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Identifying potential sites for artificial groundwater recharge using GIS and AHP techniques: A case study of Erbil basin, Iraq

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Abstract

Excessive extraction, uncontrolled withdrawal of groundwater, and unregulated practices have caused severe depletion of groundwater resources in the Erbil basin, Iraq. This situation has had a number of negative consequences on human settlement, agricultural activities, clean water supply, and the environment. Runoff harvesting and artificial groundwater recharge play a significant role in the sustainable management of water resources, particularly in arid and semi-arid regions. This study aims to: (1) delineate groundwater recharge zones using multiple thematic layers that control the groundwater recharge process, and (2) identify prospective sites and structures to perform artificial groundwater recharge. In order to generate a potential map for groundwater recharge zones, seven thematic layers are considered in this study, namely, topographic position index, geomorphology, lithology, land cover, slope, drainage-length density, and lineament-length density. After that, the analytic hierarchy process was applied to weight, rank, and reclassify these seven thematic layers. All maps are then integrated within the ArcGIS environment for delineating groundwater recharge zones. Accordingly, the resulting map categorizes the study area into five zones: extremely high, high, moderate, low, and extremely low potential for groundwater recharge. As expected, areas along the Greater Zab river show the highest possibility for groundwater recharge. Likewise, rugged eastern hills demonstrate an encouraging capacity for artificial aquifer recharge, whereas the least effective area is represented by built-up land. Based on the generated map, two dams are proposed as promising artificial recharge structures for harvesting runoff water east of Erbil city. Lastly, the resulting map of the potential groundwater recharge zones is verified using static water level data, where the coefficient of determination (R^2) achieved a satisfactory result (0.73). These findings provide crucial evidence for implementing a sustainable management plan for surface and groundwater resources. The applied method is eventually valid for regions where appropriate and adequate field data availability is a serious issue.

Keywords: Artificial recharge; groundwater; runoff harvesting; GIS; Iraq.

1. Introduction

Groundwater is one of the most extensively exploited natural resources in many parts of the world. In the past decades, groundwater extraction has immensely increased due to the development of new and affordable drilling and pumping techniques (Barbier, 2019). As groundwater resources are dynamic and interdisciplinary, they are influenced by different human activities, including urbanization, expansion of cultivated and irrigated areas, industrialization, and also by natural features such as geological structures of different compositions (Nalbantcilar & Guzel, 2006; Thangarajan, 2007; Kavaf & Nalbantcilar, 2007; Nalbantcilar & Pinarkara, 2015; Nalbantcilar & Pinarkara, 2016). According to Ahmed *et al.* (2008), over-exploitation of groundwater resources causes regional imbalances in both water demand and supply. Therefore, it has become critical to implement sustainable management plans to avoid groundwater depletion due to insufficient natural recharge.

The water resources in Iraq have considerably reduced due to the dam construction strategy in the upstream countries (Turkey, Iran, and Syria), chiefly including the Southeastern Anatolia Project (GAP) that Turkey has accomplished. The GAP project involves constructing 22 massive dams on the Tigris and Euphrates rivers to control surface water flow. After completing the GAP project, water stress dramatically increased in Iraq (Al-Muqdadi, 2019). The expansion of agricultural and industrial projects and drought conditions intensely depleted water resources in the Iraqi Kurdistan Region. Accordingly, a substantial reduction in groundwater levels has been observed in many parts of the Erbil basin. Replenishing groundwater through artificial recharge has been carried out in different parts of the world (Bowen, 1986) and some parts of Iraq (Salar *et al.,* 2018; Al-Manmi *et al*., 2021). Although precipitation is the primary source of natural recharge, it forms a small percentage, especially in dry countries (Boyko *et al.,* 2021). Hence, runoff harvesting and artificial recharge represent alternative techniques for the longevity of freshwater resources (Chowdhury *et al*., 2009). The procedure involves collecting and storing the runoff water in the subsurface to meet future water demands (Kumar *et al*., 2016).

Many scientific reports have been published worldwide on utilizing remote sensing (RS) and geographic information system (GIS) to investigate water resources. Researchers in watershed engineering and other fields have recently become increasingly interested in using GIS to fulfill site selection for artificial groundwater recharge (Rahimi *et al.*, 2014). In the study area, wars and internal conflicts have prevailed for the past decades. Thus, only a few water resources studies have been carried out using GIS and RS data. Hameed (2013) applied RS and GIS techniques to detect suitable water harvesting sites in the Erbil Governorate. In another study, Mulder *et al*. (2015) used GRACE satellite data to identify water mass variation in northern Iraq. Another study from Hameed (2017) estimated the consequences of urban growth and land-use changes on annual runoff in the Erbil subbasin using the GIS technique.

Since the region of interest is severely afflicted with water scarcity challenges, aquifer replenishment through artificial recharge is necessary to sustain the groundwater resources on a long-term basis. Due to the inadequacy of essential hydrogeological data for the entire study area, the present study is mainly built on surface parameters that control groundwater recharge. In this paper, the normalized weights of seven thematic layers are calculated using the analytic hierarchy process (AHP) and then integrated within ArcGIS 10.1. Up till now, the AHP method has represented a practical approach to identifying groundwater potential recharge zones (Akbari *et al*., 2021; Das *et al.*, 2021; Vishwakarma *et al*., 2021). The present study was designed to delineate potential zones and identify suitable sites and structures for artificial groundwater recharge in the Erbil basin based on AHP and GIS. The resulting map of potential recharge zones was visually and statistically compared with the static water level map to check the accuracy of the proposed model. Consequently, the findings provide decision-makers with a scientific basis for further assessing and sustainably managing water resources. To date, no such research has been reported in the study area.

2. Study area

The study area is mainly located within the Erbil Governorate, north of Iraq. The region of investigation lies between longitude 43°30'E - 44°17'E and latitude 35°52'N - 36°29'N. It covers about 3000 km^2, forming 20% of the Erbil Governorate's total area (Figure 1). The study area has semi-arid climate conditions with cold winter and dry-hot summer. Rainfall occurs mainly between October and May, where the average annual rainfall is approximately 400 mm (Hameed, 2013). The primary water resources in the Erbil basin include rain, groundwater, and surface water, the latter represented by the Greater Zab River (GZR). The GZR crosses the study area from the northwest, a significant source of groundwater recharge. Bastora valley surrounds the north-northeast area, in which valley flow discharges into the GZR. Recent alluvial deposits and Miocene-Pliocene formations form the primary aquifer system in the study area. This intergranular aquifer system is usually highly productive, and the discharge of many wells exceeds 30 l/s (Stevanovic & Iurkiewicz, 2009). Most croplands are irrigated by rainfall and groundwater, while surface water is frequently used for drinking and domestic purposes.

