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Erbil Basin Groundwater Recharge Potential Zone Determination Using Fuzzy-Analytical Hierarchy Process (AHP) in North Iraq

KEY WORDS:

GIS; remote sensing; groundwater; membership function; triangular fuzzy numbers

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ABSTRACT

Severe water scarcity has occurred in the Erbil Basin (EB) due to climate change and mismanagement of water resources during the past three decades. Assessment of the potential area of groundwater recharge is extremely significant for the protection and management of groundwater systems and water quality. This research aims to use the Fuzzy-Analytic Hierarchy Process (F-AHP) technique to recharge the aquifer in places in the EB that are likely to be groundwater recharge areas in a geographic information system (GIS) environment. GIS, remote sensing (RS), and F-AHP techniques were used to map the groundwater recharge potential zone in EB. Eight different geo-environmental factors were used to determine potential groundwater areas, namely: rainfall, lithology, geology, soil, slope, lineament density, land use/land cover (LULC), and drainage density (D_d). Then, the weights of the different thematic layers were assigned using a pairwise comparison matrix through the F-AHP. The total groundwater potential zone was shown to cover a very high area of 210.85 square kilometers (km^2), a high area of 188.94 km^2, a moderate area of 573.06 km^2, a low area of 1956.48 km^2, and a very low area of 216.34 km^2, according to the groundwater recharge potential zones (GWRPZs) map. As a result, nearly one-third of the areas investigated were found to have moderate-to-very high groundwater recharge potential. This type of research can provide decision-makers and local governments with a broad perspective on current and future planning for groundwater scarcity.

INTRODUCTION

Groundwater is a valuable resource and is one of the most important freshwater sources for domestic use, agriculture, and industry (Carrard, Foster, & Willetts, 2020). At present, nearly 34% of the world's water resources belong to groundwater (Cobbing, Adams, Dennis, & Riemann, 2013). Groundwater occurs in almost all landscapes (Neff et al., 2020), and all surface water features, including streams, wetlands, lakes, reservoirs, and estuaries, are usually hydraulically connected to groundwater (Winter, 1999). Groundwater in Iraq, especially in the Erbil basin, has an important role in water supply, agriculture, health, and poverty eradication in rural areas (Stevanovic & Iurkiewicz, 2009). It is usually recharged through precipitation and occasional snowmelt. However, in some topographic places, it can also be recharged by leakage from rivers, lakes, or canals (Shah & Lone, 2019). The increasing demand for limited supplies in semi-arid and dry regions is reducing groundwater levels and leading to a critical state of groundwater recharge (Scanlon et al., 2006).

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The analytical hierarchy process (AHP)-based Multi-Criteria Decision Making (MCDM) described by Saaty (1980) is a very common method and it has been applied in widespread areas, including planning and choosing the best alternative, allocating resources, and resolving conflict (Ho, 2008). Overall, the GIS-based AHP, which is a traditional method, is a suitable tool for considering multiple-criteria decision analysis problems and is simultaneously an applicable area for using fuzzy set theory (El-Din, Abd El Munim, & Mahdi, 2019). Fuzzy set theory was created to deal with the concept of partial truth values ranging from absolute right to absolute false (NGUYEN, 2021). From the late 1980s to the present, fuzzy-AHP methodologies have advanced rapidly, and countless applications based on F-AHP have been implemented and published in a variety of fields, including the environment, engineering, economics, and finance (Reig-Mullor, Pla-Santamaria, & Garcia-Bernabeu, 2020). The goal of the integrated GIS, RS, and F-AHP approaches is to classify and rank a collection of options that best match a set of criteria (Vafaei, Ribeiro, & Camarinha-Matos, 2016).

The Erbil basin covers an area of 3145 km^2, with a length of 75 km and a maximum width of 55 km. According to NA Al-Ansari, Essaid, and Salim (1981), the depth of EB wells in the 1980s was between 5 and 30 meters. Kznee (1997) stated that in 1996, the depth of wells had increased by approximately 150 to 200 meters, but by 2015, it had risen to between 300 and 600 meters. As a result, there is a significant and catastrophic depletion of groundwater, which is the worst-case scenario for the Erbil basin's aquifer system.

The main purpose of this research is to identify the groundwater potential zones for sustainable development and management using MCDA, GIS, RS, and Fuzzy-AHP techniques in the Erbil basin.

MATERIALS & METHOD

Study area

The geographical setting for the Erbil Basin is between latitudes 35° 46' N and 36° 34' N and longitudes 43° 34' and 44° 19' E. The GZR is the most important branch of the Tigris River, which springs from southeastern Turkey at an altitude of more than 4,000 m above sea level and flows into northern Iraq (Shekha, 2016). On the other hand, the Lower Zab River extends from northeast Iran to Iraq and is located south of the GZ, Figure 1. This location was chosen because it has Erbil Governorate's largest groundwater reservoir and is one of the Middle East's most important groundwater aquifers, with conglomerates, sandstones, sand, and gravel composing the bulk of the aquifer (Nadhir Al-Ansari, 2021).

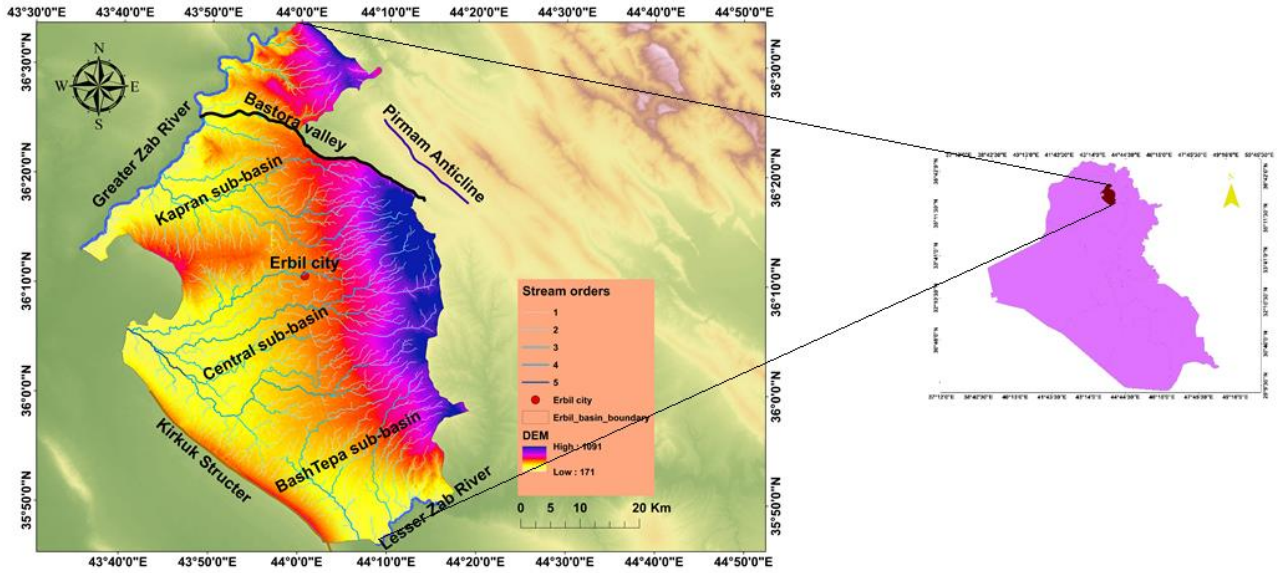


Figure (1): Location map of Erbil Basin in the Kurdistan Region of Iraq.

