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GEOINFORMATICS-BASED APPROACH FOR AQUIFER RECHARGE ZONE IDENTIFICATION IN THE WESTERN DESERT OF IRAQ

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ABSTRACT: Vast parts of the globe are facing a water scarcity problem owing to the increasing water demand of the growing population and urban expansion, and intensive agriculture and industrial activities. Arid and semiarid areas already suffer from a severe shortage of surface water supplies due to climatic conditions such as a temperature rise, evaporation rates, and diminution of rainfall amounts with discontinued intervals. Delineation of suitable sites for the groundwater potential recharging zones is one of the available solutions to recompense surface water shortages in the Al-Mohammedi basin in the Iraqi Western Desert. Recently, the utilization of modern geospatial techniques such as remote sensing (RS) data and geographic information system (GIS) in combination with multi-criteria decision-making (MCDM) approaches has proven an efficient tool for groundwater demarcation. In this study, RS data, such as Landsat 8 images and SRTM Digital Elevation Model (DEM), published geological maps, and metrological data were used to generate eight thematic layers of criteria—geomorphology, geology, lineament, rainfall, soil infiltration, slope, land use and land cover, and drainage density. All thematic maps were generated and transformed into the raster format depending on the raster conversion tool in ArcGIS 10.8 software. The output map of groundwater potential zones (GWPZs) was generated by integrating all the thematic layers according to the weightage values generated depending on the Analytical Hierarchal Process (AHP) approach. Finally, the prospective zones were examined and validated with present yield wells data. Twenty-two out of twenty-eight validation boreholes (76.87%) matched the predicted classes of the yield boreholes, and the cross-correlation value certified this result as $R^2 = 0.67$.

Keywords: GIS, RS, GWPZs, AHP, Multi-Criteria decision making

1. INTRODUCTION

Groundwater is an alternative indispensable water resource for developing urban and rural regions, specifically in arid and semiarid areas with insufficient rainfall. Globally, water scarcity problems are exacerbated by climatic change, rapid population growth, and agricultural expansion [1,2]. People living in arid regions with mutable rainfall amounts and unpredictable periods of dryness or floods, such as the Iraqi Western Desert, are the most influenced by climatic conditions and water deficiency, resulting in livelihood insecurities [3–5].

Groundwater constitutes a primary water resource for more than two billion people worldwide and provides about 50% of the total water irrigation requirements [6–8]. The exploration of suitable sites for GWPZs has become a vital component of the planning and managing of water resources, especially in rural areas [9,10]. Nevertheless, the case study of the Iraqi Western Desert is restricted by limited hydrological and climatical data. Consequently, there is an urgent need to establish an efficient and cost-effective technique for groundwater delineation in the region. The process of selecting suitable GWPZs using the traditional methods could be complex and take considerable time when several factors are considered, specifically in the largest basins with limited data.

Exploiting nontraditional approaches to water resource promotion, such as groundwater zonation, can overcome water scarcity problems in the region. Identifying the suitable sites of GWPZs could be a promising approach for water conservation and accessible secure of water for drinking, municipal, and agrarian purposes [11,12]. Demarcating the appropriate sites for GWPZs is a significant step towards promoting water accessibility and land productiveness in arid and semiarid areas.

Recently, geospatial technologies, such as remote sensing (RS) data and geographic information systems (GISs), have been employed as more effective and efficient tools for groundwater exploration than the conventional hydrological methods with time-consuming and costly approaches [8,13,14]. Currently, remote sensing (RS) data combined with the GIS platform are used as inexpensive tools that can provide valuable information and meet all the challenges of data deficiency to detect the groundwater potential with quick and desirable results [15–18]. Most of the reviewed GIS-based studies combine different features of the Earth's surface that can be derived from satellite imagery and geological sheets by employing weighted overlaying analysis in ArcGIS software [19–21].

Many studies, such as [5],[14,22], proved that the integration of RS and GIS techniques with the Analytical Hierarchal Process (AHP) method is the best way to provide a rapid delineation of the suitable GWPZs sites. The AHP approach for the multi-criteria decision-making process (MCDM) developed by Saaty in 1980 has been intensively employed and effectively performed in different fields of natural resources management [23–26]. To assign different normalized weights according to the AHP procedure, various influencing factors are ranked based on the relative importance and priorities that can be categorized in the form of a pair-wise comparison matrix of the scale values [27,28]. Multiple steps are needed to select efficacious GWPZs, including identifying a multiset of convenient criteria, analyzing the relative importance of each parameter, and delineating zones by developing adequate maps for the suitable intended sites groundwater [9,29]. The processes of determining GWPZs using geospatial techniques such as RS and GIS necessitate preparing several thematic layers for the surface and subsurface features such as geomorphology, geology, lineament, rainfall, soil infiltration, slope, land use and land cover, and drainage density. Subsequently, the output groundwater potential map of the study area can be generated using weighted overlaying analysis for all the thematic maps according to the assigned weight of each layer based on the AHP approach [11,13,30]. The unique and innovative purpose of this study is to utilize and integrate the new geospatial technology of RS data with MCDM methods, such as the AHP approach, to provide more efficient and effective planning for the sustainable management of water resources.

Validation of the GWPZs results for the study site using the yield data of a specific number of boreholes emphasizes the competence of the applied methodology, in addition to the relevance of the geo-environmental parameters employed in this study for identifying the suitable sites of the groundwater proceptivity in the region [31]. The integrated approach included two steps; the first was to identify the suitable sites of GWPZs in the Western Desert in Iraq obtained with the GIS-based MCDM procedure, and the second was to verify the output results with the location and yield discharge boreholes. The primary objective of the proposed approach was to identify the suitable sites of the potential groundwater zones in an arid region of Al-Mohammedi Valley, the Western Desert of Iraq, through integrating RS and GIS techniques with a multi-criteria decision-making analysis of the AHP approach.

