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Contribution of the fuzzy algebraic model to the sustainable management of groundwater resources in the Adamawa watershed

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Highlights

- The groundwater potential map of Adamawa is classified into four main zones.
- Zone with high potential covers more than 50 % of the total study area.
- The groundwater potential map is compliant with the spatial distribution of the contributing layers.

- Results are bound to be very helpful to policymakers, stakeholders and municipal rulers.

Abstract

Study region

The study area is located between longitudes 11–16° E and latitudes 6–8° N in the heart of Central Africa. The Adamawa Plateau is a junction watershed for Cameroon and its neighboring countries. It plays an important hydrogeological role at an international level as it hosts transboundary aquifers extending from the Federal Republic of Nigeria to the Central African Republic on a total area of 6700 km^2. It is so-nicknamed the "water tower" of Central Africa.

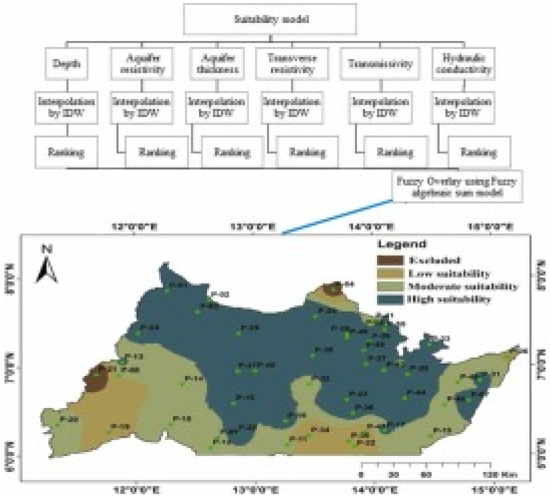
Study focus

Because of the failure of the water supply system in the region, households, the local population, and regional authorities are exploiting groundwater resources. Unfortunately, an important number of wells and boreholes are reported to be unproductive because of the nonexistence of preliminary hydrogeophysical investigation. Such investigations are expensive, time-consuming, and require cut-edge technology and expertise. The present study focuses on the assessment of groundwater potential (GWP) throughout the Adamawa region to identify localities with important water yields

New hydrological insights for the region

Contrarily to the previous investigations conducted in the region, this study uses the fuzzy algebraic model to combine six hydro-parameters contributing to groundwater occurrence in a GIS environment to assess GWP. As a result, the region is classified into four suitability levels: high, moderate, low, and null covering 54.76 %, 31.66 %, 12.24 %, and 1.32 % of the total study area respectively

Graphical Abstract



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Keywords

Central Africa; GIS environment; Groundwater potential; Hydro-parameters

1. Introduction

Water is a matchless natural resource needed for human comfort and ecosystem balance. Everybody uses it every day for drinking, bathing, or cooking. This vital and precious liquid governs plant, animal, and human life, economic growth, ecosystem equilibrium, sustainability, and the environment. Deplorably, water is a more and more scarce commodity for a large proportion of people, especially in developing countries (Gonzales et al., 2019, Xu et al., 2019). The region of Central Africa (namely Cameroon, Congo, Nigeria, and the Central African Republic), located just above the equator with one of the most important pluviometry in the world, is curiously experiencing water stress. Only the main cities are covered by the National Public Water Authority network and expect a three-time per week supply with doubtful quality water. Elsewhere, the water distribution system is outdated or inexistent. As a result, there is a blooming attempt at groundwater exploitation throughout the region with a low rate of success because of the absence of prior hydrogeophysical investigation, or surveys conducted in areas with low groundwater potential (GWP).

The Adamawa region is chosen herein as a case study for two essential reasons. It previously gave room to a set of hydrogeophysical and hydrogeological investigations where hydro-parameters were interpreted separately. In addition, this region plays the function of the watershed in an international hydrogeological system that drains Cameroon, Congo, the Federal Republic of Nigeria, and the Central African Republic, and hosts transboundary aquifers. The bedrock is faulted, presuming an important groundwater potential in the region. Aretouyap et al., 2015, Aretouyap et al., 2017, Aretouyap et al., 2018 and Bisso et al. (2019) used different geoelectrical techniques to explore this groundwater potential, but in their approaches, each contributing hydrogeophysical parameter was interpreted separately.