Data set

For this study area, USGS Earth Explorer (https://earthexplorer.usgs.gov/) was used to download Landsat 8 OLI to prepare the LULC map and SRTM-DEM to obtain the average slope, drainage network information, and drainage density map. The geological and lithological maps were

obtained from the Directorate of Surveying of Iraq, while the soil map was gained and digitized from Iraq's exploratory soil map of 1960. Table 1 summarizes the details of all the data used and the output layers.

Table (1): Details of the different data sets used in preparing the GWPM

Data type	Detail of data	Available format	Extracted layer	Generated layer	GIS data type
Satellite imagery	Landsat 8 Acquis. date 28.08.2021	ENVI 5.3	LULC	LULC	Raster
SRTM-DEM	2014-30m	TIFF	Contour, Elevation Drainage network	Slope, Hillshade, Drainage Density, Lineament Density	Raster Raster Raster
Geology & Lithology	Unit types	ESRI shapefile ESRI shapefile	Geology Lithology	Geology Lithology	Raster Raster
Soil map	Unit types	ESRI shapefile	Soil types	Soil types	Raster
Rainfall	2001-2020	ESRI shapefile	Rainfall map	Rainfall map	Raster
Depth to water level	2019	Central Ground Water Board	point	point	point

For the computation of weights of different features and thematic layers, Saaty's multi-criteria evaluation, which is the most applicable approach for solving problems, was used. The weighted index overlay method was used to combine all of the thematic layers. The data layers were then given weights to reflect their relative importance (Saaty, 1980). In general, in order to comprehend the concept of overlay analysis, two terms must be understood: "influence" and "scale value". "Influence" refers to a layer's overall importance, which is measured in percentages for each thematic layer, while the "scale value" is based on the importance of the features in the layer (Alpagut, Lopez Romo, Hernández, Tabanoğlu, & Hermoso Martinez, 2021). The least important value is one (1), and the most important value is five (5). In AHP, the percentage influence will be compared to each factor pairwise. In the current study, for example, AHP will compare rainfall to the other seven thematic layers, as well as other factors. Then, on a scale of 1 to 9, a value will be assigned. Nine (9) means "extremely important," five (5) means "strongly important," and one (1) means "equally important.", Table 2 (Saaty, 1980).

Criteria		**More important?**		**Scale 1-9**		
Rainfall	Geology		Rainfall		3	
		Lithology	Rainfall		3	
		Slope		Rainfall		3
		DD		Rainfall		5
		LULC		Rainfall		5
		Lineament	Rainfall		5	
		Soil		Rainfall		7
GEOLOGY		Lithology	Geology		3	
		Slope		Geology		3
		DD		Geology		3
		LULC		Geology		5
		Lineament	Geology		5	
		Soil		Geology		5
Lithology	Slope		Lithology		3	
		DD		Lithology	3	
		LULC		Lithology	5	
		Lineament	Lithology		5	
		Soil		Lithology	5	
Slope		DD		Slope		1
		LULC		Slope		3
		Lineament	Slope		3	
		Soil		Slope		5
DD		LULC		DD		1
		Lineament	DD		2	
		Soil		DD		3
LULC		Lineament	LULC		1	
		Soil		LULC		3
Lineament		Soil		Lineament	1	

Research Method and Procedure

Fuzzy-AHP

In the "fuzzy set" theory, there is a very precise and clear boundary to indicate if an entity belongs to a well-defined "set" of entities, and there is a sharp, crisp, and unambiguous distinction between a member and a nonmember of any well-defined "set" of entities. As a result, the fuzzy set theory will be regarded as both a natural extension of classical set theory as well as a rigorous mathematical concept (Chen, Pham, & Boustany, 2001). Fuzzy sets are a conceptual and mathematical framework for examining imprecise and ambiguous phenomena (Mentes & Helvacioglu, 2011), allowing individuals to function in ambiguous, uncertain settings and solve poorly presented problems or problems with inadequate information (Tiwary, 2009).

Furthermore, the process of "fuzzification" is the transformation of a crisp set into a fuzzy set or a fuzzy set into a fuzzier set. This operation essentially converts precise, crisp input values into linguistic variables, which are then converted into membership functions (Sridharan et al., 2018). On the other hand, de-fuzzification is defined as the process of converting a fuzzy member into a crisp member or reducing a fuzzy set to a crisp set (Nagarajan & Thirunavukarasu, 2019).
Generally, this judgment should have been supported by experience in the study area. A verbal judgment should follow certain guidelines, such as the consistency ratio (CR), to be acceptable. Moreover, if the CR consistency ratio is less than 0.05 for the 3x3 matrix, 0.09 for the 4x4 matrix, and 0.1 for larger matrices, the pairwise comparison matrix is said to be consistent (Noughabi, Raahemi, Albadvi, & Far, 2017). The CR for all items in the current study was less than 0.1, indicating that the matrix and item rating was consistent.

The pair-wise comparison matrix was generated using a denotative 9-point scale, with 1, 3, 5, 7, and 9 representing important, moderately important, strongly important, extremely strongly important, and extremely strongly important, respectively, Table 3.

Table (3): Effects and rates of factors affecting groundwater potentiality calculations (Saaty, 1980)

Definition	Relative importance	Triangular Fuzzy Number
Equal importance	**1**	(1, 1, 1)
Middle value between 1 and 3	**3**	(2, 3, 4)
Strong	**5**	(4, 5, 6)
Very strong	**7**	(6, 7, 8)
Extremely strong	**9**	(9, 9, 9)
Intermediate Values 2, 4, 6, 8 can be used to express the intermediate value	**2**	(1, 2, 3)
	4	(3, 4, 5)
	6	(5, 6, 7)
	8	(7, 8, 9)

Fuzzy-AHP is a dominant approach and has been used by many scientists to determine the potential area of groundwater (Lee, Mogi, & Hui, 2013). In this work, the fuzzy triangular number technique was used to represent a pair-wise comparison of GWRPZ selection.

