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Application of Fuzzy Logic Approach via GIS for Determining the Optimum Groundwater Wells Sites Based on the Hydro-Geoelectric Parameters

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ABSTRACT

Salah Al-Din Governorate, including the study area located in Baiji district, is considered an important agricultural area in Iraq. As these areas have become mainly dependent on ground water. As this led to the depletion of underground water reservoirs, which turned many of the wells into unproductive or poorly productive wells. Therefore, there was a need to re-evaluate the hydraulic properties in the region, and then nominate sites for drilling new wells with high productivity according to the data of this evaluation. Selecting new well sites is becoming an increasingly difficult task. All hydraulic properties and geological factors must be taken into consideration. On the other hand, GIS technology is considered one of the most reliable techniques used in the process of determining the most appropriate sites. All this is done according to the use of algorithms that depend mainly on the importance of each factor and dealing with it as a class within the selection and nomination mechanism. In this study, fuzzy logic was applied through geographic information systems technology to determine the optimum sites for new well drilling with high productivity, based on the analysis of hydro-electrical parameters of the aquifer in the region. The research region was divided into four groups by the findings map: excluded, low suitability, moderate suitability, and high suitability. The area for each suitability category was 172.53, 269.76, 131.89, 127.26 km^2 respectively.

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1. Introduction

Groundwater is an important and basic resource of the national wealth (Aretouyap et al., 2022; Abdulrazzaq et al., 2022a), and it is included in the process of human and economic development (Aladeboyeje et al., 2021; Abdulrazzaq et al., 2022b). The groundwater in Iraq is also a vital tributary to confront the shortage of surface water (Abdulrazzaq et al., 2020a), as Iraq's repeated losses from the waters of the Tigris and Euphrates rivers and their tributaries have reached frightening degrees in recent years, which has had a negative impact on the agricultural, industrial and other sectors (Abdulrazzaq, 2011). The fluctuation and irregularity of rainfall led to the transformation of large areas of land into arid areas and alarming levels that portend a dangerous future if they are not addressed by comprehensive scientific and strategic plans.

The impacts of policies made by the decision in the water industry are not confined to financial implications alone, but also encompass, with equal weight, circumstances for human safety, health, and survival, as well as the economic and social characteristics linked with these conditions, as most countries depend on this water as a water source that meets Sometimes 90% of their water needs, especially the countries of the Arab region, specifically countries devoid of surface water sources and with a desert climate. People's needs for water are increasing with the increase in industrial, agricultural and urban progress, which has made most countries' attention lately to water (Al-Janabi, 2008), and as it is It is known that the water resources available for use are constantly decreasing as a result of the increasing rates of increasing demand for water, and therefore it has become necessary to expand studies and research in the detection and investment of groundwater, which requires various investigations for the purpose of identifying the underground aquifer and how to renew it and the method of extraction. Water-bearing rock units called aquifers (Todd, 1980). A water aquifer is a formation or group of geological formations with good permeability and porosity, saturated with water, and having the ability to pass economic quantities of water through springs or wells (Walton, 1970).

Arbitrary water well drilling, on the other hand, may result in aquifer degradation when it is not conducted in accordance with a well-thought-out plan for identifying suitable well exploration locations with high productivity. As a result, a strategy for selecting well locations in order to maximize groundwater development should be devised. The ability to create a plan for locating suitable drilling places is mostly reliant on specific factors that reflect the quality and quantity of groundwater that may be extracted from the aquifer. Geoelectrical measures are used in this context to quantify the thickness and depth of the aquifer, as well as to evaluate water quality and other factors that may be estimated using these observations. Several criteria can also be integrated utilizing modern GIS software and the Multi-Criteria Evaluation (MCE) approach to discover potential drilling sites. GIS is a geographic database management system for managing data from a variety of sources. It's a useful tool for site selection studies since it stores, analyzes, and presents data according to user-defined criteria (Abdulrazzaq et al., 2020b). The MCE methodology is a decision-making method that integrates qualitative and quantitative data by dissecting it in a systematic sequence and using numerous criteria (Chan et al., 2008; Nakamo, 2021).

