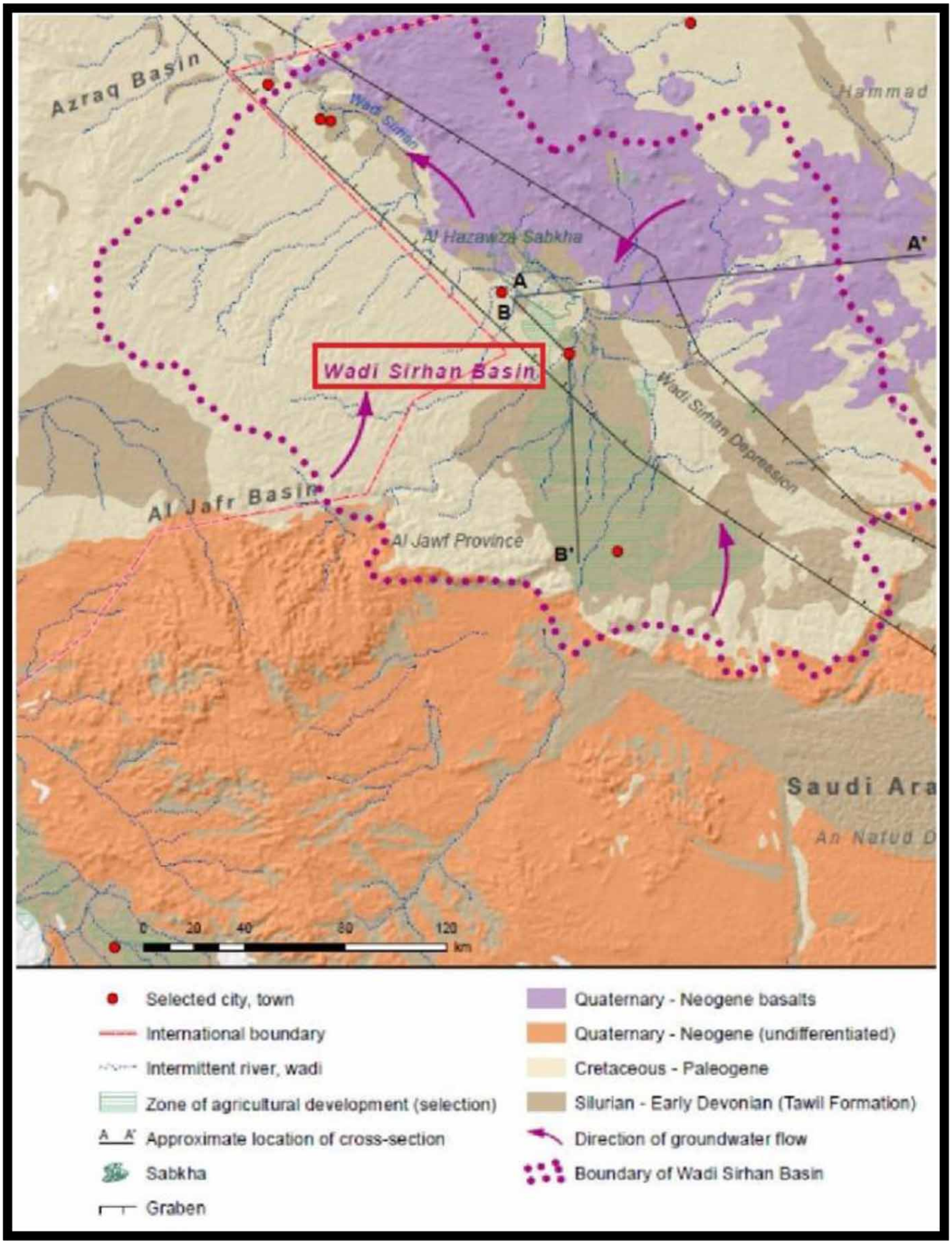


Figure 9 | Map of the groundwater flow and discharge within the Tawil quaternary aquifer system in Wadi Sarhan Basin (UN-ESCWA & BGR 2013; TWAP 2015).

CONCLUSIONS

Groundwater is the main water resource in Jordan; however, limited annual precipitation negatively affects the amount of surface and groundwater. This study applied cost-effective and time-saving remote sensing and GIS techniques to delineate the groundwater RP zones in the Al-Sarhan Basin. The study categorized the groundwater potential zones as low, moderate, and high potential zones. The high-to-moderate groundwater recharging potential extended to approximately 75% of the Al-Sarhan area, whereas 25% of the area was classified as a low groundwater potential zone. The study also revealed that approximately 7% of groundwater wells were located in regions with a low RP, 21% in regions with moderate groundwater potential, and 72% in regions with high groundwater potential. This study provides insights for developing prospective guidelines that decision-makers can follow to propose, design, and implement sustainable recharging projects within the concerned areas. Furthermore, this groundwater potential zone map could facilitate proper planning and management of groundwater usage in other arid and semiarid regions.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships, and they are not affiliated with or involved with any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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