2. RESEARCH SIGNIFICANCE

The applied approach of integrating RS and GIS techniques with the AHP method represents a baseline framework for the efficient assessment of the groundwater potential recharging zones and can be used by planners and researchers for further hydrological studies in the targeted area. To achieve sustainable management of the groundwater in the Iraqi Western Desert, this study provides a primary methodology and significant database for the local management of water resources by adopting the groundwater perspective map.

3. STUDY AREA DESCRIPTION

The study area (AL-Mohammedi valley basin) is situated in the Western Desert of Iraq, Anbar province, on the right bank of the Euphrates River. AL-Mohammedi valley basin has an area of about 2303.12 km^2 and lies between $33^\circ\ 0'\ 0''$ N - $33^\circ\ 45'\ 0''$ N longitude and $42^\circ\ 0'\ 0''$ E - $43^\circ\ 0'\ 0''$ E latitude, with an average elevation between 59 and 365 m (Fig. 1). This area was selected because of the present orientation for groundwater mapping and the possibility of future investment in the region. Because of the seasonal fluctuation in temperature, evaporation, and relative humidity with varying rainfall amounts (less than 150 mm annually), the present study area can be classified as an arid region [32–35]. The average annual rainfall in the area is up to 150 mm, and the evaporation rate is about 3300 mm, with the annual temperature mean between 31.6 °C and 33.8 °C [36,37].

The rainfall season extends from October to May, while the peak of the driest period is from June to August. Owing to the harsh climatical conditions and water scarcity problems, the population density in the Western Desert of Iraq is unequally distributed and does not exceed five persons per kilometer [38]. Although most of the study region is considered barren land, numerous sites are covered with croplands, and other types of grass vegetation grow throughout the rainy season [39,40]. Three classes of soil texture, such as clay loam, sandy clay loam, and silty loam, are the most common in the study site. The geological formation of this area consists of four main formations characterized by sandstone, claystone, and limestone terrains. Stream orders in the study site are dense, especially in the western parts of the basin and combine to pour into the mainstream of the valley and then into the Euphrates River [41]. The current study area is considered a relatively important region in the Iraqi Western Desert, as it ensures the central valley receives a massive amount of rainfall through the rainy seasons. Hence, the present study area was adopted because of the current trends for groundwater exploitation and the potential for investment in its future planning.

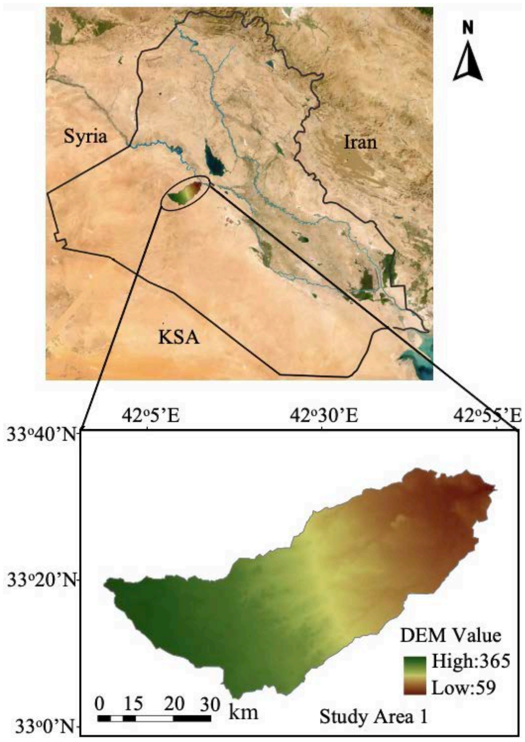

Fig. 1 Location map of the study area

4. DAND METHODOLOGY

The available data of geospatial techniques and the intelligibility of GIS have produced data sources for accurate planning and management of GWPZ projects. Several geo-environmental criteria were used to identify GWPZs in the study area, such as geology, geomorphology, land use and land cover, soil infiltration, rainfall, slope, drainage density, and liniment density. The approach to groundwater potential zonation is a complicated procedure owing to the direct influence of different constraints on the decision support system. Therefore, the present study proposed an effective technique of three phases to simplify this procedure: (1) Preparing all required thematic layers from different data sources by conducting multi-steps in ArcGIS. (2) Normalizing different weights and ranks for each thematic map and subclass based on the AHP approach. (3) Integrating all thematic layers based on the assigned weights to generate the potential groundwater map and compare the results with actual yield wells data. The proposed methodology in this study is presented in Fig. 2.

The database used to produce diverse thematic layers in ArcGIS10.8 software for the preparation of GWPZs includes: (1) A geological map derived from the Geological Survey of Iraq (IGS) along with the Al-Ramadi sheet at scale 1:250,000. (2) Landsat 8 OLI satellite image with a spatial resolution of 30 x 30m acquired in May 2020 from the United States Geological Survey USGS (http://earth explorer.usgs.gov) utilized to generate land use and land cover map (LULC) by conducting a supervised classification depending on image classification tool in ArcGIS 10.8 software. (3) The diversity of the Geomorphological units in the basin was mapped according to Landsat 8 OLI satellite image and the Geological Survey of Iraq (IGS) maps. (4) Slope and drainage density maps were produced from the SRTM Digital Elevation Model (DEM) data with a spatial resolution of 30 x 30 m. (5) Metrological data on the average annual rainfall from five stations were utilized to generate the rainfall map based on the Inverse Weighted Distance (IDW) tool in ArcGIS10.8 software. (6) Soil texture map with characteristics was obtained from the world soil classification by the Food and Agricultural Organization (FAO) in 2007 with a scale of 1: 5 000 000. (7) The lineament density layer was mapped from Landsat 8 OLI image and the DEM hill-shade map.