The fuzzy model has been proven operative for such hydrological surveys. Shao et al. (2020) recognized groundwater potential zones in semi-arid Shanxi Province (China) using the fuzzy algebraic model. Pathak and Bhandary (2020) used a multi-layer fuzzy inference system in a GIS to assess groundwater vulnerability Mallik et al. (2021) analyzed groundwater suitability for drinking using GIS-based fuzzy model.
The goal of this project is to use the MCE approach with GIS as a decision-making tool to choice the best drilling site for new wells. The hydro-geophysical characteristics produced from the vertical electrical soundings (VES) data are used to choose the best locations. The findings of this study have applications in groundwater management, as well as agricultural, livestock, and human livelihoods.

2. Study Area

2.1 The Location of the Study Area

The study area is located within Salah al-Din Governorate between the city of Baiji in the north and Tikrit in the south, along the western bank of the Tigris River (Figure 1), between longitudes 43° 40' - 43° 56' and latitudes 34° 35' - 34° 54'. It is bordered from the east by the Tigris River, from the west by Tikrit Subsurface Anticline (TSA), from the south by Wadi Sheshin, and the sand dunes from the north and northwest. The area is semi-rectangular, with a length of about 45 km, and a total area of about 700 km^2.

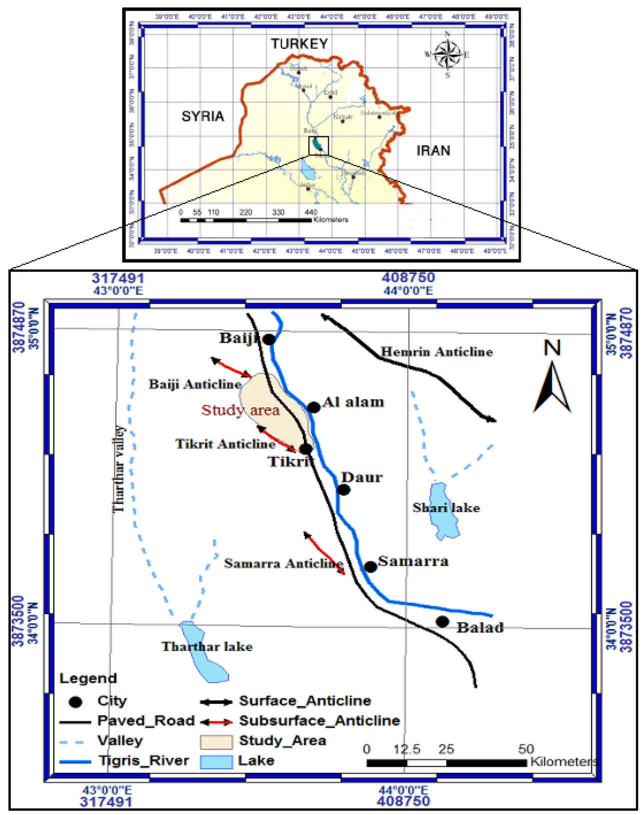

Figure 1. A site map of the study area

2.2 The Topographic and Tectonic Setting

The area is generally flat, with a few ripples for some small valleys that head to the east and southeast towards the Tigris River. A major portion of the research region is covered by river terraces, about two-thirds of the area, and they are covered with gypsum soil with gravel. As for the heights of the earth's surface, they range from 160 meters above sea level at its western borders near the TSA and descend eastward towards the Tigris River until they reach 100 meters at the river bank. The geomorphology and topography of the region in general are related to its geological and structural situation, in addition to the processes of erosion and weathering (Al-Ani, 1997). Among the most important geomorphological phenomena observed in the region are valleys, as the region is characterized by the presence of two types of valley systems and several ranks up to the fifth level, in which seasonal rainwater flows, the first is known as the tree system and the second is known as the parallel system. The density of these valleys increases in the western part of the region near the TSA, which is in the form of a dense superficial drainage system that heads towards the east and then deviates towards and south-east to drain into Wadi Sheshin and then into the Tigris River. These valleys are characterized by a slight slope, filled with fine-grained calcareous deposits. As for the northern and northwestern part, it is characterized by the lack of valleys that end with flood depressions inside the region, in which rains gather in the form of valleys that greatly help in replenishing the groundwater (Al-Jubouri, 2011). A number of small valleys stretch from the boundaries of the river terraces and head east towards the Tigris River in the eastern half of the area next to the Tigris River. The flow of the minor valleys switches direction to the west in the west of Tikrit's subsurface fold, which marks the region's southwestern boundary. The presence of cliffs and the mass destruction of cliffs along the Tigris River, as well as the presence of sand dunes and sand plates, are among the other geomorphological occurrences (Al-Ani, 1997).