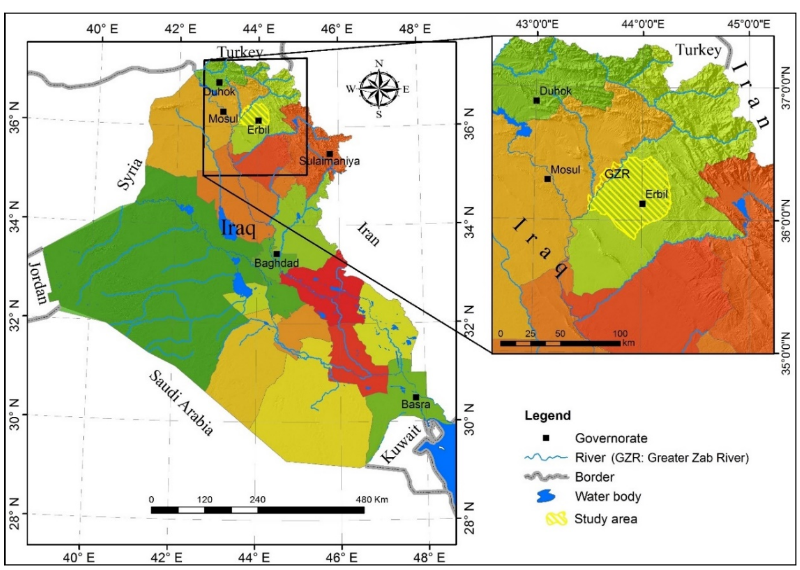

Fig. 1. Location map of the study area.

3. Geological setting

The collision of Arabian and Eurasian plates shaped Iraq's modern tectonic features (Salar *et al*., 2018). Iraq territory is divided into three main tectonic zones: (1) Stable Shelf, (2) Unstable Shelf (US), and (3) Zagros Suture Zone. The US involves the Mesopotamia Foredeep, the Foothill Zone (FZ), the High Folded Zone, and the Imbricated Zone. Furthermore, each of these zones has its characteristics; age, rock type, thickness, and structural evolution. Surface folds are an essential characteristic feature of the US. Besides, the rocks of the US were affected by Alpine orogeny during the Mesozoic Era. The study area is a part of the FZ, which comprises long-narrow anticlines (trending NW-SE) of different amplitude and broad synclines containing thick Miocene-Quaternary molasse (Jassim & Goff, 2006; Othman *et al*., 2018).

Five geological formations crop out in the study area: Pila Spi, Fatha, Injana, Mukdadiya, and Bai Hassan. Pila Spi Formation belongs to the Middle-Upper Eocene age and consists of well-bedded, porous, chalky, bituminous, poorly fossiliferous limestone (Jassim & Goff, 2006). Fatha Formation of the Middle Miocene age is divided into two parts; the lower portion comprises thick reddish and greenish silty claystone, thin-bedded limestone, and grayish sandstone. In comparison, the upper part is composed of alternating beds of gypsum, anhydrite, and salt, interbedded with limestone, marl, and reddish-brown clastics. Injana Formation (Late Miocene age) consists of coarsening-upward cycles of brown, red, grey claystone, siltstone, and sandstone, with thin limestone gypsum horizons. Mukdadiya Formation of Late Miocene–Pliocene age comprises alternating layers of pebbly sandstone, coarse sandstone, claystone, and siltstone. Bai Hassan Formation, which belongs to the Pliocene-Pleistocene age, mainly consists of coarse and thick fluviatile conglomerate, sandstone, and claystone. At the same time, the Quaternary deposits of the Pleistocene-Holocene age cover a considerable part of the investigation area, such as sediments of slope and floodplain, river terraces, and polygenetic. Coarse clastics characterize the sediments of Quaternary deposits, a mixture of conglomerate and gravel intermixed with clay and sand (Sissakian & Al-Jiburi, 2012).

4. Materials and methods

4.1 Data acquisition

GIS-AHP-based model and multi-parametric data sets were applied in this study to determine potential recharge zones and find suitable sites for artificial groundwater recharge in the Erbil basin. Hence, seven frequently used factors were identified that control groundwater recharge. These factors include topographic position index (TPI), geomorphology, lithology, land cover, slope, drainage-length density (DD), and lineament-length density (LD). The Iraq geological survey (GEOSURV) provided pre-existing maps of four layers with a scale of 1:250,000 (geomorphology, lithology, land cover, and lineament). Because these four maps were in paper format, they were first scanned and georeferenced to the UTM coordinate system in zone 38 north. After that, the four maps were digitized in ArcGIS 10.1.

The ASTER Global Digital Elevation Model (ASTER GDEM) at 30 m resolution was obtained from the United States Geological Survey (USGS). Moreover, the slope, TPI, and drainage map were derived from the ASTER GDEM. The static water level data from 101 randomly distributed monitoring wells over the entire study area were gathered from the GEOSURV. These collected data were utilized to generate a thematic map for each of the seven factors and validate the results. Thus, the weights of different themes and their corresponding features were assigned using the integrated GIS and the AHP method. Afterward, the seven generated thematic maps were overlayed by raster calculation for mapping and identifying potential recharge zones. Later, based on runoff availability, ASTER GDEM, TPI class, and drainage network map, two basins were chosen to implement artificial groundwater recharge. Lastly, the generated map was compared with the static water level map to validate the proposed methodology.

4.2 Preparation of thematic layers

4.2.1 Elevation

The elevation represents an essential factor that plays a vital role in deriving TPI, drainage networks, watershed delineation, and slope maps. According to Salar et al. (2018), elevation has an inverse relationship with groundwater recharge; the lower the height, the higher the possibility of surface water accumulation and infiltration, where surface water tends to flow towards lower elevations. ASTER GDEM is nominally the most detailed GIS layer with public access (Hengl & Reuter, 2011). The elevation map is derived from the ASTER GDEM. The study area elevation ranges from 176 to 1182 m above sea level (Figure 2a).

4.2.2 Watershed delineation

Watershed delineation is the process of defining an area that contributes surface water flow to a single outlet point. Amid technical development in geospatial software, GIS became a widely used hydrologist tool for delineating the watershed boundary (Castronova & Goodall, 2014). ArcGIS calculates diverse terrain processing components for watershed delineation, including determining flow direction, flow accumulation, depression filling, extracting stream network, and outlets. In the present study, the watershed was delineated and derived from the ASTER GDEM as input data using the watershed tools in ArcGIS 10.1. The study area comprises 13 watersheds, generally elongated in the NE-SW direction (Figure 2b).

4.2.3 Topographic position index (TPI)

TPI is the difference in elevation between the central cell and the average elevation of neighboring cells with a predetermined radius (Wilson & Gallant, 2000). Further, TPI is widely used in hydrology, geomorphology, agriculture, geology, aquifer recharge, hydrogeology, forest management, climatology, behavioral ecology, bathymetry, archaeology, risk management, and wildlife management (De Reu *et al.*, 2013; Nalbantcilar *et al.*, 2009). In the current study, the TPI layer was derived from the ASTER GDEM using the open-source SAGA GIS software. The search radius of the kernel was set to 6000 m with a 30 m output cell size. The TPI is calculated based on the following equation (Othman *et al.*, 2018):

$$TPI = Ec - Ea \tag{1}$$

$$Ea = \frac{1}{n_M} \sum_{i \in m} E_i \tag{2}$$

where Ec is the elevation of the central cell, Ea is the average elevation of surrounding cells, and Ei is the elevation of the cell (i) within the kernel-matrix (M), which includes (n) cells. A positive TPI value suggests the cell is near the top of a ridge or hill, and a negative value proposes the cell is close to the bottom of a valley. Zero value could mean either a mid-slope area or flat terrain (Tagil & Jenness, 2008). TPI map is classified in this study into five classes (Figure 3a).