Triangular fuzzy numbers

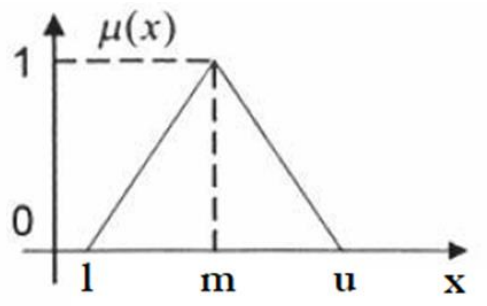


Figure (2): Membership function for triangular fuzzy numbers adapted after Shao, Huq, Cai, Altan, and Li (2020)

The fuzzy triangular number μ(x) can be depicted in Figure 2, which is easily presented in formula **1**. The fuzzy numbers 1, 2, and 3 represent the lower (*l*), middle (*m*), and upper (*u*) numbers from the triangular membership function, respectively, whereas the function value μá (x) is referred to as the grade of membership of (x) in á (x-axis). The fuzzing values will be used to replace the single and intermediate numbers in the fuzzy scale importance numbers (*l, m, u*). Where l ≦ m ≦ u, simultaneously, l = m = u, and it is a non-fuzzy number by convention.

$$\mu_{á}(x) = á = (1, 2, 3) \quad \textbf{(1)}$$

Furthermore, for two triangular fuzzy numbers $\check{A}_1 = (l_1, m_1, u_1)$ and $\check{A}_2 = (l_2, m_2, u_2)$, the main operational laws are expressed as formula **2**:

$$\check{A}_1 \oplus \check{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (2)$$

Formula **3** will be used to convert the crisply valued into fuzzy numbers in order to obtain the fuzzy pairwise metrics.

$$\textbf{á}^{-1} = (l, m, u)^{-1} = (1/u, 1/m, 1/l) \quad \textbf{(3)}$$

Fuzzy-AHP was proposed by Buckley (1985), in which calculating weights through the geometric mean will be applied, by multiplying two fuzzy numbers, Formula **4** multiplied fuzzy number equation.

$$\check{A}_1 \otimes \check{A}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 * 1_2, m_1 * m_2, u_1 * u_2) \quad (4)$$

Then, the fuzzy geometric mean and the procedures for determining the weights of the criteria can be calculated by Buckley (1985) as formula **5**:

$$\tilde{w}_i = \tilde{r}i \otimes (r_1 \oplus r_2 \oplus \ldots \oplus r_n)^{-1} \quad \textbf{(5)}$$

By implementing formula **6** for adding two fuzzy numbers, the reciprocal of the sum will be calculated.

$$\check{A}_1 \oplus \check{A}\,2 = ((l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (6)$$

Finally, the de-fuzzification method by applying the center of area (COA) method, formula **7**, will be used in order to obtain the fuzzy weights. The end process is obtaining the total normalized weight, which is 1.

$$\textbf{(COA)} = (l + m + u/3) \quad \textbf{(7)}$$

The final step is to conduct a test to determine the extent of consistency associated with the comparison matrix using the consistency ratio (CR) formula **8**.

$$\textbf{Consistency ratio (CR)} = \textbf{CI / RI} \quad \textbf{(8)}$$

2.3.3. Empirical illustration

The AHP model has been developed through four stages: weight assignment, the development of a pairwise comparison matrix, a consistency ratio (CR) check for fuzzy pairwise comparison, and determining weight normalization. Thus, the next step will be to replace the relative importance scale for all numbers after creating the pairwise comparison matrix, Table 4, and the relative importance scale with crispy values, Table 5.

Table (4): Pairwise comparison matrix for drainage density of the study area

Matrix	0 - 0.87	0.87 - 1.75	1.75 - 2.62	2.62 - 3.50	3.50 - 4.38
0 - 0.87	1	3	5	7	9
0.87 - 1.75	1/3	1	3	5	7
1.75 - 2.62	1/5	1/3	1	3	5
2.62 - 3.50	1/7	1/5	1/3	1	3
3.50 - 4.38	1/9	1/7	1/5	1/3	1

Table (5): displays the pairwise comparisons scale used in the Fuzzy-AHP method (Tseng et al. 2008)

Linguistic scale for the importance	Triangular fuzzy scale Triangular	fuzzy reciprocal scale
Just equal	(1, 1, 1)	(1, 1, 1)
Equally important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important (WMI)	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important (SMI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important (VSMI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important (AMI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Table (6): A fuzzified pairwise comparison matrix assigned a fuzzy number of drainage densities in the study area

Matrix	0 - 0.87	0.87 - 1.75	1.75 - 2.62	2.62 - 3.50	3.50 - 4.38	Fuzzy geometric mean value $r`_i$
0 - 0.87	(1, 1, 1)	(2, 3, 4)	(4, 5, 6)	(6, 7, 8)	(9, 9, 9)	(3.3658, 3.9363, 4.4413)
0.87 - 1.75	(1/4, 1/3, 1/2)	(1, 1, 1	(2, 3, 4)	(4, 5, 6)	(6, 7, 8)	(1.6437, 2.0321, 2.4914)
1.75 - 2.62	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	(2, 3, 4)	(4, 5, 6)	(0.7962, 0.9979, 1.2457)
2.62 - 3.50	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	(2, 3, 4)	(0.3981, 0.5306, 0.6034)
3.50 - 4.38	(1/9, 1/9, 1/9)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	(0.2228, 0.2619, 0.2941)

Thus, the fuzzification, formula **2**, is replacing the scale of relative importance like (1, 3, 5, 7, and 9) with fuzzy numbers. On the other hand, the fuzzy reciprocal numbers (1/3, 1/5, 1/7, and 1/9) in Table 4 will be converted to fuzzy numbers by using formula **3** as presented in Table 5. Then, the geometric mean based on Buckley (1985) will calculate the weights. Consequently, the fuzzy geometric mean value will be calculated using the formula **4** to multiply two fuzzy numbers. As a result of taking the fifth root, the lower, middle, and upper points will be all multiplied by the lower, middle, and upper points, Table 6. All other values will be calculated in the same way.

$$((1*2*4*6*9)^{1/5}, (1*3*5*7*9)^{1/5}, (1*4*6*8*9)^{1/5}) = (3.3658, 3.9363, 4.4413)$$

By implementing formula **4**, the fuzzy weights for each criterion will be calculated. However, before this step, it should add all geometric values by applying formula **5** to get the summation of two fuzzy numbers.

$$A_1 * A_2 = (l_1, m_1, u_1) * (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad \textbf{(9)}$$

(3.3658, 3.9363, 4.4413)
(1.6437, 2.0321, 2.4914)
(0.7962, 0.9979, 1.2457)
(0.3981, 0.5306, 0.6034)
(0.2228, 0.2619, 0.2941)
(6.4266, 7.7588, 9.0759) = Total
(1/9.0759, 1/7.7588, 1/6.4266) = (0.1102, 0.1289, 0.1556) = reciprocal number

In the next step, the fuzzy geometric mean values were then multiplied by the reciprocal of the geometric mean summation (0.1102, 0.1289, 0.1556).

(3.3658, 3.9363, 4.4413) * (0.1102, 0.1289, 0.1556) = (0.3709+0.5074+0.6911)/3=0.5231
(1.6437, 2.0321, 2.4914) * (0.1102, 0.1289, 0.1556) = (0.1811+0.2619+0.3876)/3=0.2769
(0.7962, 0.9979, 1.2457) * (0.1102, 0.1289, 0.1556) = (0.0877+0.1286+0.1938)/3=0.1367
(0.3981, 0.5306, 0.6034) * (0.1102, 0.1289, 0.1556) = (0.0439+0.0684+0.0939)/3=0.0687
(0.2228, 0.2619, 0.2941) * (0.1102, 0.1289, 0.1556) = (0.0245+0.0337+0.0457)/3=0.0346

Furthermore, the de-fuzzification process will be applied by using formula 6. Thus, the lower, middle, and upper weights were added together and divided by 3 in order to get the fuzzy weights. Usually, the total of the criteria weights is not acceptable due to its values being more than

1. Therefore, the weights must be normalized by dividing each weight by the total weight in order to obtain the normalized eights, as shown in Table 7.