2.3 Geological Setting

The exposed rocks in the region range in age from the middle Miocene to Quaternary deposits. The Injana Formation, which is exposed in the northern portion of the research region as illustrated in Figure 2, is the oldest exposed formation in the region. It also unfolds in Wadi Sheshin, which represents the southern boundary of the study area. The age of this formation is the late Miocene, and the formation is divided into two main members, the first one (Lower member) is consists of alternating layers of mudstone, siltstone and sandstone, where the second member (Upper member) is consists of alternating fractured sandstone and mudstone layers and siltstone layers of little thickness. Quaternary deposits also cover a large area of the study area that divided into two parts (Pleistocene and Holocene). Pleistocene sediments is consists mainly of gravel deposits represented by river terraces deposits, as well as other deposits such as gypsum soil (Gybkarite). Gravel deposits comprise a substantial portion of the research area, the gravel varies in size from boulders to gravel, and it is poorly interconnected, which led to the creation of a good layer for water penetration into the aquifers (Al-Ani, 1997). The sedimentary facies of these assemblies were divided into four facies, namely (mud pebbles, sandy clay pebbles, sandy pebbles, and sandy clay pebbles) (Basi & Karim, 1990). Gypsum soil, on the other hand, covers a considerable portion of the land and contains gravel, sand, silt, and clay deposits, and it is rich in secondary gypsum, and is classified as gypsum facilitation. Holocene sediments is consists of fine sediments group from different sources, as like Flood plain deposits, Valley and depression fill deposits (Al-Janabi, 2008), and Aeolian deposits (Jassim & Goff, 2006).