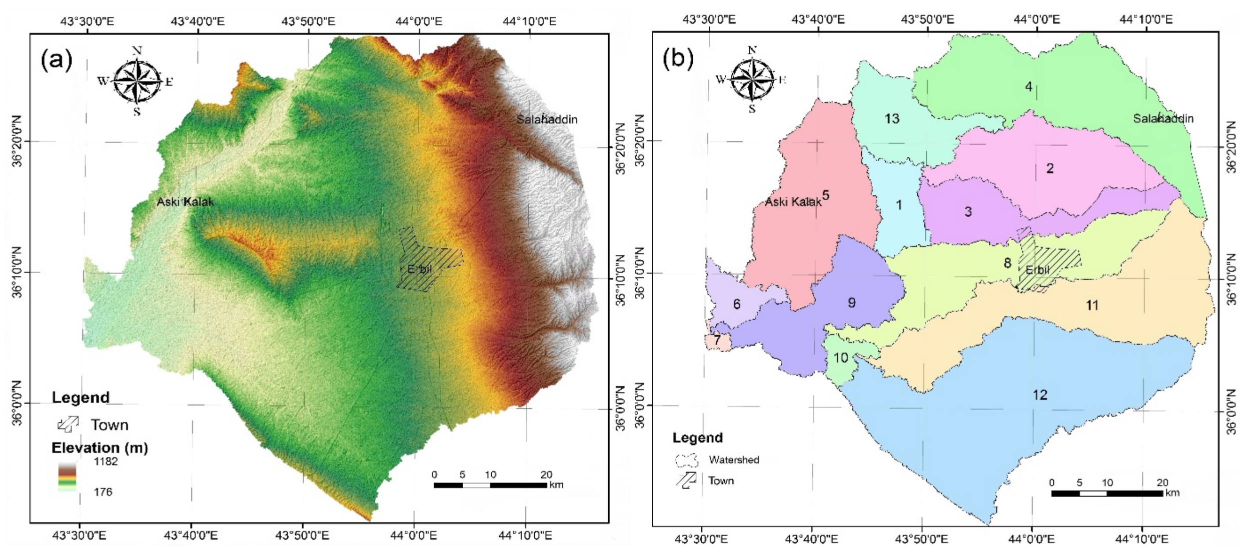

Fig. 2. Maps of (a) elevation and (b) watershed delineation of the study area.

4.2.4 Slope

The slope is the incline of a terrain's ground surface measured in degrees from 0 to 90. Besides, it is the steepest slope of a plane defined by the cell and its eight surrounding cells (Bajjali, 2018). According to Aluko & Igwe (2017), the slope represents another factor that plays an essential role in predicting water flow direction; it controls groundwater recharge and discharge processes. The flat plains tend to hold more rainwater and consequently facilitate the recharge process. In contrast, mountainous areas with high slope degrees have a high potential for runoff and low infiltration capability (Singh *et al.*, 2013). The spatial distribution of the slope demonstrates noticeable variations from the northeastern part to the southwestern area of the investigated basin (Figure 3b).

The slope layer was generated from the ASTER GDEM using ArcGIS, and it is grouped into five classes.

4.2.5 Lithology

The lithological character of exposed rocks and sediments significantly governs groundwater recharge (Shaban *et al*., 2005). Two lithological units exist in the study area, Tertiary formations and Quaternary sediments. Tertiary formations occupy the higher elevation areas, namely Pila Spi, Fatha, Injana, Mukdadiya, and Bai Hassan. In comparison, lowlands within the study area belong to the Quaternary sediments. Pila Spi Formation is represented by well-bedded and highly fractured limestone (Sissakian & Al-Jiburi, 2012). The fissured aquifer of Pila Spi is a substantial source of groundwater; in some cases, well productivity might achieve 40 l/s. The heterogeneous facies of Fatha and Injana formations comprise sandstones, marls, gypsum, anhydrite, sand, clays, and conglomerates. Groundwater in both formations is generally brackish with relatively more fresh water in Injana Formation. Since Fatha and Injana formations have repetitive cycles of impermeable rocks, the groundwater resources are insignificant and could solve only local water needs (Stevanovic & Iurkiewicz, 2009).

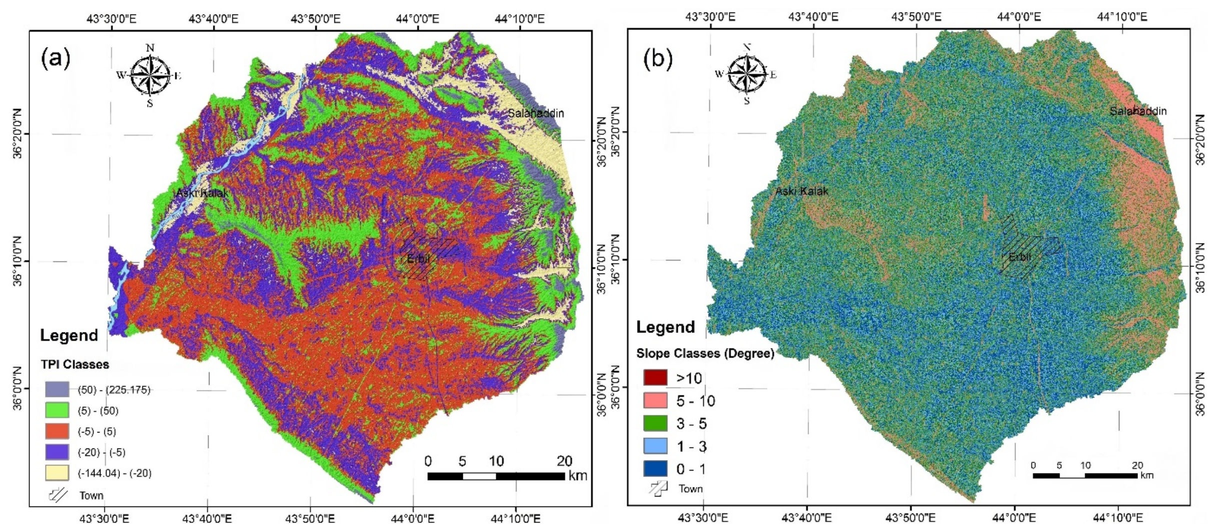

Fig. 3. Maps of (a) topographic position index (TPI) and (b) slope of the study area.