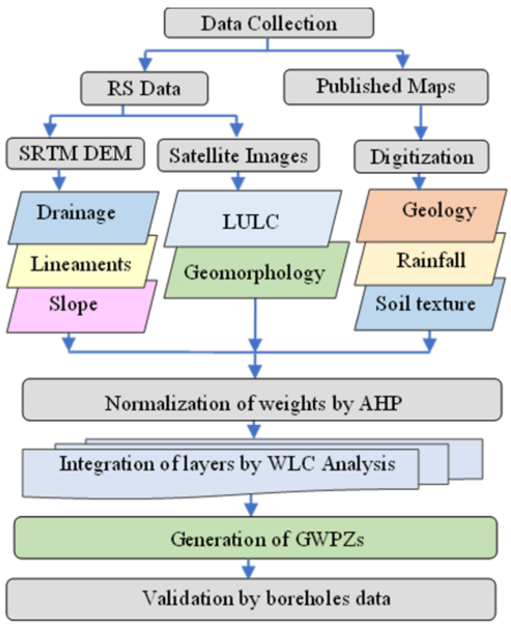

Fig. 2 Flowchart of research methodology.

4.1 Geomorphology

Geomorphological characteristics of an area play a considerable role in the assessment of potential groundwater as it dominates the subsurface water movement.

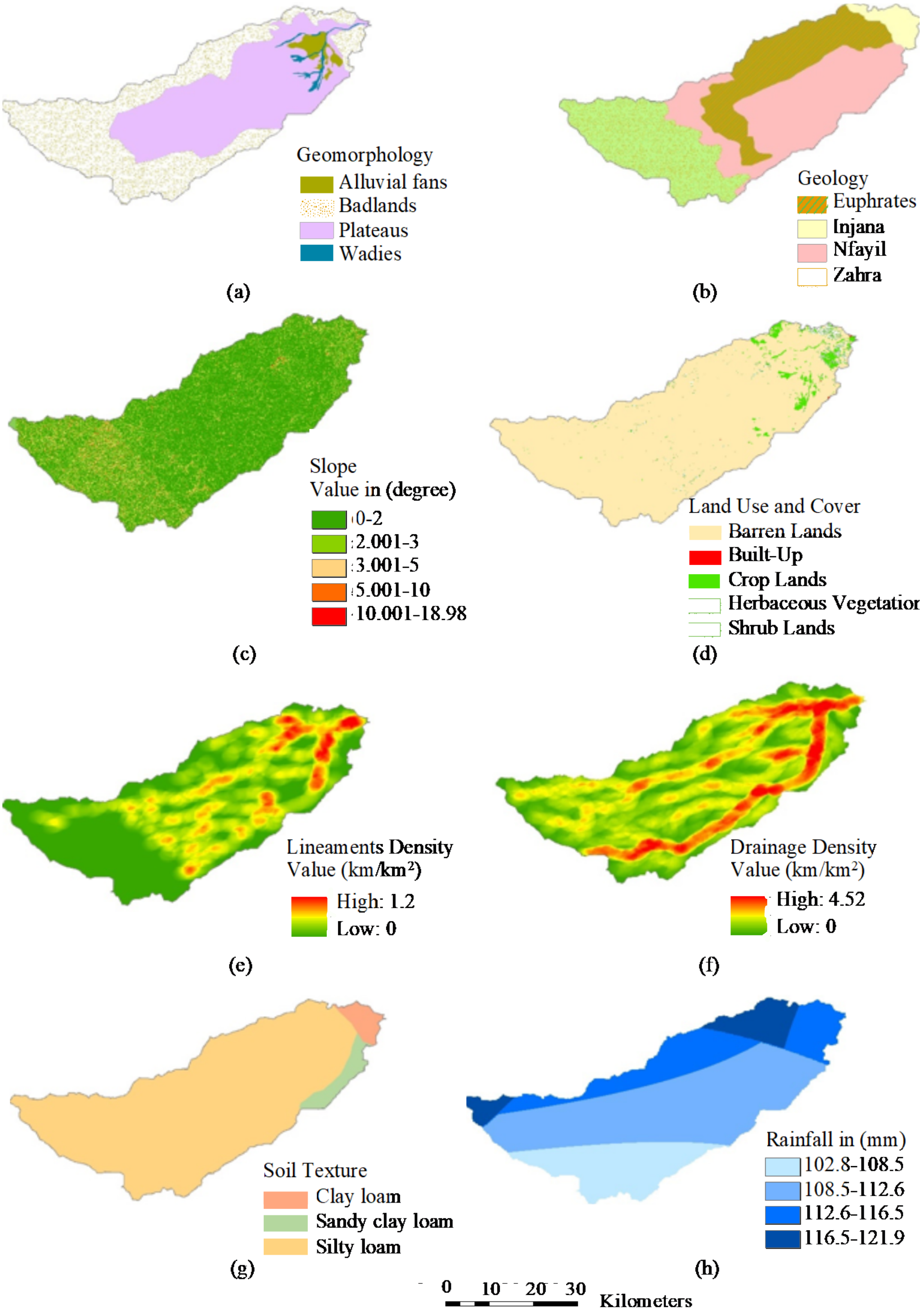

Fig. 3 Thematic maps of (a) geomorphology, (b) geology, (c) slope, (d) land use and land cover, (e) lineament density, (f) drainage density, (g) soil texture, (h) and rainfall

Different geomorphological erosional and depositional units of the earth have been generated by various processes such as surface water flow, wind action, groundwater fluctuation, and geological tectonic actions. In this study, the geomorphological parameters that control the groundwater occurrences in the study area were derived from Landsat 8 OLI satellite images with a spatial resolution of 30 x 30 m.