Table (7): A De-fuzzification process and the normalized weights of drainage densities in the study area

DD Values	The De-Fuzzification process	Fuzzy weights $\tilde{w}_i$	Normalized weights
1	(0.3709+0.5074+0.6911)/3=0.5231	0.5231/1.04= 0.5029	0.5029
2	(0.3709+0.5074+0.6911)/3=0.5231	0.2769/1.04= 0.2662	0.2662
3	(0.3709+0.5074+0.6911)/3=0.5231	0.1367/1.04= 0.1314	0.1314
4	(0.3709+0.5074+0.6911)/3=0.5231	0.0687/1.04= 0.0661	0.0661
5	(0.3709+0.5074+0.6911)/3=0.5231	0.0346/1.04= 0.0334	0.0334
Total		1.04	1.00

Groundwater Potential Index

The Groundwater Potential Index (GWPI) is a dimensionless quantification index method that combines thematic layers to produce groundwater potential scores for various locations. The fuzzy-AHP method was used to determine the ratings and weight values for each of the parameters (Kumar, Singh, & Singh, 2021), which were then used to calculate the GWPI as follows:

$$GWPI= [R_w * R_r + L_w * L_r + Ge_w * Ge_r + Sl_w * Sl_r + Lu_w * Lu_r + D_{dw} * D_{dr} + LN_w * LN_r + S_w * S_r] \quad (10)$$

where GWPI stands for Groundwater Potential, R stands for rainfall, L stands for lithology, Ge stands for geology, Sl stands for slope, Lu stands for land use/land cover, Dd stands for drainage density, LN stands for lineament, and S stands for slope. In addition, the weight of each thematic layer used is marked by the subscript 'w', and the rating of the features in each thematic layer is marked by the subscript 'r.'

RESULTS

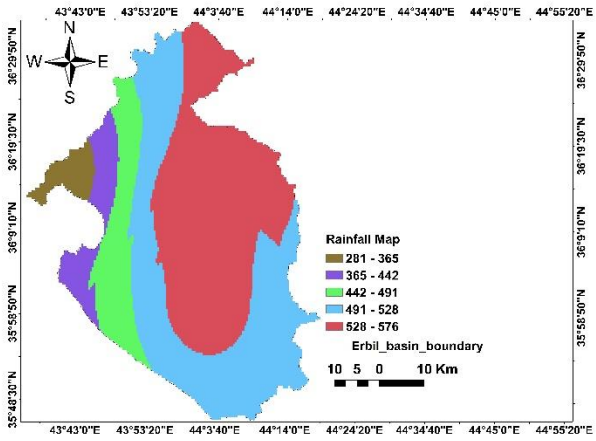
The availability of groundwater generally depends on rainfall, geology, lithology, soil, lineament density, drainage density, lulc, and other factors. Hence, all the thematic maps of the current study area have been prepared according to the previously described methods. The following is a description of the prominent aspects of these topics. Eight factors were used to determine the highly penetrable and porous terrain, due to the identification of appropriate recharge zones.

Rainfall

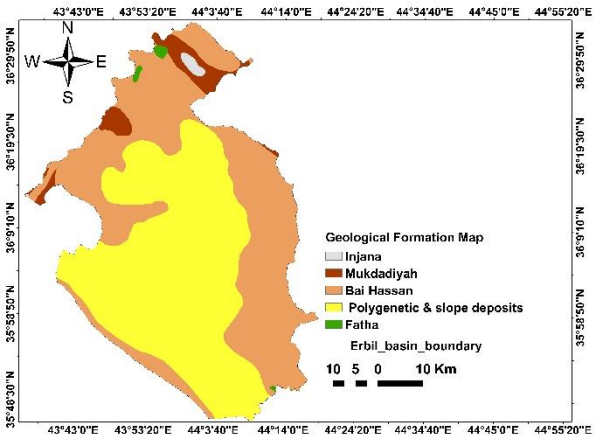
The rainfall map of EB is shown in Figure 3a. The maximum amount of rainfall is about 576.9 mm/year and the minimum value is about 281 mm/year. Furthermore, as you move westward, the amount of precipitation decreases gradually. The mean annual precipitation of this basin was about 467 mm during the last 20 years (2000–2020).

Geology

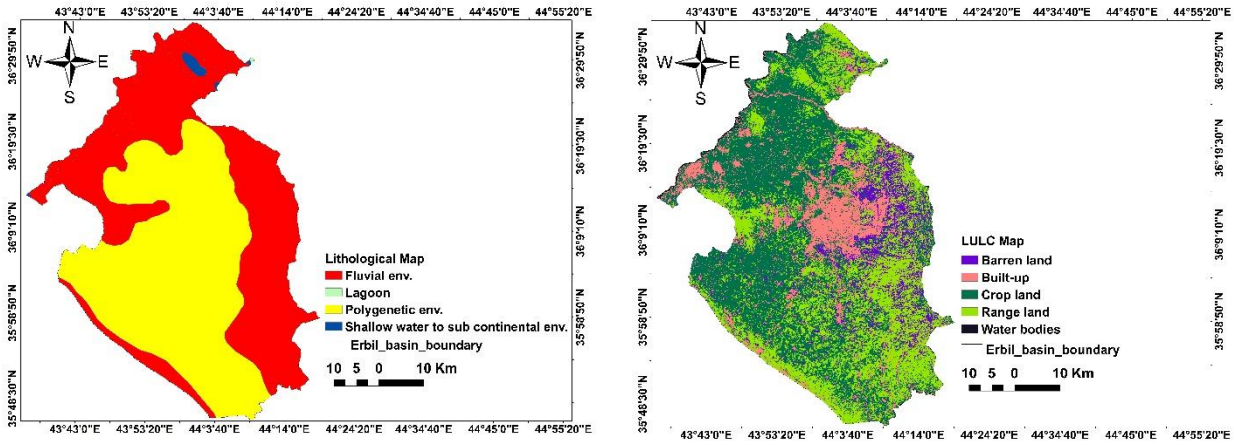
The study area's dominant units are the quaternary deposit (polygenetic deposit) and the Bai-Hassan formations, which have good permeability and play an important role in groundwater supply and characterize the rainwater harvesting area. Thus, the surface drainage network contributes to the accumulation of surface flows in this area (Saleh, Al-Ansari, & Abdullah, 2020).



a



b



c d

Figure (3): (a) Average rainfall map, (b) Geological map, (c) Lithological map, (d) LULC map of the study area.

Lithology

The lithological features of the study area are mainly formed by the polygenetic environment, which is mainly a composite of alluvial sediments such as silt, clay, sand, and a mixture of gypsum and iron; and conglomerate aquifers in the quaternary and Pliocene within the formation of Bai Hassan (Saleh et al., 2020). A small portion of a fluvial environment can be seen in the north of the study area, with a small portion of the shallow water sub-continental environment and lagoon, Figure 3c.