The heterogeneous lithology of Mukdadiya and Bai Hassan formations covers a large surface in the study area. With a massive thickness, it consists of a successive repetition of pebbly sandstone, sandstone, claystone, siltstone, and conglomerate (Sissakian & Al-Jiburi, 2012). These repetitive cycles of fine, medium, and coarse-grained textures are typical characteristics of this aquifer system. Several deep wells were drilled in the Mukdadiya-Bai Hassan aquifer with relatively high discharge; some wells exceeded 30 l/s (Stevanovic & Iurkiewicz, 2009). The unconsolidated Quaternary sediments cover large areas in the investigation region, mainly four types: river terraces, floodplains, slopes, and polygenetic sediments, forming the study area's central aquifer system (Sissakian & Al-Jiburi, 2012). In the present study, the lithological map was obtained from the GEOSURV. The geological formations and Quaternary deposits are classified into nine classes according to their impact on groundwater recharge (Figure 4a).

4.2.6 Land cover

The land cover represents a fundamental indicator for selecting suitable sites for artificial groundwater recharge (Singh *et al.*, 2013). It includes the distribution of residential areas, soil type, and vegetation cover. The vegetation cover plays a vital role in the infiltration capacity, where the root system of plants increases soil porosity. Accordingly, it raises water infiltration into the subsurface (Shaban *et al*., 2005). The runoff, infiltration, and evapotranspiration vary based on the type of land cover. Croplands comprises increased infiltration rates and decreased runoff components, whereas bare and built-up lands tend to have high runoff and low infiltration and recharge (Anbazhagan *et al*., 2005). The land cover map was gathered from the GEOSURV and classified into seven classes: agricultural land, bare land, field, mixed-barren land, waterbody, irrigated land, and the built-up parts (Figure 4b).

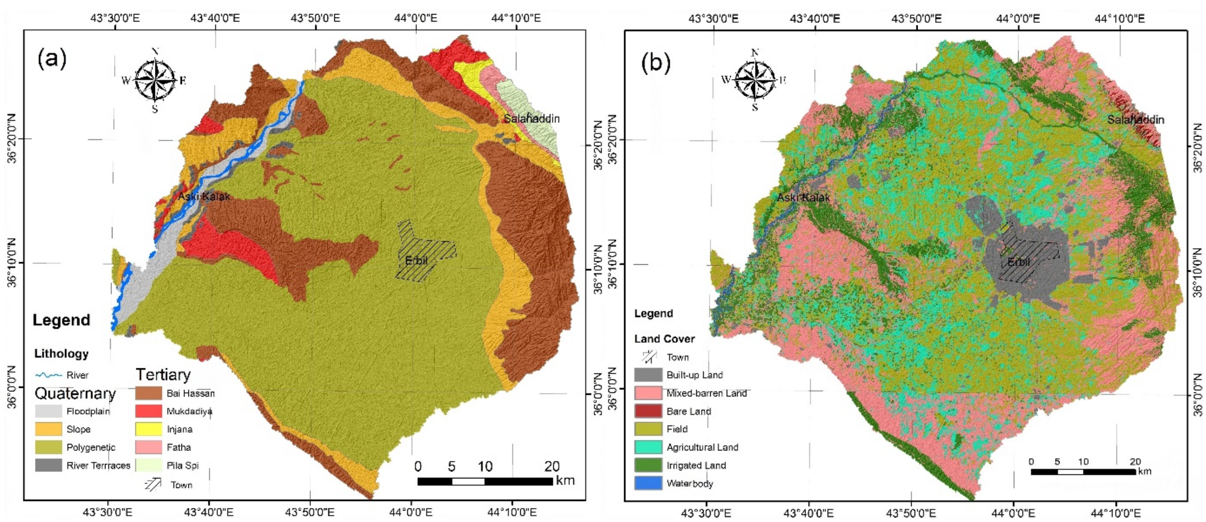

Fig. 4. Maps of (a) lithology and (b) land cover of the study area.

4.2.7 Geomorphology

Geomorphology refers to studying the earth's physical land-surface features such as hills, plains, and beaches. It investigates landforms and the processes that fashion them. Further, the water and rock cycles are crucial for understanding landform evolution (Huggett, 2011). Aluko & Igwe (2017) stated that geomorphology is one of the controlling factors for assessing potential groundwater recharge sites. Different structural features and landforms are significantly helpful for identifying prospective areas of groundwater occurrence. Broad plains with moderate slopes, alluvial fans, and pediments are considered favored locations for developing artificial groundwater recharge projects (Rahimi *et al.*, 2014). In this study, the geomorphological map was obtained from the GEOSURV. The study area includes eight geomorphological units of floodplain and island, terraces, badland, depositional glacis, cuestas and hogbacks, erosional glacis, infill valley, and structural ridge. Each geomorphological feature shows a typical influence on aquifer recharge (Figure 5a).

4.2.8 Drainage-length Density (DD)

The DD is expressed as the total length of all channels per the drainage basin's total area (km/km^2), which describes the closeness of channel spacing (Singh *et al.*, 2013). Numerous factors control the formation of a drainage system, like lithology, geological structure, soil properties, slope angle, infiltration rate, and vegetation cover (Salar *et al.*, 2018). According to Chowdhury *et al.* (2009), an inverse relationship exists between permeability and drainage density. The higher the drainage density, the lower the infiltration of rainwater, and vice versa. DD may indicate a channel system's development, surface runoff, rock permeability, and infiltration rate. Thus, it can be considered an indirect indicator of an area's suitability for artificial aquifer recharge. The DD value is computed from the following equation (Yeh *et al.*, 2009):

$$DD = \frac{\sum_{I=1}^{i=n} Si}{A} \tag{3}$$

where Si denotes the total length of drainage in km, and A is the area in km^2. In this study, the DD map was derived from the ASTER GDEM with a search kernel radius of 6000 m using ArcGIS 10.1. Strahler classification was used to assign a numeric order to link the drainage networks. The DD map is grouped into four classes based on its significance for identifying suitable sites for groundwater recharge (Figure 5b).