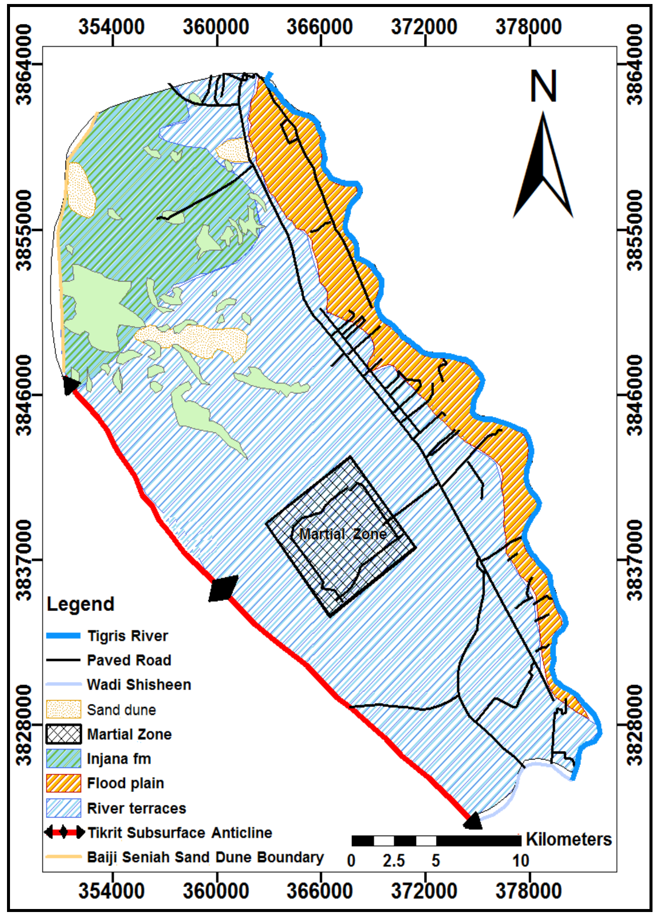

Figure 2. Geological map of the study area

3. Materials and Methods

3.1 Hydro-Geophysical Data

The hydro-geoelectric characteristics produced from 40 well-distributed VES stations to cover the majority of the research region are used to determine the best groundwater well placements, as illustrated in Figure 3. The bulk resistivity and thickness of the aquifer are the main geoelectrical characteristics acquired from the VES analysis (Figure 4). The aquifer's hydro-geoelectric properties include depth, resistivity, thickness, Longitudinal conductance, and Transmissivity. These characteristics are the most influential since they reflect the amount and quality of possible groundwater that will be collected from this location. The data set utilized in this investigation is shown in Table 1. Longitudinal conductance (S) can defined as the sum of all the thickness/resistivity ratios of n − 1 layers which overlie a semi-infinite substratum of resistivity. It can be represented by the following equation:

$$S = \frac{h}{\rho} \quad \text{.......} \quad (1)$$

Where S is the longitudinal conductance, measured in (Ω-1), h is the thickness of the layer in meters, and ρ is the resistivity of the layer in (Ω.m) (Kirsch & Yaramanci, 2009).

Transmissivity is defined as the ability of the aquifer to pass water through a vertical section of the aquifer with an area of one square unit area at the prevailing temperature (Walton, 1970). The transmissivity coefficient depends on the value of the hydraulic conductivity of the sediments that make up the aquifer and on the thickness of the layer saturated with groundwater, as in the following equation:

$$\mathbf{T = K\,.\,b} \qquad (2)$$

Where T is the transmissivity in (m^2/day), K is the hydraulic conductivity in (m/day), and b is thickness of the layer saturated with groundwater in in meters.

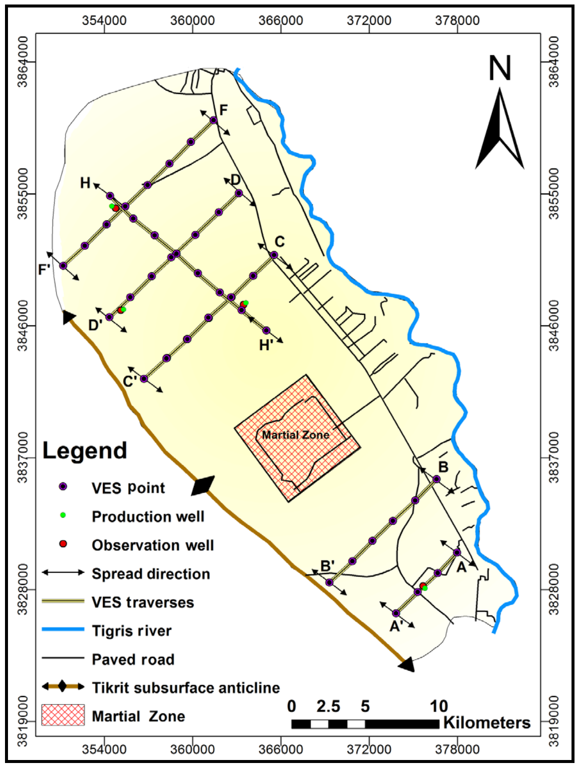

Figure 3. A map depicting the VES locations and the geoelectric traverse direction