LULC

The study area was categorized into five classes, namely: cropland, 1389.05 km^2, which has a maximum area; rangeland, 1013.3 km^2, built-up area, 431.32 km^2, barren land, 305.11 km^2, and water bodies, 17.063 km^2. Cropland and rangeland have a better ability to recharge and retain groundwater than built-up and barren land areas, Figure 3d. In areas of dense cultivation, groundwater recharge and storage are more likely, whereas infiltration and recharge are less likely in exposed bare rock and built-up areas.

Soil Type

Four types of soil dominate the study area, viz., (1) brown soils, deep phase; (2) brown soils, medium and shallow phases; (3) lithosolic soils in limestone; and (4) lithosolic soils in sandstone and gypsum, Figure 4a. Moreover, the first type dominates 83.1% of the total area and has gravel silt-clay layers with surface cracks under the brown soil layer, which is an appropriate type of soil for infiltration. The second type covers 13.64% and represents brown soil with medium to shallow phases covered by a layer of gravel and silty loam, which can be considered a proper type of soil for infiltration, while the third and fourth types are very poor classes for infiltration.

Slope

The slope of the EB was derived from the digital elevation model (DEM) and was classified into five categories ranging from 0 to 57.86. The areas having a 0-3.6^o slope are categorized as "very good" areas and cover 34.50% of the study area. While areas that have a 3.6^o to 7.03^o slope are categorized as "good" areas and cover 36.32% of the study area. "Moderate" areas have a slope degree of 7.03^o–11.34^o and cover 19.74% of the area. Those areas with an 11.34^o –17.92^o slope are considered "poor" for groundwater occurrence and cover 7.45%. However, areas that have 17.92^o–57.86^o of slope and cover 1.99% are defined as "very poor" due to the higher slope, which causes higher runoff due to increasing the amount of runoff with slope. Thus, roughly more than 70% of the EB is dominated by the flat terrain in the central part, which reasonably reduces the runoff movement, Figure 4b.

Lineament Density

The lowest value of lineament density of the study area ranges between 0 and 0.15 km/km^2. This part covers almost 1011 km^2 of the total area. However, the highest value of lineament density in the study area ranges between 0.60 and 0.75 km/km^2 and covers 216 km^2, which means the

higher the probability of groundwater occurrence, while the moderate value of lineament density ranges between 0.30 and 0.45 km/km^2 and covers 761 km^2 of the total area, Figure 4c.

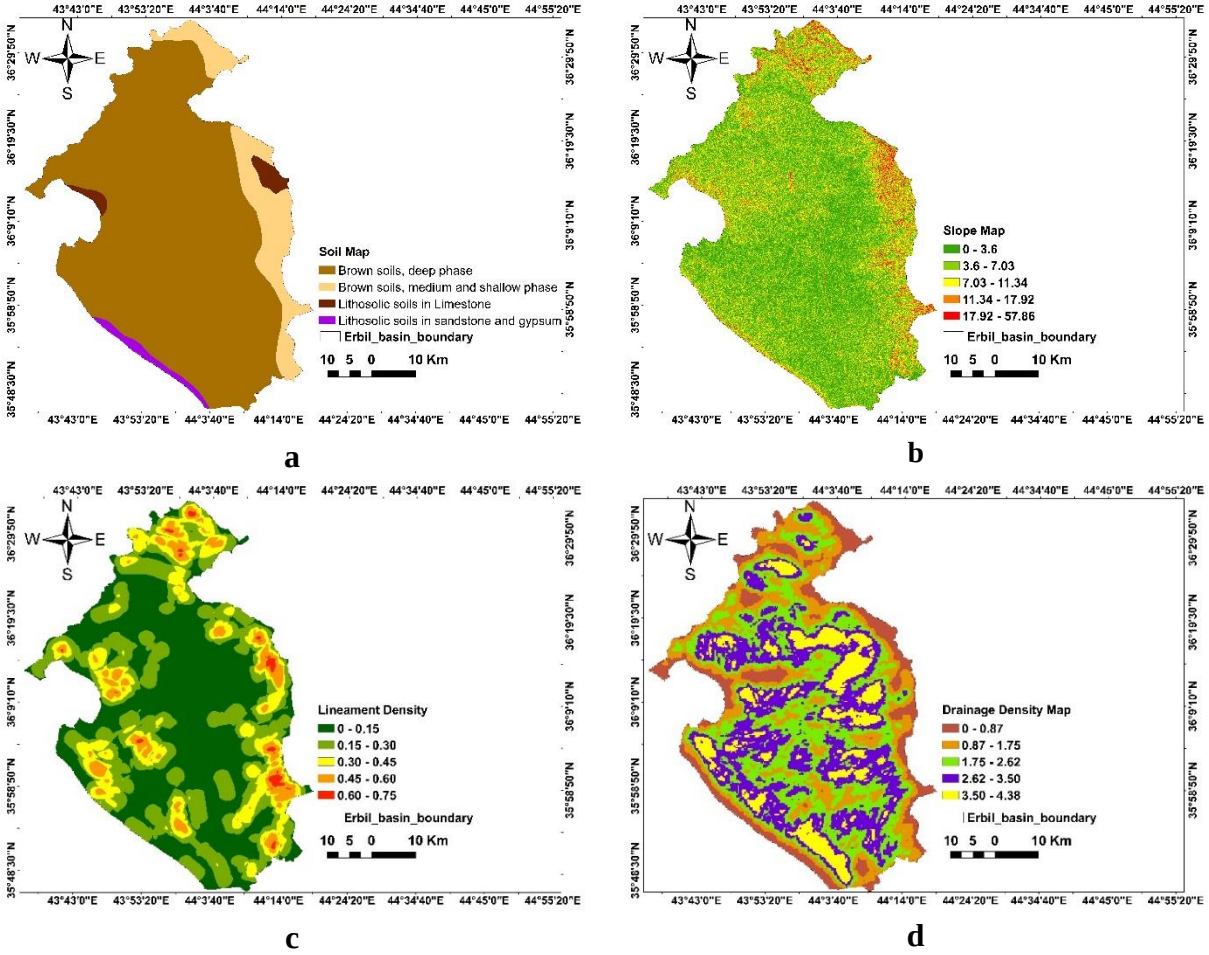


Figure (4): (a) Soil map, (b) Slope map, (c) Lineament density, (d) Drainage density of the study area

Drainage Density

In the current study, a drainage density map was applied to define the highly permeable and porous terrain due to the identification of suitable recharge sites. The D_d of the current study area has been categorised into five classes: "very high" (3.50–4.38 km/ km^2) covers 305 km^2 of the area; "high" (2.62–3.50 km/km^2) covers 601 km^2, "medium" (1.75–2.62 km/km^2) covers 878 km^2, "low" (0.87–1.75 km/km^2) covers 797 km^2 and "very low" (0–0.87 km/km^2) covers 573 km^2, respectively. Furthermore, taking into account from a recharge point perspective, areas with low D_d are given high weight and vice versa, as shown in Figure 4d.

DISCUSSION

The results showed that groundwater in Erbil basin follows the topography of the region, so it flows from the east to the west, which was also confirmed by (Al-Tamir, 2008). Moreover, the east side revealed that it contains deeper groundwater levels than the west part of the study area, which has shallower groundwater levels, Figure 5. Therefore, groundwater withdrawals have expanded dramatically over the past 30 years, globally and in the EB region in particular.