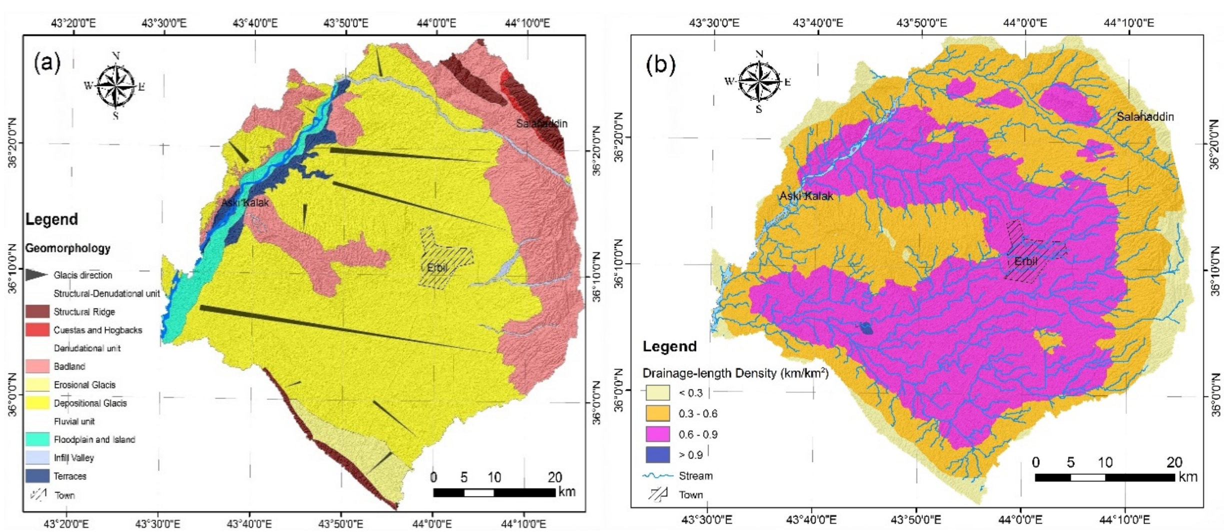

Fig. 5. Maps of (a) geomorphology and (b) drainage-length density of the study area.

4.2.9 Lineament-length Density (LD)

Lineament is a visible straight or curved linear feature on the ground surface. It can be human-made structures like canals and roads or geological structures such as fractures, cleavages, stream networks, faults, folds, and various discontinuity surfaces. Besides, lineaments can be mapped either in field surveys or by using remotely sensed data (Yeh *et al.*, 2009). Lineaments are an indispensable guide for groundwater exploration, where many successful groundwater investigations for determining drilling sites were based on the lineaments map (Teeuw, 1995). Jhariya *et al*. (2016) stated that the intersection of lineaments defines a potential groundwater recharge zone.

The lineaments map of the study area was obtained from the GEOSURV. This map was extracted by visual interpretation from LANDSAT MSS images. LANDSAT images' interpretation was primarily based on the lineaments and folds delineation in Iraq (Al-Amiri, 1982). The lineaments map was scanned with 300 dpi and georeferenced to the UTM coordinate system in Zone 38 north, then digitized in ArcGIS 10.1. The LD is defined as the total length of lineaments per unit area (km/km^2) and calculated through the following formula (Yeh *et al*., 2009):

$$LD = \frac{\sum_{I=1}^{i=n} Li}{A} \tag{4}$$

where Li is the total length of lineaments in km, and A is the area in km^2. An area with high LD indicates high secondary porosity, consequently, a high potential for groundwater recharge (Yeh *et al*., 2009). The LD map is classified into three classes (Figure 6).

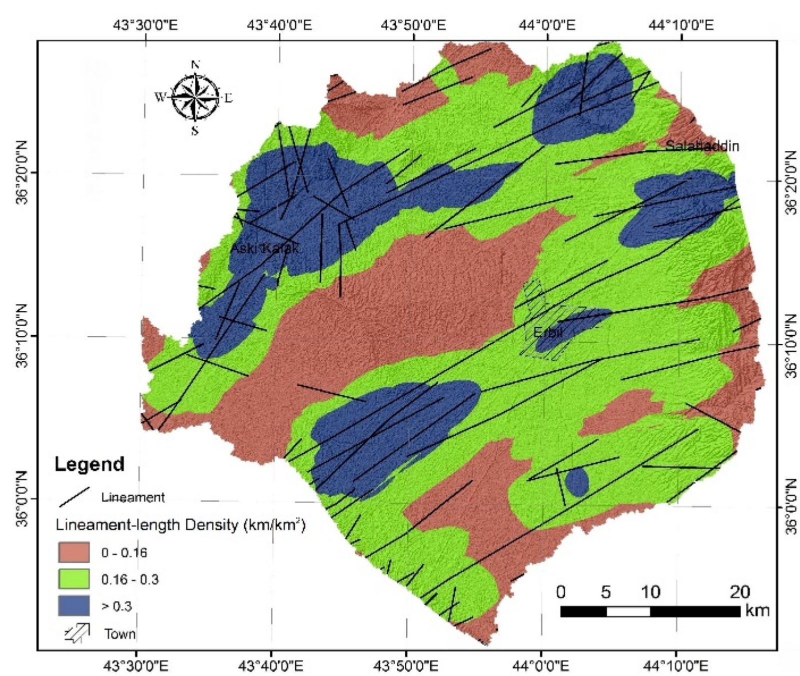

Fig. 6. Lineament-length density map of the study area.

4.3 Analytic Hierarchy Process (AHP)

This method was initially developed by Saaty (1990) as a verbal scale that enables decision-makers to incorporate subjective knowledge and experience naturally and intuitively (Saaty & Vargas, 2012). AHP is a mathematical method for organizing and analyzing complex decisions with multiple attributes (Al-Abadi & Al-Shamma'a, 2014). It decomposes a complex multi-criteria decision problem into a multi-dimensional hierarchical structure of criteria, objectives, and alternatives (Stojanovic *et al*., 2015). In other words, AHP formulates a decision problem in the form of a hierarchy structure, where a hierarchy is an efficient approach for organizing complex systems. In a typical hierarchy, the top levels indicate the overall objective of the decision problem. The elements influencing the decision are signified at an intermediate level. The lowest level comprises the decision options. After a hierarchy is built, the decision-maker starts a prioritization procedure to determine the relative importance of elements in each hierarchy level, where the elements in each level are compared as pairs with respect to their importance in making a decision (Al-Abadi & Al-Shamma'a, 2014). In the present study, the layers are reclassified and mapped using the AHP method in the ArcGIS environment to delineate potential groundwater recharge zones. Table 1 illustrates ratings on a nine-point continuous scale (Saaty & Vargas, 2012).

The AHP method is used for weighting and rating the input parameters for delineating prospective recharge zones. This was based on a previous literature review that applied these controlling factors for mapping aquifer recharge zones (Jhariya *et al*., 2016; Aluko & Igwe, 2017; Salar *et al.*, 2018). The utilized themes are TPI, geomorphology, lithology, land cover, slope, DD, and LD. Based on the reviewed literature, these themes and their features were weighted, ranked, and reclassified using the AHP method. The weights of different themes were assigned on a scale of 2-9 based on their relative importance for the recharge process. Likewise, the weight of each feature class of a particular theme was assigned on a scale of 1-7 (Table 2). Thus, the feature classes of each theme were quantitatively weighted as very good (weight 6-7), good (weight 5-6), moderate (weight 3-5), poor (weight 2-3), and very poor (weight = 1-2).

Table 1. The fundamental scale of AHP.