The six major geomorphological landforms most common in the Western Desert of Iraq of are structural-denudational origin, denudational origin, fluvial origin, evaporation origin, solution origin, and eolian origin [36]. Several features of these landforms favor the occurrence and potential for groundwater exploration [42–44]. The study area is characterized predominantly by limestone, sandstone, and claystone terrains and some erosional and depositional geomorphic properties revealed by hills, wadies, and undulating surfaces. The geomorphologic aspects of the Al-Mohammedi basin were mapped into four landforms of plateaus, wadies, alluvial fans, and badlands (Fig. 3a).

i. Plateaus: Plateaus are one of the largest landforms of the Western Desert due to their structural position in the stable shelf. These landforms are formed flat-topped through the ancient geological periods on mutable rocks. Plateaus are raised flat areas surrounded by remaining mountains that can be seen in plains and are considered a good index for the presence of groundwater. Plateaus occupy the middle and northern parts of the basin with an areal extent of 1106.04 km^2, about 48.02% of the total area of the basin.
ii. Alluvial fans: Alluvial fans are sediment buildup from streams or rivers forming a gradient landform, similar to an open fan or a cone portion. These features are often formed at the base of mountains or valleys. They occur as gently undulating plains with gentle slopes and cover 53.92 km^2, about 2.34% of the study area.
iii. Badland: Topographic features of badland are well observed in the Iraqi Western Desert. Its constitution depends on the faults and joints system, lithologic, climatic, and environmental conditions. Hence, it results from transporting the consolidated substances by erosional and weathering processes. Badland forms 1117.1 km^2, about 48.5% of the study area.
iv. Wadies: Infilled valleys are represented by the mainstream channel of the basin and its tributaries. The trends of these wadies often parallel each other, as the primary direction of the slope is toward the north and northeast. Infilled valleys have a poor potential for groundwater because of the density of drainage patterns, which leads to rapid runoff. These landforms constitute 26.11 km^2 with an area extension of 1.13% out of the study region.

4.2 Geology

Geological formations play a significant role in the occurrence, movement, storage, and quality of groundwater. The geological data on the study area were derived from the conventional maps of the Iraqi geological sheet for the 2012 version [38]. These formations unevenly influence groundwater availability due to their various compositions and geological age.

Three main aquifer types—confined, unconfined, and mixed—have been identified in the Western Desert, including Euphrates, Mulussa, Anah and Dammam, Umm Er Radhuma, Muhaiwir, Fatha, and Gaara [45,46]. The high water-bearing formations underneath the Iraqi Western Desert are Euphrates and Injana, while other geological formations, such as Zahrah, Nfayil, and Fat`ha, are not classified as productive aquifers. However, they include groundwater in some places during the rainfall season because of their locations above the regional level of groundwater or structural and lithological properties [47]. The geological structure of the study region comprises four main types of geological formations of Euphrates, Injana, Nfayil, and Zahra (Fig. 3b).

i. Euphrates Formation: The lithologic composition of this formation mainly consists of fossiliferous, limestone, chalky, and dolomitic. The limestones are primarily located near the surface with a weathered and fractured structure and have good permeability [48,49]. The transmissivity range of this formation is between 3 and 1750 m^2/day. The Euphrates formation occupies the west and northwestern parts of the study site in the Al-Mohammedi basin with an area of 588.46 km^2, about 25.55% of the whole study region.
ii. Injana Formation: The texture of the Injana formation comprises interbedded clay stones, sandstones, and siltstone. This formation represents the main groundwater aquifer with clastic rocks and a thickness of up to 70 m in the central parts, with transmissivity rates between 21 and 927 m^2/day [47]. The Injana formation is located in the northern parts of the study region and covers 105.6 km^2, about 4.58% of the total study area.
iii. Nfayil Formation: The Nfayil formation is largely exposed over the Iraqi Western Desert. Its lithologic composition consists of: (1) Lower member comprises two cycles of green marls and grey fossiliferous limestones. (2) Upper member contains cyclic sediment, consisting of siltstone, sandstone, and reddish-brown claystone with thin limestone and green marl horizons. This geological formation covers 934.27 km^2, about 40.56% of the entire study region.

iv. Zahra formation: This formation occupies the south and southwestern parts of the study site with an area of 674.83 km^2, about 29.3% of the whole study area. The primary lithologic composition of the Zahra formation is limestone, sandy and silty claystone, calcareous sands, and purple sandy marls.

4.3 Slope

The slope criterion is a controlling factor in aquifer recharging as it governs the rates of water percolating into the subsurface layers and is largely used in identifying potential groundwater zones. The slope degree map of the Al-Mohammedi watershed was derived directly from the SRTM DEM map data using the ArcGIS 10.8 software (Fig. 3c). The slope gradients of the study area varied from 0 to 18.93° and were categorized based on the slope angels into five classes as flat (0°–2°), very gentle (3°–4°), gentle (4°–5°), moderate (5°–10°) and steep (>18.93°) slopes. Flat surface lands with mild slopes are considered favorable for groundwater recharging as they retain the water for long periods, while areas with relatively steeper slopes have diminished infiltration rates because of the increased runoff. The slopes of less than 2° are relatively convenient for recharge, as they permit water to percolate with sufficient time, whereas the zones with slopes higher than 10° are less suitable for aquifer recharging [17,50,51]. Using the AHP approach, higher ranks were allotted to relatively lesser slopes with higher recharging potential, while higher slopes were given lower ranks.

4.4 Land Use and Land Cover

Land use and land cover (LULC) are among the primary influential factors in groundwater recharge. LULC affects several hydrogeological processes in the water cycle, such as surface runoff, infiltration rates, and evapotranspiration [26]. In the vegetation areas, infiltration rates are increased, and surface runoff is decreased, compared to urban and barren lands where the lack of vegetation cover results in a predominantly rough land surface.

The study area LULC features were mapped using remote sensing techniques, as they provide excellent high-resolution data on the local distribution of surface cover and land uses quickly and at a lower cost compared with classic methods. Landsat 8 OLI satellite image with a spatial resolution of 30 x 30m was utilized to analyze the LULC units in the study site by conducting a supervised classification process with the help of the image classification tool in the ArcGIS 10.8 software.The LULC map of the study region shown in Fig. 3d, includes five types of LULC patterns of croplands (2.65%), herbaceous vegetation (2.34%), shrublands (0.13%), barren lands (94%), and built-up (0.04%). Croplands are an excellent indicator of groundwater recharge; therefore, they were assigned a higher rank in the study. Shrublands have a significant role in the recharging of groundwater aquifers. The infiltration rates are proportional to the density of herbaceous vegetation as it causes higher infiltration rates and lesser runoff amounts. Thus, bot shrublands and herbaceous vegetation were assigned relatively high or good ranks. The barren lands and built-up classes were given low ranks because of their low infiltration rates.