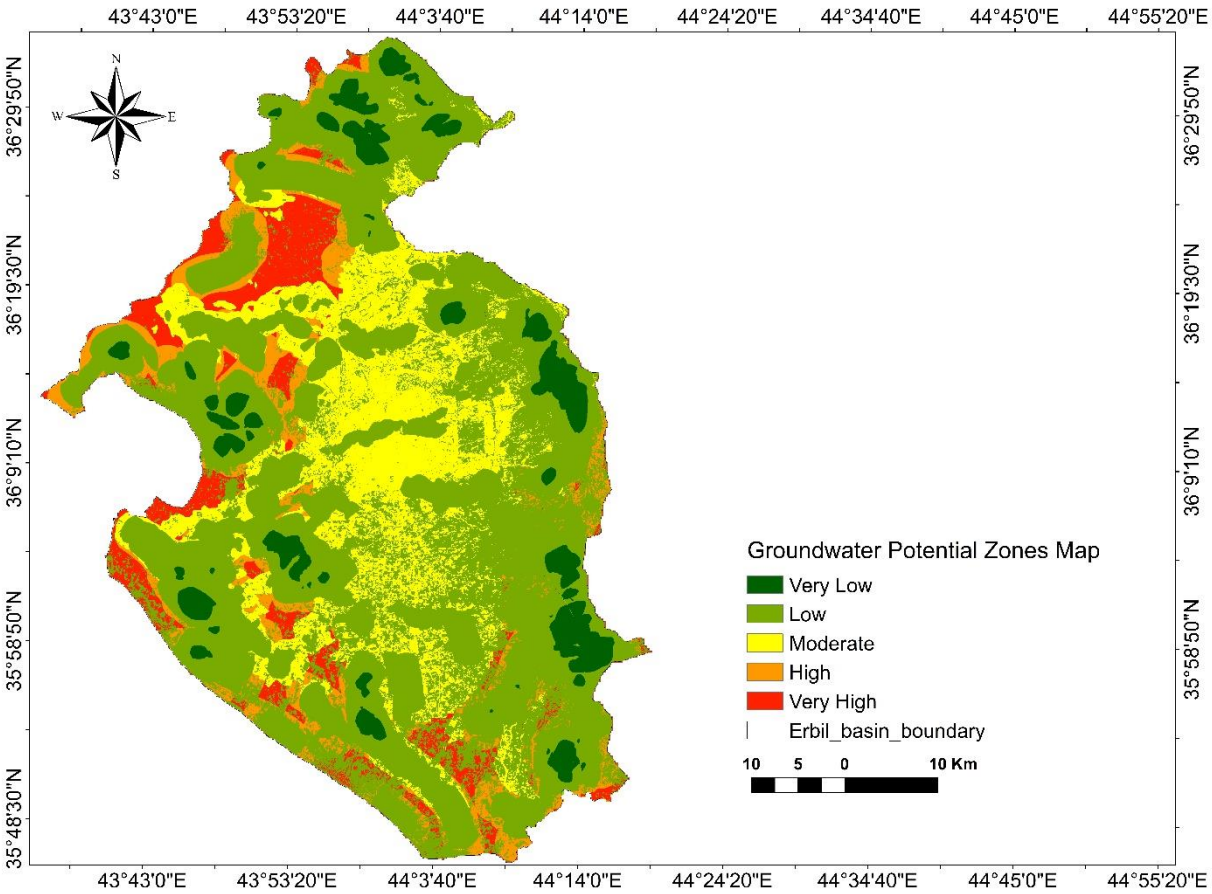


Figure (5): The groundwater potential zones map of the study area

Furthermore, the groundwater potential zone in Figure 5 shows also that about 210.85 km^2 of the total area falls under the "very high GWRPZ". However, the "high" GWRPZ occupies about 188.94 km^2, and 573.06 km^2 lies under the "moderate" GWRPZ. Conversely, the "low GWRPZ" covers the largest area of the study area, with 1956.48 km^2, whereas 216.34 km^2 of coverage lies under the "very low GWRPZ". Thus, the sustainable development of groundwater in this study basin could benefit from the GWRPZ map. This implies that recharging the groundwater is best done in areas with "very high" and "high" potential groundwater. This can also be confirmed by the depth of wells, which have lower depths in meters compared to the other well sites.

Moreover, the results showed also that the rainfall and the lithological factors were the most suitable and promising groundwater potential zones due to the good porosity and permeability caused by the loose and unconsolidated sediments, which almost cover 80% of the current study (Al-Tamir, 2008). The effect of the rainfall was the major source of groundwater storage. Thus, the higher the precipitation intensity, the greater the groundwater recharge, and vice versa. Overall, the GWRPZ map illustrates that the study area is a suitable zone for aquifer recharge. Therefore, this study is useful for decision-makers to define a plan to recharge groundwater. Furthermore, a careful management plan is required to make better use of the groundwater resources (Çelik, 2019).

The AHP approach was used to obtain weight values for all the thematic layers, followed by the fuzzy rating values of the attribute classes and sub-classes for each individual thematic layer. Table 8 displays that the most relevant parameter in the current work is lithology, having a weight value of 0.3843, followed by rainfall and geology, with weight values of 0.2515 and 0.1599, respectively. Moreover, other factors affecting groundwater potential with their descending weights are slope (0.0696), drainage density (0.0563), LULC (0.0393), soil (0.0236), and lineament density (0.0155). However, the F-AHP specified the total weight and rating values for each individual sub-category. Also, from Table 8, the rainfall sub-class (528–576) was the most effective parameter with a weight value of 0.1840, followed by sub-categories of shallow water to the sub-continental environment and fluvial environment factors with weight values of 0.1551 and 0.1428, respectively.

Additionally, it is observed that wells, symbolized in a triangle, are located in the north and south-western parts of the basin and are mostly close to and even far from the GZR, and have a very high groundwater potential. This reveals that some of the western parts of the EB are active zone for recharging the groundwater table and that they can be selected for an artificial recharge zone.