Rank	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extremely importance

4.4 Integration of thematic layers and validation

Integration of thematic layers is an analytical technique for multiple attribute considerations like site selection or suitability modeling (Salar *et al.*, 2018). Groundwater potential refers to the possibility of groundwater occurrence in a particular area. It is a function of several hydrologic and hydrogeological parameters (Jha *et al.*, 2010). Further, an appropriate assessment of groundwater potential can serve as a valuable tool for sustainably managing an aquifer system (Al-Abadi & Al-Shamma'a, 2014). In this study, the delineation and identification of prospective groundwater recharge sites are implemented through weighted overlay processes and combinations of the seven thematic layers in the ArcGIS environment. Salar *et al*. (2018) stated that the weighted linear combination represents the most frequently used technique for multi-criteria evaluation. The assigned weights of these seven themes are shown in Table 2. The map of potential groundwater recharge zones (PGWRZ) in the Erbil basin is calculated by the raster overlay algorithm using the following equation (Salar *et al*., 2018):

$$PGWRZ = \sum_{i=1}^{n} xiwi \tag{5}$$

where xi is the weight of theme i, wi is the weight of feature i, and n is the number of themes (Table 2). Values of the different factors were normalized to obtain a unified scale so that all thematic layers would be positively correlated. The resulting map determined five potential zones for groundwater recharge.

For the validation, we used static water level data that was obtained from the GEOSURV. These data comprise 101 monitoring wells dug in the study area. In addition to the visual interpretation between the PGWRZ and the interpolation map of the static water level, the R^2 was used to verify the accuracy of the applied model to identify suitable sites for artificial aquifer recharge.

Table 2. Assignment of weight for the themes and their corresponding features.

Theme	Weight	Feature	Ranking
Topographic position index	9	(-144) - (-20)	7
		(-20) - (-5)	6
		(-5) - (5)	4
		(5) - (50)	2
		(50) - (225)	1
Geomorphology	8	Floodplain and Island	7
		Terraces	7
		Infill Valley	6
		Depositional Glacis	5
		Badland	4
		Cuestas and Hogbacks	3
		Erosional Glacis	3
		Structural Ridge	1

Lithology	7	Pila Spi Formation	7
		Bai Hassan Formation	7
		Mukdadiya Formation	7
		River terraces	6
		Floodplain	5
		Injana Formation	4
		Polygenetic	4
		Slope	3
		Fatha Formation	2
Land cover	6	Water Body	7
		Irrigated Land	7
		Agricultural Land	6
		Field	5
		Bare Land	5
		Mixed-Barren Land	4
		built-up	1
Slope (degree)	5	0 - 1.0	7
		1.0 - 3.0	6
		3.0- 5.0	4
		5.0 - 10	3
		> 10	1
Drainage-length density (km/km^2)	3	0 - 0.30	5
		0.30 - 0.60	4
		0.60 - 0.90	3
		> 0.90	2
Lineament-length density (km/km^2)	2	0.30 - 0.60	4
		0.16 - 0.30	3
		0 - 0.16	1

5. Results

This study generated a potential map for the groundwater recharge zones using weighted overlay processes of seven parameters: TPI, geomorphology, lithology, land cover, slope, DD, and LD in the ArcGIS environment. The resulting map is classified into five categories: extremely low, low, moderate, high, and extremely high (Figure 7). The findings indicate that sites with high and extremely high recharge classes are located in the rugged eastern hills, areas along the GZR, and northern parts of the study area and occur in the lower reaches of the valleys, lowlands, and coarse-grained rock units of Mukdadiya and Bai Hassan formations. These high and extremely high classes also involve Quaternary sediments like floodplains and river terraces. Several geomorphological features and land cover classes are dominated in high and extremely high recharge zones, such as floodplain and island, badland, infill valley, mixed-barren land, and irrigated land, where this area provides appropriate conditions for percolating rainwater to recharge the subsurface aquifers.

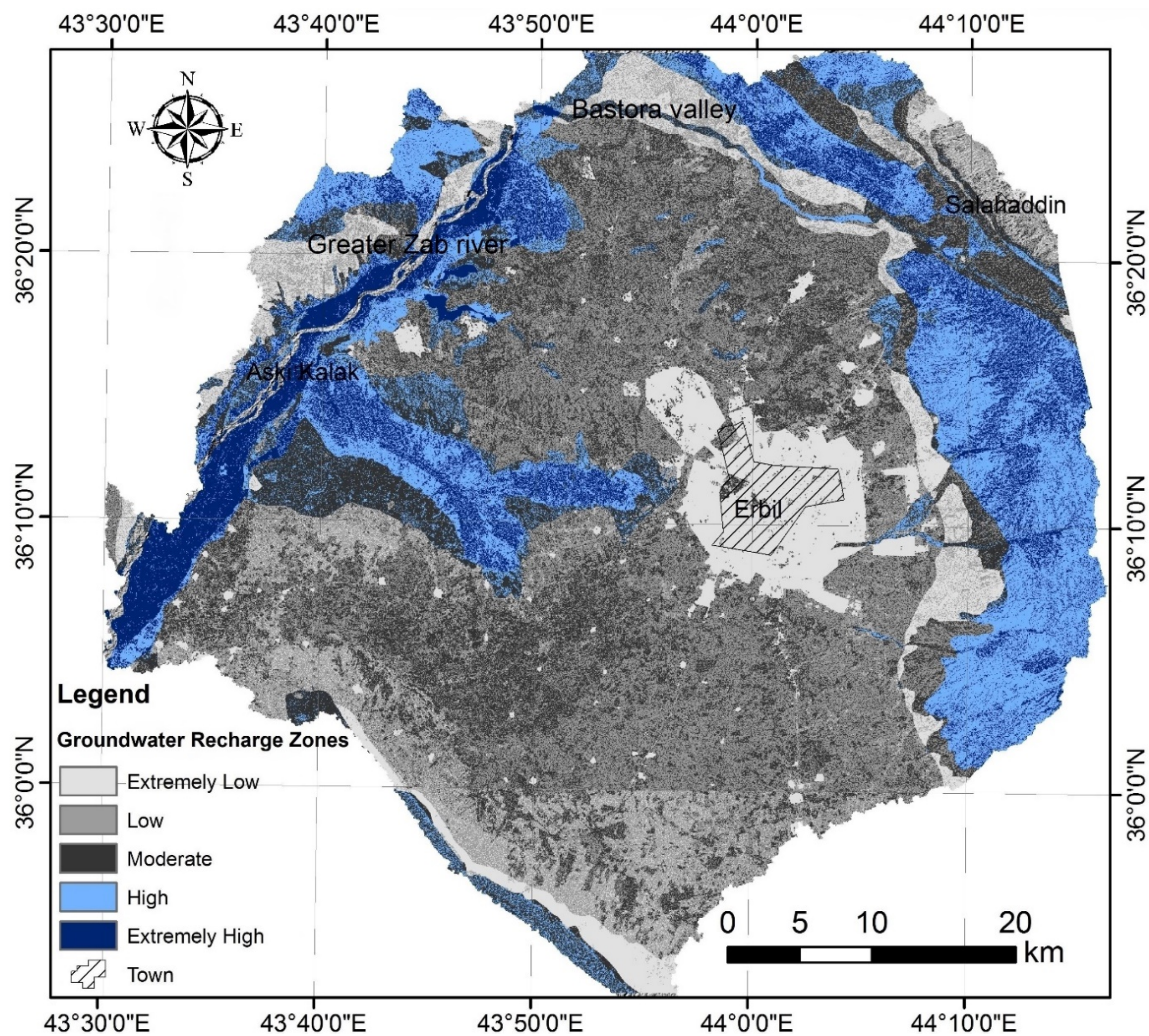

Fig. 7. Map of potential groundwater recharge zones (PGWRZ) in the study area.