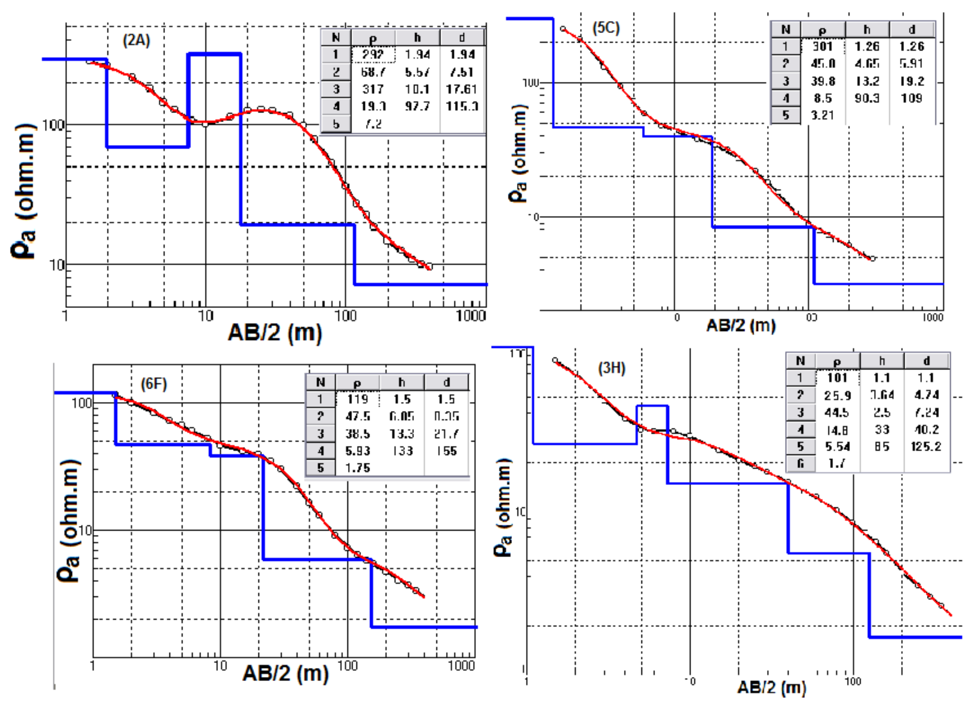

Figure 4. VES quantitative interpretations from VES data

Table 1. The aquifer's hydrogeophysical data.

#	VES Name	Long. (UTM)	Lat. (UTM)	Depth (m)	Aquifer resistivity (Ω m)	Aquifer thickness (m)	Longitudinal conductance (Ω^{-1})	Transmissivity (m^2/day)
1	1A	378000	3830463	24.5	33.8	93.61	2.770	999.022
2	2A	376692	3829070	17.61	19.3	97.7	5.062	773.037
3	3A	375368	3827790	13.74	25.9	93.7	3.618	883.209
4	4A	373858	3826330	17.44	52.9	89.8	1.698	1176.455
5	1B	376644	3835478	32.71	65.2	91.8	1.408	1277.348
6	2B	375159	3834038	28.91	30.2	91.7	3.036	940.851
7	3B	373696	3832620	27.76	14.7	95.4	6.490	643.766
8	4B	372256	3831274	32.04	14.7	100	6.803	664.327
9	5B	370909	3829880	35.62	36.7	91.4	2.490	1024.530
10	6B	369330	3828440	30.23	41.1	94.2	2.292	1087.143
11	1C	365568	3850779	28	9.14	79.5	8.698	356.693
12	2C	364151	3849363	30	12.6	75.55	5.996	474.609
13	3C	362643	3847900	27	20.5	76.66	3.740	693.487
14	4C	361110	3846507	26	11.5	79.44	6.908	456.646
15	5C	359670	3845020	19	8.5	90.3	10.635	381.096
16	6C	358277	3843766	21	10.7	84.57	7.904	452.487
17	7C	356744	3842327	26	9.14	79.53	8.701	356.857
18	1D	363153	3855006	35	6.73	68.63	10.198	158.860
19	2D	361807	3853705	33	13.8	79.75	5.779	537.950
20	3D	360227	3852173	27	8.58	87	10.140	368.448
21	4D	358602	3850640	24	10.2	80	7.843	407.338
22	5D	357255	3849340	24	7.55	81.54	10.800	284.314
23	6D	355815	3847900	23	10.7	61	5.701	309.845
24	7D	354376	3846553	24	8.37	70	8.363	262.705
25	1F	361435	3859975	23.4	8.81	79.23	8.993	339.152
26	2F	359902	3858489	30.4	6.12	117	19.118	350.283
27	3F	358463	3857003	19.4	9.58	124.23	12.968	572.113
28	4F	356930	3855563	26	6.67	147	22.039	487.516
29	5F	355467	3854123	22	5.05	137.4	27.208	336.551
30	6F	354143	3852869	22	5.93	133	22.369	391.325
31	7F	352704	3851429	30.6	5.05	96.3	19.069	181.368
32	8F	351218	3850036	29	14	99	7.071	638.637
33	1H	354422	3854820	22	14.1	129	9.149	757.311
34	2H	356001	3853287	24.3	6.27	107	17.065	321.846
35	3H	357441	3852126	40.2	5.54	85	15.343	167.305
36	4H	358927	3850872	35.1	10.46	50.8	4.857	220.051
37	5H	360413	3849525	24	9.47	59.3	6.262	244.188
38	6H	361899	3848225	27	10.2	68.53	6.719	339.771
39	7H	363339	3847017	25	7.6	62.8	8.263	173.180
40	8H	365011	3845624	39	7.23	72.6	10.041	214.702