Table (8) Fuzzy weights and rating of parameters used and their attributes

Parameters	Sub-classes	Fuzzy AHP		
		Weight of the parameters	Rating of the attribute class	Total weight
Lithology	Fluvial environment	**0.3843**	0.3716	0.1428
	Lagoon		0.0539	0.0207
	polygenetic environment		0.1708	0.0656
	Shallow water to the sub-continental environment		0.4037	0.1551
Drainage Density (km^{-1})	0 - 0.87	**0.0563**	0.5029	0.0283
	0.87 - 1.75		0.2662	0.0149
	1.75 - 2.62		0.1314	0.0073
	2.62 - 3.50		0.0661	0.0037
	3.50 - 4.38		0.0334	0.0018
Geology	Polygenetic & slope deposits	**0.1599**	0.3737	0.0597
	Bai Hassan		0.3737	0.0597
	Fatha		0.0829	0.0132
	Injana		0.0389	0.0062
	Mukdadyah		0.1308	0.0209
Lineament density	0.60 - 0.75	**0.0155**	0.5204	0.0080
	0.45 - 0.60		0.2753	0.0042
	0.30 - 0.45		0.1364	0.0021
	0.15 - 0.30		0.0454	0.0007
	0 - 0.15		0.0225	0.0003
LULC	Rangeland	**0.0393**	0.1434	0.0056
	Cropland		0.1199	0.0047
	Water bodies		0.6221	0.0244
	Barren land		0.0603	0.0023
	Built-up		0.0541	0.0021
Rainfall	528 – 576	**0.2515**	0.7318	0.1840
	491 – 528		0.1519	0.0382
	442 – 491		0.0631	0.0158
	365 – 442		0.0363	0.0091
	281 – 365		0.0151	0.0037
Slope	0 - 3.6	**0.0696**	0.5018	0.0349
	3.6 - 7.03		0.2656	0.0184
	7.03 - 11.34		0.1312	0.0091
	11.34 - 17.92		0.0718	0.0049
	17.92 - 57.86		0.0296	0.0020
Soil	Brown soils, deep phase	**0.0236**	0.4566	0.0107
	Brown soils, medium, and shallow phase		0.2097	0.0049
	Lithosolic soils in Limestone		0.1095	0.0025
	Lithosolic soils in sandstone and gypsum		0.2242	0.0052

The wells from the central and eastern parts of the basin, on the other hand, show the deeper to deepest groundwater tables, respectively, and are in the basin's moderate to very low groundwater potential zones. As a result, the groundwater potential zone can be seen to have a negative relationship with the groundwater level, Figure 6.

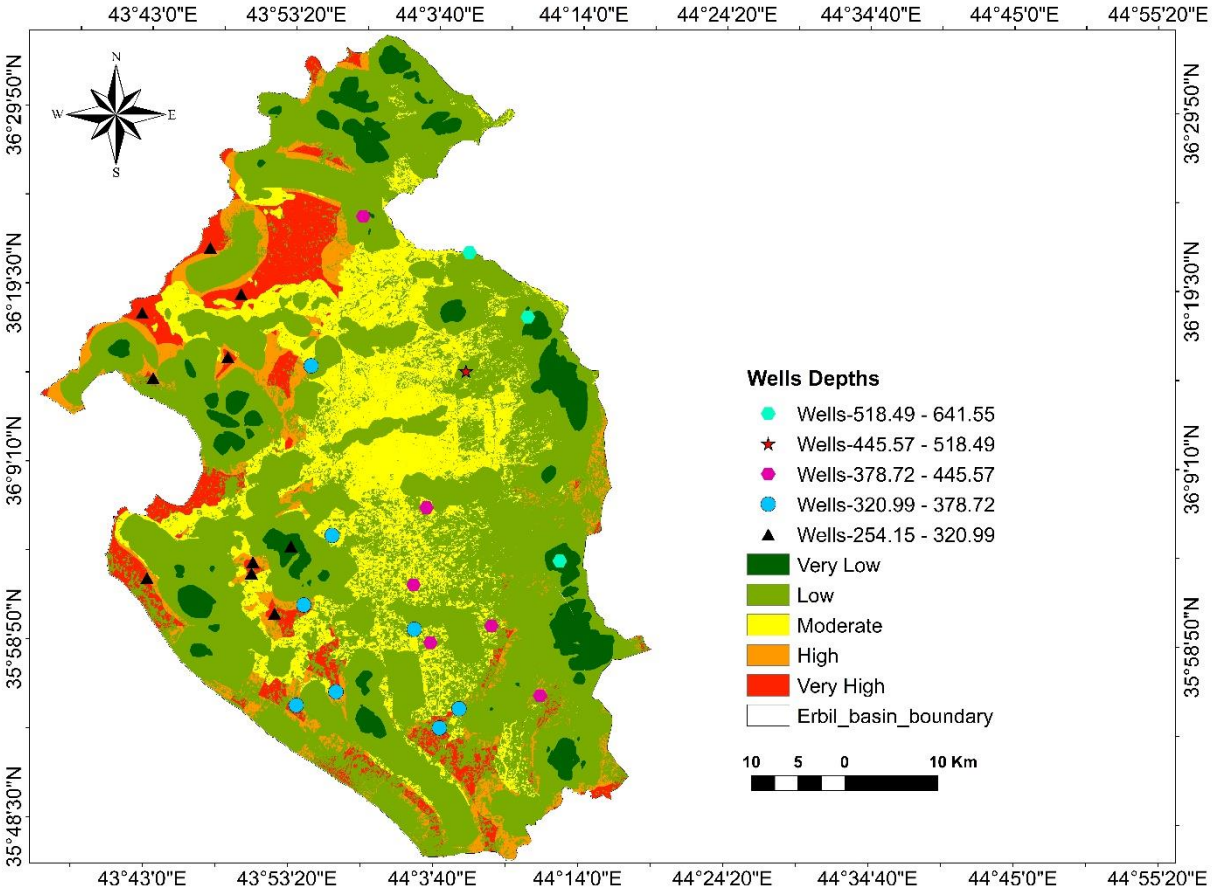


Figure (6): Groundwater potential zones map of the study area and model validation through the wells.

Validation of GWPZ maps

To verify the accuracy of the Fuzzy-AHP model, 28 observation wells of groundwater table data from the General Directorate of Subsurface Water were obtained and compared to a GWPZ map. Wells' locations were plotted on a post-GWRPZ map in ArcGIS. The depth of the groundwater table below the surface ranges between 254.15 and 641.55 meters. The findings revealed that 9 of the 28 wells were accurately located in potential zones of very high groundwater Figure 6, which were classified as having a shallower depth to groundwater level with depths ranging from 254.15 to 320.99 meters, compared to the other wells, which had depths ranging from 518.49 to 641.55 meters. Subsequently, six out of eight wells were identified in the high groundwater recharge zones, with depths ranging from 320.99 to 378.72 meters. While five of six wells belonged to areas with moderate potential for groundwater. However, one well was located in the lower GWRPZ, and two of the last three wells were located in very low areas, Figures 6 & 7.