Considerable areas with extremely low, low, and moderate recharge classes are situated in the Salahaddin district, the majority of Bastora valley, southwestern, and most central part of the study area consisting of fine-grained rock units of Injana, Fatha, and Pila Spi formations. Moreover, these three classes contain polygenetic and slope Quaternary sediments. Geomorphologically, erosional glacis, depositional glacis, cuestas and hogbacks, and structural ridges are the dominant features. While prevailing land cover classes are bare land, built-up land, field, agricultural land, and mixed-barren land. Overall, these conditions caused an extremely low to moderate possibility for groundwater recharge to occur. The total area of high and tremendously high groundwater recharge classes equals 25.6% of the Erbil basin. The remaining 74.4% of the study area is categorized under extremely low to moderate potential for aquifer recharge (Table 3).

Table 3. Classes of PGWRZ in the Erbil basin.

PGWRZ Class	Area (%)	Area (km^2)
Extremely high	9.8	294
High	15.8	474
Moderate	28.2	846
Low	32.8	984
Extremely low	13.4	402

The eastern part is primarily hilly with a deep-narrow drainage network compared to the study area's southern and western portions. Although this area demonstrates excellent lithological conditions for groundwater recharge, the steep slopes impede runoff accumulation and, consequently, its infiltration into the underground. As a result, the ASTER GDEM, TPI layer, and drainage network map were used to propose two basins for dam construction as promising artificial recharge structures east of Erbil city (Figure 8 a-b).

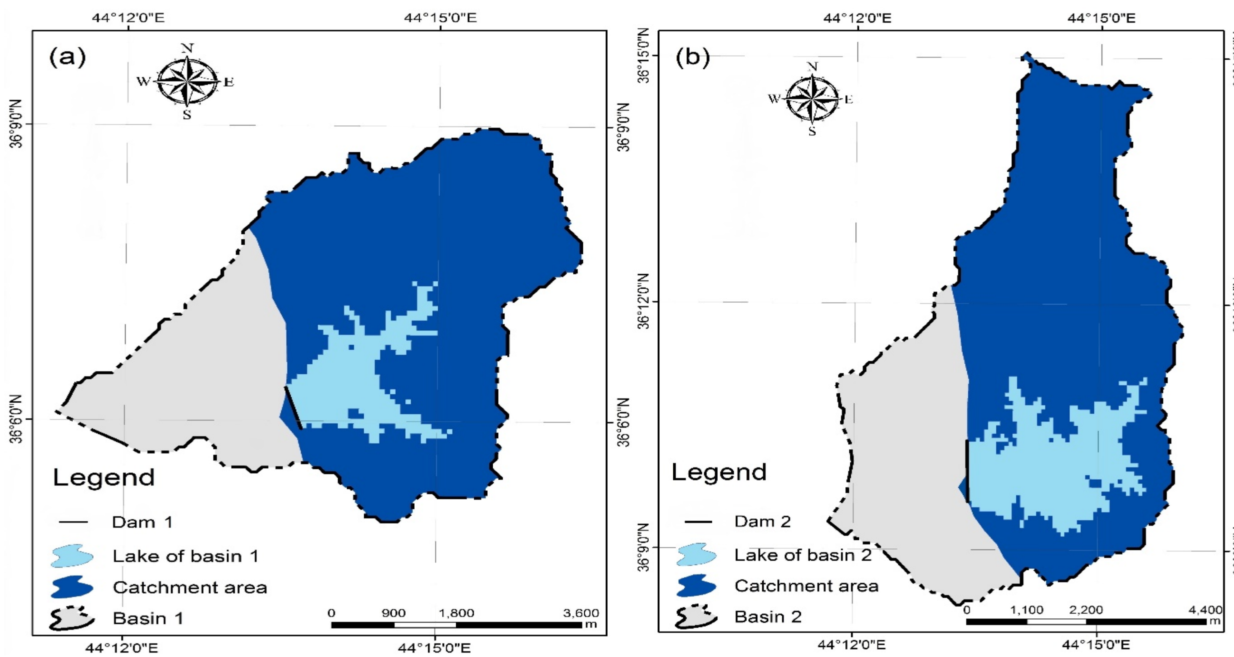

Fig. 8. Maps of two proposed basins for artificial groundwater recharge in the study area.

Two factors controlled the site selection of the suggested dams. Foremost, the availability of surface runoff that could be stored in the reservoirs during the wet season. The highest concave TPI class was the second crucial factor for accumulating surface water in the proposed basins. Besides that, other factors for good runoff accumulation conditions are vital, such as soil type, land use, and antecedent soil water content (Gabriels *et al.,* 2022). Table 4 demonstrates the properties of the proposed dams using ArcGIS tools. These findings are generated based on the utilization of surface parameters only. Therefore, the results need to be interpreted with caution.

Table 4. Properties of the proposed dams east of Erbil city.

Proposed dam	Elevation (m) above sea level	Dam height (m)	Dam length (m)	Storage capacity (km^3)
Dam 1	848	46	850	1.935
Dam 2	1060	69	1085	4.542

6. Discussion

As the first study in its field in the Erbil basin, AHP identified the most suitable sites for the application of artificial aquifer recharge using multiple criteria within the ArcGIS environment. It is interesting to note that 25.6% of the study area showed an encouraging capability to perform artificial groundwater recharge. However, 74.4% of the investigated region revealed extremely low to moderate potency for aquifer recharge. The spatial distribution of the promising classes is concentrated along the main river channel, Bastora valley, and the eastern hills of the study area. Coarse-grained rock units occupy these zones with a substantial percentage of Quaternary sediments.

Excessive groundwater extraction for agricultural purposes and a low natural recharge rate in the Erbil basin led to a sharp decline in groundwater levels. Rainfall occurs mainly from October to May and frequently reaches 400 mm/year in the study area. Therefore, runoff harvesting and artificial groundwater recharge represent alternative methods to replenish groundwater storage. The slope in both proposed basins (Figure 8) is steep, which subsequently drains available rainwater into a seasonal canal south of Erbil city. Thus, the objective is to construct two dams in the proposed basins to collect surface runoff during the rainy season and recharge the underlying aquifer. Besides, check dams are recommended recharge structures in Bastora valley to harvest rainwater and recharge the subsurface aquifer. Simultaneously, flooding and injection well methods are applicable in the surrounding areas of the GZR. Consequently, these water conservation structures influence the natural regime and regulate aquifer exploitation within the management frame.