4.5 Lineaments Density

Lineaments are rectilinear or curvilinear features of the Earth's surface representing subsurface crustal structures such as faults, joints, fractures, etc. These factors have relative hydrogeological importance as they produce the passages for groundwater movement through the high permeability and secondary porosity media [33,52–54]. The lineament density map was identified using Landsat 8 OLI satellite image data and the correlation with joints, faults, fractures, and bedding planes from the Hill-shade tool in ArcGIS 10.8. Lineaments length density for an area equals the total lengths of appointed lineaments divided by the concerned area, which is expressed in the formula below [29]:

$$Ld=\sum_{i=1}^{n}\frac{L_i}{A}\ \left(km^{-1}\right) \quad (\mathbf{1})$$

Where Li is the length of the lineament feature (km), and A is the grid area (km^2). Regions with a high lineament density can directly identify suitable groundwater and are considered good indicators for potential groundwater sites as they widely contribute to the recharging process of groundwater aquifers. The lineament density values in the study area are illustrated in Fig. 3e and range between 0 and 1.2 km^{-1}. These values have been regrouped into five categories, and the areas with ranges between 0.89 and 1.2 km^{-1} were given a higher rank as they denote the most permeable zones.

4.6 Drainage Density

Drainage density is the measure of total drainage stream lengths divided by the unit area in a specified area of the watershed [31]. Drainage density is governed by many aspects of the Earth's subsurface, such as slope gradient and soil properties, and the geologic features, such as the nature and structure of the underlying rocks [6]. The drainage patterns are considered the outcome of the controlling factors of surface runoff, and they mainly influence the production and transportation of sediment particles in the drainage basin. Impermeable sub-surfaces are the result of high drainage density due to weak subsurface materials, little vegetation, and hilly terrain. So, they play a considerable role in delineating groundwater potential zones by having a reversible permeability function [55]. The SRTM DEM data with a spatial resolution of 30 m were used to extract the network drainage patterns for the study region. Afterward, the drainage density map was generated using the line density tool in ArcGIS 10.8 software.

The drainage density values of the studied area ranged from 0 to 4.52 km^{-1}, as shown in Fig. 3f. The study area was categorized into five classes based on density value. The regions with values varying from 2.34 to 4.52 km^{-1} were denoted as high-density zones located in the middle hilly terrains and northwest lands of the basin and were given lower ranks because of their poor groundwater potential. The regions with a range between 0 and 0.439 km^{-1} were given a high rank because of their higher potential for groundwater zones.

4.7 Soil Infiltration

Infiltration is the permeation process of surface water into the subsurface layers of soil. It is one of the most significant hydraulic characteristics of soil for agricultural and hydrological studies as it plays a primary role in groundwater recharge and quantification of irrigation activities [15],[56]. Soil texture has a direct influence on the infiltration rates due to the variations in porosity and permeability properties determined by various particle sizes [57]. The soil texture map for the Al-Mohammedi basin was derived from the Food and Agricultural Organization (FAO) classification of the world soils in 2007 (http://www.fao.org/soils-portal/n). Three major types of soil texture, namely silty loam, clay loam, and silty clay loam, are distributed across the study region. It is notable from Fig. 3g that the majority of the study region is dominated by silty loam soil covering an area of 2142 km^2, while the clay loam and sandy clay loam cover relatively small areas of 70 km^2 and 91 km^2, respectively. Using Table 1 values, the soil infiltration thematic map of the study area was generated for the proposed approach to GWPZs delineation.

Textures, such as clay loam and silty clay loam, provide a weak water-holding capacity as soils with poor drainage and permeability and were, thus, ranked low. Sandy loam soils have a higher water-holding capacity and were ranked high; this type of soil is better drained and considerably permeable and has a high water-recharge capacity.

Table 1 Infiltration rates for different textures [57]

no.	Soil textures	Infiltration rate (mm/hr.)
1	Gravelly loamy sand	30
2	Sandy loam	20-30
3	Loamy sand	15-20
4	Sandy clay loam	10-15
5	Silty clay loam	7.5-10
6	Clay loam	5-10
7	Clay	1-5

4.8 Rainfall

Rainfall is the most significant influencing parameter in the recharging and fluctuation of groundwater in any area, and it constitutes the primary water source in the hydrological cycle [57]. Rainfall represents the major source of surface water, and depending on its intensity, it can form a surface runoff and the base flow, which will percolate into the subsurface layers [58]. Average rainfall amounts were gathered from the Iraqi Meteorological Organization and Seismology data was obtained from rain gauge stations [59].

The Iraqi Western Desert has an insufficient number of rain gauge stations to estimate all the rainfall data over the region. The rainfall season in the study extended from October to May with discontinuous intervals. In this study, the data from five metrological stations, shown in Table 2, were utilized to generate the rainfall map with an inverse distance weighted (IDW) interpolation method in ArcGIS 10.8 software. The annual rainfall amounts for the study area, presented in Fig. 3h, varied from 102.8 mm to 121.9 mm and were regrouped into five categories.

The highest amounts of rainfall were reported in the western parts of the study area, gradually diminishing toward the eastern parts. The higher ranking was assigned to the high rainfall classes; rainfall of >121.9 mm was considered suitable for groundwater recharging and vice versa.

Table 2 Metrological stations around the area of study [59].