3.2 Criteria Layers Standardization

The initial stage in merging criterion layers is to unify the layers into a single scale. The fuzzy liner membership technique was employed to standardize all classes in this investigation. This stage transforms the layer into such a scale with a value ranging from 0 to 1, with 1 denoting a suitable zone and 0 denoting an unsuitable region. According to Benz et al. (2004), the fuzzy linear equation is as follows:

$$\mu(X) = \begin{cases} 0 & \text{if } x < min \\ 1 & \text{if } x > max \\ \frac{(x - min)}{(max - min)} & \text{otherwise} \end{cases} \quad \text{................ (3)}$$

3.3 Fuzzy Overlay

This stage uses overlay processing to aggregate all layers of the standards to predict the best site for drilling groundwater wells.

GIS methodologies were used to generate the suitability study, which was based on numerous criterion layers. All criterion layers were combined in ArcGIS 10.8 to create a map with a fuzzy overlay that depicted the optimal location for drilling new groundwater wells. A flowchart of the appropriateness model is shown in Figure 5. In a multi-criteria superposition analysis, the fuzzy overlay tool may be used to examine the chance of a phenomena belonging to several categories happening. The possible approaches for integrating data based on group theory analysis are listed in the overlay type. Five approaches are available in ArcGIS (fuzzy gamma, fuzzy product, fuzzy and, fuzzy or, and fuzzy sum). Fuzzy gamma is employed in this research as the output of fuzzy sum and fuzzy product that are both increased to the intensity of gamma operator. According to Baidya et al. (2014), the generic function is as follows:

$$\mu\,\text{combination} = \begin{cases} \prod_{i=1}^{n} \mu_i & \text{(For Fuzzy algebraic product)} \\ \prod_{i=1}^{n} (\mu_i - 1) & \text{(For Fuzzy algebraic sum)} \\ (\text{Fuzzy algebraic Sum})^{\lambda} \times (\text{Fuzzy algebraic product})^{(1-\lambda)} & \text{(For Fuzzy gamma)} \end{cases} \quad ..(4)$$