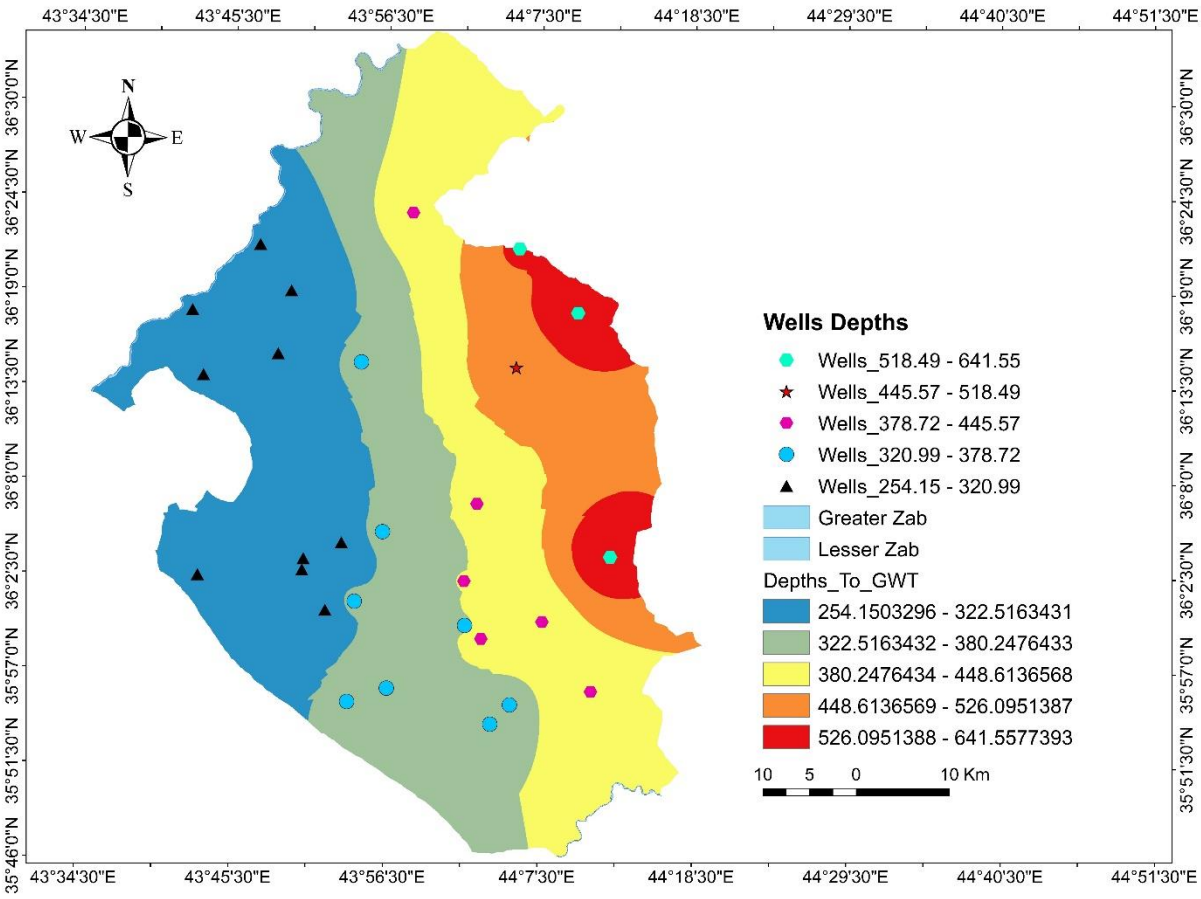


Figure (7): Groundwater level depths in the Erbil basin

CONCLUSIONS

The main themes of the present study were the availability of groundwater and associated human perceptions. The delineation of potential groundwater zones was performed by applying "weighted overlay classification" using the spatial analyst method in ArcGIS. This research demonstrates the usefulness of RS, GIS, and the integrated Fuzzy-AHP technique for the identification of groundwater potential zones. Concerning the relative importance of various parameters of the current study, rainfall and lithology were the two most influential ones, while geology, slope, drainage density, LULC, lineament density, and soil were the least influential. The most effective criteria for the potential area of groundwater in the study area were the rainfall subcategories (528-576) mm, shallow water to the sub-continental environment, and fluvial environment factors with weight values of 0.1840, 0.1551, and 0.1428, respectively.

RECOMMENDATIONS

According to this study, a series of weirs (small dams) should be built along the Bastora River's valley to raise the groundwater level, which is critical, since the composition of this valley mainly consists of conglomerates and gravel according to geological and lithological settings that infiltrate the unconfined and semi-confined aquifer. Moreover, the Bastora valley was once a riverbed (Ghaib, 2009), but it is now a full-fledged valley, especially during summer and autumn. It is noteworthy that in winter and spring, there is very little runoff. It can be explained that the groundwater flows from the northeast to the southwest in the study area, which could be related to groundwater recharge of the groundwater by the Bastora valley in the past, and it was a groundwater recharge area of the Erbil basin. As a result of the widespread and increasing consumption by the population of the city Erbil, groundwater has been depleted.

Additionally, it is also necessary to artificially recharge the wells with a pumping rate of 10,000-15,000 m^3/day distributed among 20 to 30 injection wells, which leads to an annual increase in groundwater levels in the selected areas. Hassan, Nile, Mahdi, Wesseling, and Ritsema (2021) investigated the simulation work and found that injecting treated water through 20 wells would raise

the groundwater table by more than 91 km^2 and 136 km^2 for pumping rates of 5000 and 10,000 m^3/day, respectively. Moreover, this will result in an annual elevation of 7 to 20 millimeters in the Kerbala desert in Iraq.

Acknowledgments

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Conflict of Interest

The author declares no conflict of interest.

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تحديد المواقع المحتملة لإعادة تغذية المياه الجوفية لحوض أربيل باستخدام عملية التسلسل الهرمي التحليلي الضبابي(F-AHP) في شمال العراق

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الكلمات المفتاحية:
نظم المعلومات الجغرافية ؛ الاستشعار عن بعد؛ المياه الجوفية؛ وظيفة عضوية؛ أرقام ضبابية مثلثة

الخلاصة

حدثت ندرة حادة في المياه في حوض أربيل بسبب تغير المناخ وسوء إدارة الموارد المائية خلال العقود الثلاثة الماضية. إن تقييم المواقع المحتملة لتغذية المياه الجوفية مهم للغاية لحماية وإدارة أنظمة المياه الجوفية ونوعية المياه. يهدف هذا البحث إلى تحديد المواقع المحتملة للمياه الجوفية باستخدام تقنية عملية التحليل الهرمي الضبابي (F-AHP) لإعادة شحن الخزان الجوفي في منطقة حوض أربيل. تم استخدام تقنيات نظم المعلومات الجغرافية (GIS)والاستشعار عن بعد (RS) و طريقة التحليل الهرمي الضبابي لرسم خريطة للمنطقة المحتملة لإعادة شحن المياه الجوفية في منطقة حوض أربيل. تم استخدام ثمانية عوامل جيوبيئية مختلفة لتحديد مناطق المياه الجوفية المحتملة، وهي: هطول الأمطار ، والجيومورفولوجيا، والجيولوجيا ، والتربة ، والأنحدار ، وكثافة الخطوط ، واستخدام الأراضي / الغطاء الأرضي، وكثافة الصرف. بعد ذلك ، تم تعيين أوزان الطبقات الموضوعية المختلفة باستخدام مصفوفة مقارنة زوجية من خلال F-AHP. تبين أن إجمالي المنطقة المحتملة للمياه الجوفية تغطي مساحة عالية جدًا تبلغ 210.85 كيلومترًا مربعًا ، ومساحة عالية تبلغ 188.94 كم^2، ومساحة معتدلة تبلغ 573.06 كم^2، ومساحة منخفضة تبلغ 1956.48 كم^2، مع منطقة منخفضة جدًا تبلغ 216.34 كيلومترًا مربعًا، وفقًا لخريطة المناطق المحتملة لتغذية المياه الجوفية (GWRPZ). نتيجة لذلك ، تم العثور على ما يقارب من ثلث المناطق التي تم فحصها لديها إمكانية إعادة تغذية المياه الجوفية متوسطة إلى عالية جدًا. يمكن لهذا النوع من البحث أن يزود صانعي القرار والحكومات المحلية بمنظور واسع حول التخطيط الحالي والمستقبلي لندرة المياه الجوفية.