Stations	Location		Avg. annual rainfall (mm)
	Longitude.	Latitude.	
Anah	41.95	34.37	142.529
Qaim	41.02	34.38	140.624
Ramadi	43.32	33.45	110.512
Nukhaib	42.27	32.03	72.63
Rutbah	40.28	33.03	116.65

5. NORMALIZING AND ASSIGNING WEIGHTS FOR THE THEMATIC LAYERS

The prospective groundwater zones are influenced by soil, geomorphology, geology, land use and land cover, lineaments, rainfall, slope, and drainage density [60]. These theme layers have been converted into raster format depending on the conversion tool in ArcGIS software and reclassified according to different assigned ranks. Various assigned weights and ranks were given to the influence factors and subclasses based on their relative importance and impact on the groundwater potential. Analytical Hierarchal Process (AHP) is a multi-criteria decision-making (MCDM) systematic method for solving complicated decision problems through a comparative judgment and arrangement of priorities [61]. The analysis of complex spatial problems identifies the main components of the problem by developing a hierarchal structure that includes the organizing of objectives, features, and alternatives.

Based on the opinion of hydrological and geological experts, a questionnaire of comparison rankings on the Saaty's 1–9 scale was used to compare all the parameters with each other based on the relative importance through a pair-wise comparison matrix as shown in Table 3 to assign different weightage values for each thematic layer. Consequently, the pair-wise comparative ratings were considered as the input data, whereas the proportional weights of the theme layers were the output data. For the present study, an 8 X 8 comparison matrix has been made, the relative importance parameters between thematic layers in the pair-wise comparison matrix are selected from Saaty's 1–9 ranking scale shown in Table 4. The final weights of the thematic maps are the average eigenvector values that are affiliated with the maximum eigenvalues of the normalized matrix [31,62]. For calculations, Gm is the geomorphology, Ge is the geology, Ld is the lineament density, Si is the soil infiltration, Rf is the rainfall, LULC is the land use and land cover, S is the slope, and Dd is the drainage density layers. The normalized weights and ranks for each thematic layer and its subclasses are presented in Table 3. Equation (1) below can be used to determine the consistency ratio (CR):

$$\boldsymbol{CR = \frac{CI}{RI}} \quad (\mathbf{2})$$

Where RI is the random value index which depends on the matrix order, and CI is the consistency index expressed by the following equation:

$$\boldsymbol{CI = \frac{\lambda_{max}}{n-1}} \quad (\mathbf{3})$$

Where λ_{max} is the principal eigenvalue of the normalized matrix, and n is the number of theme layers. Saaty 1980 proposed that the consistency ratio (CR) should be less than 0.10 and, as a result, the comparison values would be consistent [23]. The present study's average estimated consistency index (CI) value was 0.051, whereas the corresponding value of CR was 7.3 (less than 0.10) for all thematic layers. It is clear that there was a rational proportion of consistency in the applied pair-wise comparison matrix; hence, the allotted weights for each individual theme were 0.24, 0.20, 0.16, 0.12, 0.09, 0.08, 0.07, and 0.04 specified for the geomorphology, geology, slope, lineament, soil infiltration, rainfall, land use and land cover, and drainage density, respectively (Fig. 4).

6. DELINEATION OF GWPI

The groundwater potential index (GWPI) is a nondimensional quantity that assists in anticipating the potential groundwater zones in a targeted area. The weighted linear combination (WLC) method is utilized to calculate the GWPI based on the following equation [55,62,63]:

$$GWPI = \sum_{w=1}^{m}\sum_{i=1}^{n}(\boldsymbol{W_i} \times \boldsymbol{X_j}) \quad (\mathbf{4})$$

Where W_j is the assigned weight for the jth thematic layer, X_i is the grade value for each class referring to the jth layer, m is the total number of thematic layers, and n is the total number of classes. The GWPI can be estimated from Eq. (5).

$$GWPI = Gm_w Gm_r + Ge_w Ge_r + Si_w Si_r + Ld_w Ld_r + Rf_w Rf_r + Lu_w Lu_r + S_w \boldsymbol{S_r} + Dd_w Dd_r \quad (5)$$

Table 3 The pair-wise comparison matrix for eight parameters.

Parameters	Gm	Ge	S	Ld	Si	Rf	LULC	Dd
Gm	1	1	2	3	3	3	3	4
Ge	1	1	1	2	3	3	3	4
S	1/2	1	1	2	2	2	2	2
Ld	1/3	1/2	1/2	1	2	2	2	3
Si	1/3	1/3	1/2	1/2	1	2	2	3
Rf	1/3	1/3	1/2	1/2	1/2	1	2	3

LULC	1/3	1/3	1/2	1/2	1/2	1/2	1	3
Dd	1/4	1/4	1/2	1/3	1/3	1/3	1/3	1

Table 4 Saaty's scale index for various values of n

n	RI
1	0
2	0
3	0.58
4	0.89
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

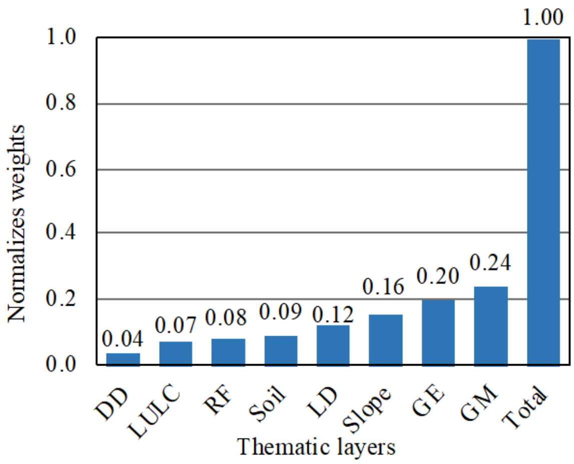

Fig. 4 The assigned weights for the thematic layers to prepare the groundwater potential map.

Where Gm is the geomorphology, Ge is the geology, Si is the soil infiltration, Rf is the rainfall, Lu is the land use and land cover, S is the slope, Dd is the drainage density layers, and 'w' and 'r' are the assigned weights derived from the AHP approach for each theme layer and the ranks for the subclass features, respectively, as presented in Table 5.

The resulting values of GWPI varied from 210 to 479 and were recategorized using a quantile classification approach into five zones of very poor (< 250.8), poor (250.8-297), moderate (297.001-367), good (367.001-420), and very good (> 420). The quantile classification method indicates that each category comprises an equal digit of features. This method was applied by several studies because of the efficient results in classification [6,55].