Essentially, the resulting map of PGWRZ was visually compared with the static water level map to check the applicability of the proposed sites for implementing artificial groundwater recharge (Figure 9 a-b). Results show that both suggested basins are located within the high to extremely high suitability classes for groundwater recharge. From the standpoint of runoff harvesting, high to extremely high recharge areas are suitable for surface water harvesting due to their deep-narrow drainage network. The formations that crop out in the northeastern and northwestern parts of the study area are highly porous (Mukdadiya and Bai Hassan). These formations represent encouraging recharge zones for the underlying aquifers. Most of the Quaternary sediments, except river terrace sediments located in the central part of the study area, are poorly permeable due to their high clay contents (Sissakian & Al-Jiburi, 2012). Stevanovic & Iurkiewicz (2009) performed two artificial aquifer recharge tests in the vicinity of Erbil; the first test relied on gravitational recharge, while the second one consisted of the injection of water under pressure. It was concluded that water injection is more effective than the gravitational recharge method, where under a pressure of 8 bar, it was possible to inject a maximum of 6 l/s continuously. At the same time, the natural infiltration rate did not exceed 0.125 l/s. Accordingly, the stored surface runoff in the two proposed basins could be injected under pressure through injection wells to recharge the aquifers artificially. Also, stored water might irrigate neighboring croplands or be transferred to the city of Erbil by a drainage network. Figure 10 illustrates the correlation analysis between the static water level and the PGWRZ, which shows a substantial result ($R^2 = 0.73$).

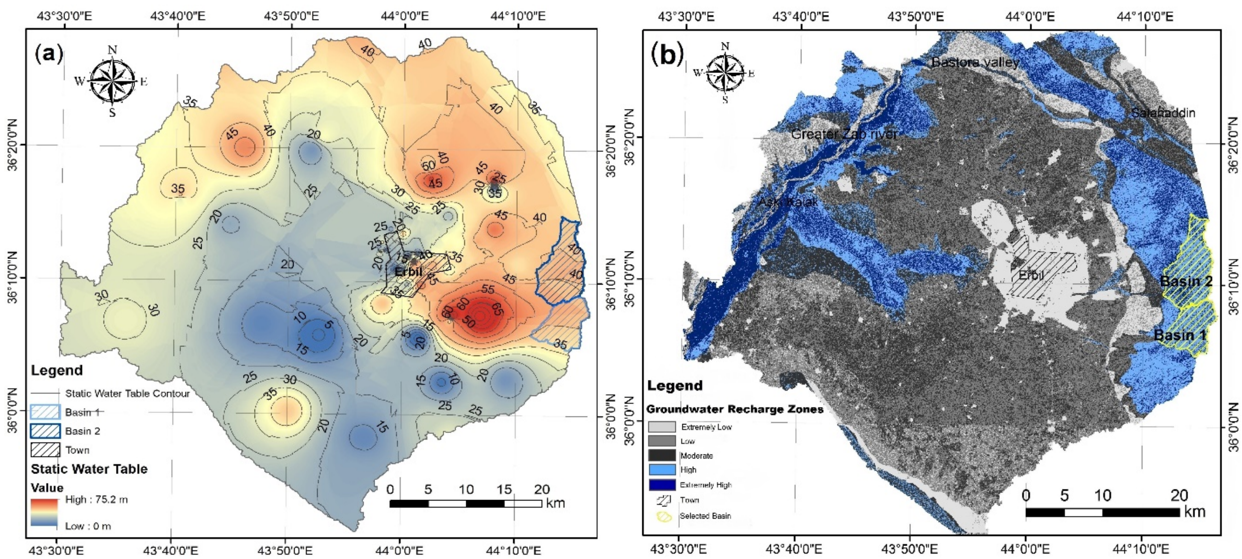

Fig. 9. Maps of (a) static water level and (b) PGWRZ in the study area.

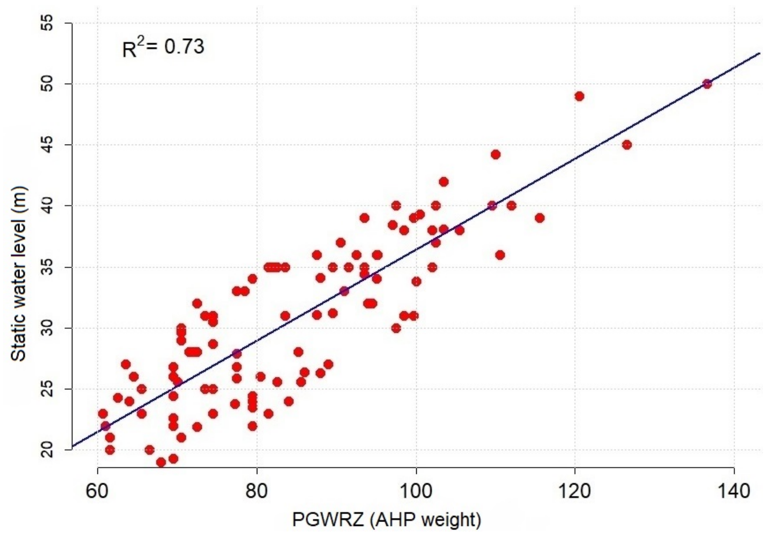

Fig. 10. Scatter plot of the static water level and the PGWRZ.

Further, the direct and reasonable relationship verified that the AHP model suggested in this study is acceptable. This finding has significant implications for developing a sustainable plan to replenish depleted groundwater in the Erbil basin through artificial recharge. Further research with more focus on groundwater flow modeling is therefore recommended. To develop a full picture of groundwater recharge, additional studies will be needed to investigate surface water quality in terms of particles and chemical components, where both are critical for artificial recharge.

7. Conclusions

For the first time, this study delineated the potential groundwater recharge zones in the Erbil basin and identified two prospective sites for performing artificial aquifer recharge using a multi-criteria approach. The statistical validation shows that the GIS and AHP techniques provide a powerful integrated tool for evaluating water resources condition in areas with different scales. Based on visual and statistical comparisons, multiple parameters demonstrated a substantial impact on groundwater recharge in the study area, namely slope, lithology, DD, TPI, land cover, geomorphology, and LD. The resulting PGWRZ map in the investigated basin is classified into five recharge classes: extremely low, low, moderate, high, and extremely high. The eastern hills, Bastora valley, and areas along the GZR are located within the high to extremely high recharge zones.

The high to extremely high recharge zones are characterized by variable units of conglomerate, gravel, sandstone, and clay, which are mainly advantageous for groundwater recharge due to their high hydraulic conductivity. These promising recharge zones cover 25.6% of the Erbil basin. In contrast, extremely low to moderate recharge classes include most central, northern, southern, and southwestern parts, making 74.4% of the entire watershed. The most prominent finding to emerge from this study is that eastern hills demonstrated encouraging suitability for rainwater harvesting and artificial groundwater recharge. Consequently, two basins are proposed for collecting valley flow and storing it in the underlying aquifer. This investigation establishes a preliminary basis to formulate a long-term plan for managing water resources in the Erbil basin. Since the study was mostly limited to surface data, it is recommended to perform further hydrogeological analysis to evaluate the aquifers' properties. Despite its exploratory nature, this study offers insight into sustainable aquifer management in arid and semi-arid regions.

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