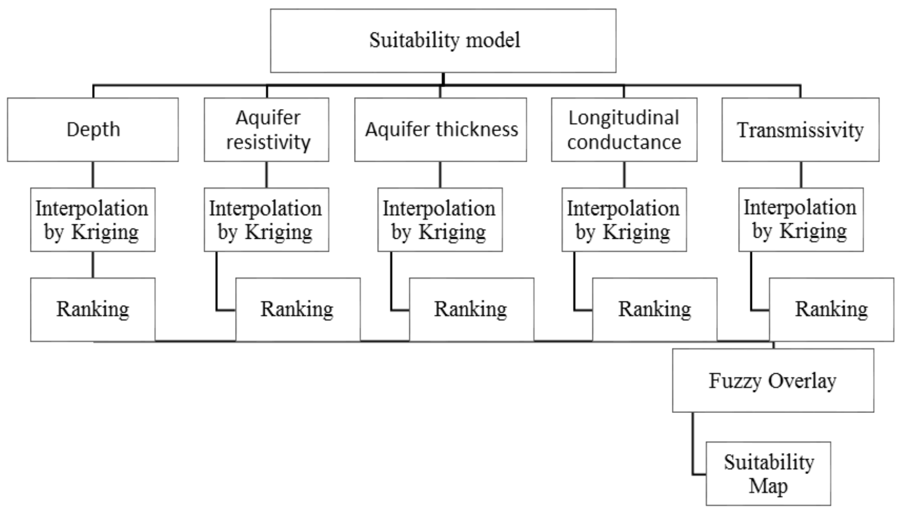

Figure 5. Flowchart of the Suitability model

4. Results and Discussion

4.1 Interpolation of the Criteria Layers

The criterion layers were used to evaluate the GIS and hydro-geoelectric factor combination's results. Using the GIS method of aggregating intersections (i.e. the values of depth, resistivity, thickness, longitudinal conductance, transmissivity). As indicated in Figure 5, Kriging interpolation method was applied to interpolate layers of hydro-geoelectric parameters (Figure 6). Depth values range from 23 to 32 m, resistivity values range between 5-70 Ω m, the thickness ranges from 52 to 160 m, and longitudinal conduction values ranging between 3 to 20 Ω^{-1}, while conductivity values vary from 160 to 1500 m^2/day.

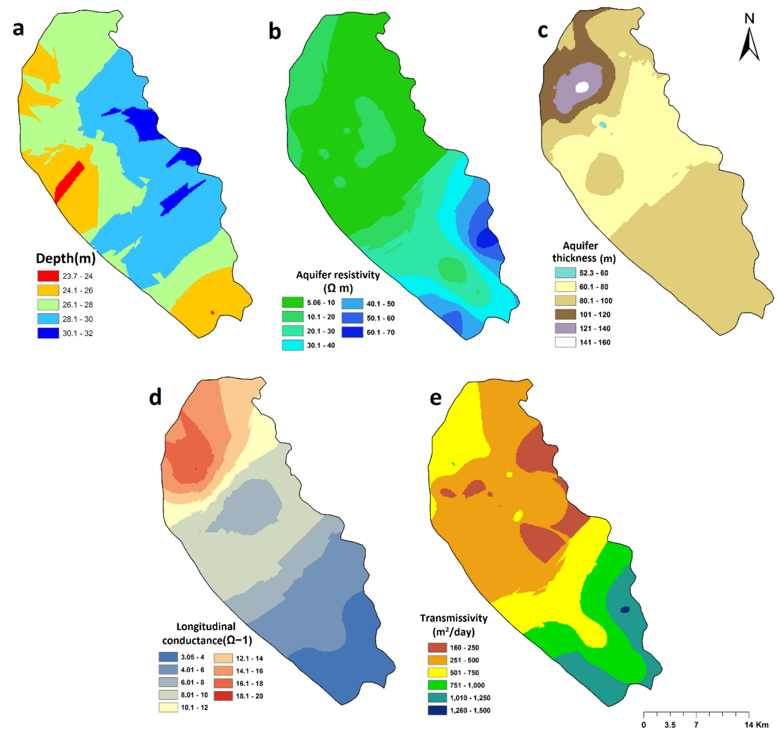

Figure 6. Interpolation of the criteria layers (a-Depth, b-Resistivity, c-Thickness, d-Longitudinal conductance, e-Transmissivity) using Kriging method.

4.2 Site Suitability Model

The initial step in developing a site relevance model was to harmonize all levels of the criterion. The linear fuzzy membership (FLM) method is used for this stage. The fuzzy linear membership of the five criterion layers employed in this investigation is shown in Figure 7. Finally, using a fuzzy gamma overlay, these factors are integrated to create a suitability map, as illustrated in Figure 8. The research region was divided into four groups by the findings map: excluded, low suitability, moderate suitability, and high suitability. Table 2 displays the total area as well as the proportion of each category that has been determined and explained. The research was necessary because the northwest section of the study region is considered to be ideal for digging additional groundwater wells that meet the specified specifications.