7. RESULTS AND DISCUSSION

The prospective groundwater zones were delineated by analyzing various parameters such as geomorphology, geology, slope, land use and land cover, lineament density, drainage density, soil infiltration, and rainfall based on the integrated AHP method with geospatial technologies.

7.1 Ground Water Potential Zones (GWPZs)

The systematized analysis of the GIS-based AHP approach on weighted factors has produced a suitable map for groundwater recharge prospective zones in a raster format using the weighted linear combination (WLC) method through the ArcGIS environment. On the basis of the quantile method, the values of the GWPI were regrouped into five classes of groundwater potential zones: very poor (88.63 km^2), poor (539.57 km^2), moderate (1025.32 km^2), good (557.6 km^2), and very good (92.04 km^2) representing about 3.85%, 23.43%, 44.52%, 24.21%, and 4% of the studied area, respectively.

As shown in Fig. 5, the very good prospective groundwater zones were located in the west and eastern portions of the watershed. Moreover, the northern sides of the basin fall under a very poor class of groundwater potential zones due to the steep slope, high drainage density, and lithology with low permeability. The obtained results of the present study were compared with other studies from both global and regional perspectives.

The data on the geo-environmental factors utilized to delineate the GWPZs in the Al-Mohammedi basin were compared with other studies on diverse environmental conditions and suggested that the criteria adopted in this study are sufficient to identify the GWPZs. Among the eight geo-environmental parameters, geomorphological landforms, lineament density, and geological formations are the most efficient criteria governing the movement and occurrence of groundwater in the Al-Mohammedi basin. As a result, higher weights of 0.24, 0.20, and 0.12 were assigned to the geomorphology, geology, and lineament density, respectively, indicating a stronger influence of the geomorphological characteristics on recharging and availability of groundwater zones. Wadi fills and alluvial fans attendant with lineaments are also considered reliable for groundwater development, whereas denudation-formed areas such as badlands with lower lineament density have poor groundwater potentiality.

The results show that the good and very good classes of prospective zones are situated in the middle and western parts of the basin. Moreover, the south and southeastern parts of the study area fall in the poor and very poor categories of prospective groundwater zones because of their steep slopes, denudational hills, and high density of stream drainage.

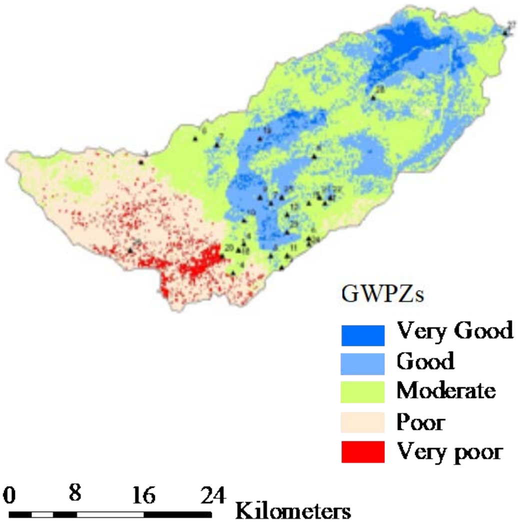

Fig. 5 Groundwater potential map of the study area.

7.2 Validation of GWPZs Map

Validation is the most important criterion for any model to increase the reliability of the proposed methodology and ensure that the specified requirements are sufficient and correct. The yield data of 28 groundwater boreholes have been collected to verify the groundwater potential map of the study site. Locations and veritable yield data of these boreholes are presented in Table 6. Considering the field observations and the data of the Iraqi General Commission for Groundwater, the yield values of the borewells were classified into three groups: poor (< 3 lps), moderate (3–7 lbs), and good (>7 lps) [31]. The boreholes in the poor prospective zone had an average yield of 1.2 lpm, whereas, in the moderate prospective zone zones, the average yield was relatively higher at 4.5 lpm.

Table 5 Normalized weights and ranks of eight criteria adopted in the AHP method

Parameter	Feature class	Scale Value	Normalized weights %
Geomorphology	Plateaus	5	24
	Alluvial fans	4	
	Badlands	3	
	Wadies	2	
Geology	Euphrates	5	20
	Injana	4	
	Nfayil	3	
	Zahra	2	
Slope (in degree)	0-2	5	16
	2-3	4	
	3-5	3	
	5-10	2	
	10-18.93	1	
Lineament density (km/km^2)	0-0.22	1	12
	0.23-0.44	2	
	0.45-0.66	3	
	0.67-0.88	4	
	0.89-1.2	5	
Soil infiltration (in mm)	10-15	5	9
	7.5-5	4	
	5-10	3	
Rainfall	102.8-108.5	2	8
	108.501-112.6	3	
	112.601-116.5	4	
	116.501-121.9	5	
Land use & Land cover	Croplands	5	7
	Herbaceous land	4	
	shrub lands	3	
	Barren lands	2	
	Built-up	1	
Drainage density (km/km^2)	0-0.439	5	4
	0.44-1.01	4	
	1.02-1.62	3	
	1.63-2.33	2	
	2.34-4.52	1	

Table 6 Locations and yield data for GWPZs validation points.

Well ID	Location		Q (*LPS*)	Actual Yield Remark	Predicted Yield Remark	Agreement between Actual and Predicted Remarks
	Longitude	Latitude				
1	42.41	33.17	0.60	Poor	Good-Moderate	Disagree
2	42.37	33.35	7.50	Good	Good-Moderate	Agree
3	42.23	33.32	3.90	Moderate	Poor-Moderate	Agree
4	42.42	33.18	4.27	Moderate	Moderate	Agree
5	42.55	33.33	2.18	Poor	Poor-Moderate	Agree
6	42.54	33.19	1.38	Poor	Poor-Moderate	Agree
7	42.47	33.25	4.37	Moderate	Good	Disagree
8	42.47	33.16	7.50	Good	Good-Moderate	Agree
9	42.45	33.26	7.50	Good	Good-Moderate	Agree
10	42.42	33.22	7.50	Good	Good-Moderate	Agree
11	42.5	33.16	7.50	Good	Good-Moderate	Agree
12	42.5	33.23	7.50	Good	Good-Moderate	Agree
13	42.49	33.14	8.25	Good	Good-Moderate	Agree
14	42.4	33.13	16.92	Good	Good	Agree
15	42.54	33.25	10.13	Good	Poor-Moderate	Disagree
16	42.33	33.36	7.56	Good	Good-Moderate	Agree
17	42.57	33.25	13.50	Good	Good-Moderate	Agree
18	42.41	33.17	1.23	Poor	Good-Moderate	Disagree
19	42.45	33.36	6.87	Moderate	Good	Disagree
20	42.38	33.16	22.50	Good	Good-Moderate	Agree
21	42.56	33.26	17.50	Good	Good-Moderate	Agree
22	42.58	33.26	12.00	Good	Good-Moderate	Agree
23	42.5	33.2	10.00	Good	Good-Moderate	Agree
24	42.54	33.18	0.81	Poor	Poor-Moderate	Agree
25	42.49	33.26	7.50	Good	Good-Moderate	Agree
26	42.21	33.17	3.60	Poor	Poor-Moderate	Agree
27	42.90273	33.5413	1.60	Poor	Good-Moderate	Disagree
28	42.65928	33.4304	7.34	Good	Good	Agree

The good and very good classes of prospective zones of the watershed had an average value of well yield of 10.7 lpm. Similarity analysis was conducted between the actual yield and predicted yield acquired from the prospective map to estimate the accuracy of the GWPZs and compare the results with the correlation value (Fig. 6).

The following steps were used to estimate the accuracy of the resultant prospective map:

i. The total number of existing bore wells = 28;
ii. Number of borewells with the similarity between the actual and expected yield range = 22;
iii. The prediction accuracy =

$$\frac{\text{Total number of borewells under similarity agreement}}{\text{Total number of the surveyed borewells}}$$

$$= \frac{22}{28} = 78.57\ \%$$

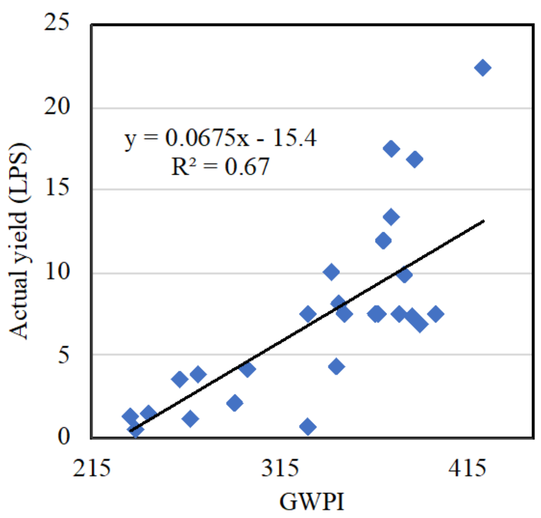

Fig.6 Cross plots between the groundwater potential index (GWPI) and the actual yields of borehole

The results of similarity analysis revealed that 22 out of the 28 validation points (78.57%) met with the predicted yield classes, and the value of the cross-correlation also certifies this as $R^2 = 0.67$. Accordingly, the GIS-based AHP approach applied in this study provides a reliable and factual result. The produced groundwater potential map could be a useful tool for the planning of water resources management and inclusive assessment to promote the exploration of groundwater projects for future planning.

8. CONCLUSION

The delineation of the GWPZs technique is considered the optimum alternative for managing water resources in the arid environment of the Iraqi Western Desert. This study proposed a cost-effective methodology to explore the suitable sites for GWPZs on a large scale in arid areas despite the limited available data. Geospatial techniques and the multi-criteria decision-making analysis (MCDA) were effectively used to analyze multiple datasets for better decision-making in water management projects. Remote sensing techniques, conventional maps, and metrological data provided the spatial information required to identify all the used criteria. Eight thematic layers of geomorphology, geology, slope, lineament, soil infiltration, rainfall, land use and land cover, and drainage density were considered in this study as influence parameters for locating the suitable sites of GWPZs. The Delineation process was carried out using the weighted linear combination (WLC) method by integrating RS and GIS techniques with the AHP method. This integrated approach helped assess the suitability of the predicted groundwater zones for the targeted study area. Different assigned weights for each thematic layer and ranks for subclasses were generated depending on the AHP approach. The resultant potential groundwater maps were reclassified into five categories viz. very good (92.04 km^2), good (557.6 km^2), moderate (1025.32 km^2), poor (539.57 km^2), and very poor (88.63 km^2) potential zone. These prospective zones respectively constitute 4%, 24.21%, 44.52%, 23.43%, and 3.85% of the catchment basin area. The regions such as alluvial fans and sandy lower plateaus characterized by the landforms associated with gentle slopes and a high density of lineaments with developed agricultural and vegetation cover have a very good potential for groundwater. The prospective groundwater zones were successfully verified with the locations and yields of existing boreholes. Similarity analysis was carried out for each borewell by comparing the actual yields with the predicted yield classes of the potential zones. They were also well-correlated by conducting the cross-correlation analysis with a coefficient value of $R^2 = 0.67$. The positive linear relationship between the groundwater potential index (GWPI) and borehole yield data suggests an efficiency of GWPZs delineation and the suitability of the utilized geo-environmental parameters in demarcating the groundwater potential map of the area. Consequently, according to the results of this study and the prediction accuracy for the prospective map, the applied methodology can be considered a helpful framework for the efficient assessment of the groundwater potentiality and recommended as support in future studies in other regions, especially in data-deficient conditions. In summary, the results of the present study demonstrate that the integration of RS and GIS-based AHP techniques can be effectively applied to map groundwater potential zoning. Hence, the resultant groundwater potential map could be a valuable tool for planning water resource management and inclusive assessment promoting exploration and planning of future groundwater projects.

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