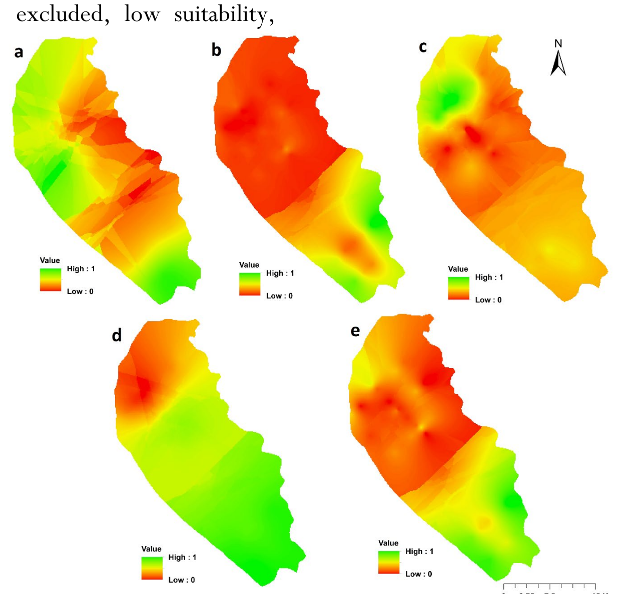

Figure 7. Liner membership of the criteria layers (a-Depth, b-Resistivity, c-Thickness, d-Longitudinal conductance, e-Transmissivity) using fuzzy method.

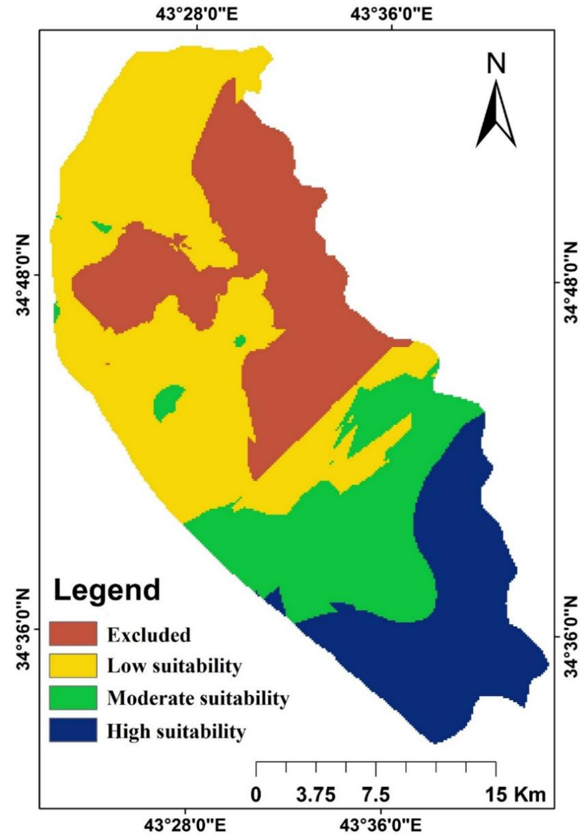

Figure 8. Site suitability map using fuzzy gamma algorithm

Table 2. The total area and percentage for each suitability category

Category	Area (km2)	Percentage
Excluded	172.5365	24.59677
Low suitability	269.7671	38.45794
Moderate suitability	131.891	18.80235
High suitability	127.2654	18.14293
Total	701.46	100

5. Conclusions

This study demonstrated the capabilities of the multi-criteria evaluation technique via GIS in analyzing the suitability for selecting suitable sites for drilling new groundwater wells in the southeastern and northwestern part of the study area. Groundwater appropriateness study immediately aids the community in alleviating the water situation. Based on hydrogeoelectric data, a multi-criteria evaluation approach using GIS software and fuzzy logic is utilized to select the best places for digging new groundwater wells. Excluded, low, moderate, and high appropriateness were the four categories used to categorize the research region. According to the study, the southern and southwestern parts of the study region should be ideal for digging additional groundwater wells that meet the recommended specifications. The many governmental agencies engaged in the management of water resources in Salah al-Din Governorate should implement this strategy. Furthermore, further research in this area is needed to establish a scientific foundation for an effective water management system in Iraq.

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