The global groundwater quality of the region was assessed from the thirty-four existing boreholes and said to be good with a groundwater quality index equal to 82.11 (Aretouyap et al., 2014a). This value makes the local groundwater of acceptable quality, but that investigation didn't address the aquifer productivity. The potential impact of climate variability on regional water resources was investigated and depicted that rivers, springs, and wells are being dried up due to climate change (Aretouyap et al., 2014b). Geoelectrical parameters such as hydraulic conductivity and transmissivity were already determined from the available pumping tests, where an empirical relationship between aquifer thickness, resistivity, and experimental hydraulic conductivity allowed to compute the hydraulic conductivity values for the remaining thirty-six vertical electrical sounding (VES) points and interpolate them for the whole study area (Aretouyap et al., 2015). The porosity values were assessed to range between 0.19 and 0.43 (Aretouyap et al., 2017). By proposing the VES as an alternative technique to the pumping test, Aretouyap et al. (2018) obtained hydraulic conductivity values ranging from 0.4 to 6.0 m/day. More importantly, a meticulous analysis of transmissivity values disclosed the presence of two aquifer tendencies in the region. This hydrogeophysical investigation carried out by Aretouyap et al. (2018) was deepened by establishing two more relationships between aquifer parameters: the first one between the transverse resistance and the modified transverse resistance, and the second one between the transmissivity and the modified transverse resistance. This enabled computation and interpolation of the transmissivity values to range from 4 to 17.4 m^2/day for the whole region (Aretouyap et al., 2019a). Although a complementary approach, namely the inverse slope method (ISM), was utilized to verify and confirm the results obtained previously using the curve matching method (CMM) when interpreting VES data (Aretouyap et al., 2020), there was a shortcoming in the whole methodological conception. Indeed, preceding investigations considered the study area as a single uniform geological unit. Consequently, to fix this issue, new sequential relationships based on the geological settings were established between electrical data and hydrogeological parameters (Aretouyap et al., 2021). As a result, transverse resistance, thickness, resistivity, transmissivity, and hydraulic conductivity are modified and updated, particularly in their mean values to be as follows: from 8.59 to 777.6 Ω^2.m, from 31 to 4.9 m, from 225 to 30.8 Ω.m, from 31.15 to 31 m^2/day and from 2.74 to 0.3 m/day respectively.

However, all those studies and other similar ones that are not abovementioned (Aretouyap et al., 2019b, Bisso et al., 2019) attempted to assess the aquifer productivity of the Adamawa region by analyzing the conducive factors individually. The present work is therefore an experimental new approach to elaborating the groundwater potential (GWP) by combining key contributing parameters into a single one. This may help to have a global and easy view of GWP spatial distribution in the region. The fuzzy algebraic model has been proven effective for such hydrological investigations. Pathak and Bhandary (2020) used a multi-layer fuzzy inference system in a GIS environment to assess groundwater vulnerability. Shao et al. (2020) identified GWP zones in semi-arid Shanxi Province (China) using the fuzzy algebraic model. Abdulrazzaq et al. (2020) identified and demarcated GWP zones in Imo (Nigeria) by combining geophysical data and a fuzzy gamma operator model. Mallik et al. (2021) analyzed groundwater suitability for drinking using GIS-based fuzzy logic.

The Adamawa Plateau has been frequently investigated for groundwater exploration and exploitation. Various parameters influencing groundwater occurrence and storage have been previously assessed separately using different approaches (Aretouyap et al., 2014a, Aretouyap et al., 2014b, Aretouyap et al., 2015, Aretouyap et al., 2017, Aretouyap et al., 2018, Aretouyap et al., 2019a, Aretouyap et al., 2019b, Bisso et al., 2019). New insights in the methodological approach required an update of previous findings (Aretouyap et al., 2021). However, the interpretation of those hydro-parameters to assess the groundwater potential of the region remains separately and individually. This article aimed at producing a global overview of the GWP spatial distribution in the region by combining the six contributing parameters. Those parameters are aquifer depth, resistivity, thickness, transverse resistivity, transmissivity, and hydraulic conductivity.

The present investigation mainly aims at using the fuzzy algebraic model in a GIS environment to demarcate GWP zones of the Adamawa region for sustainable management of (ground)water resources in this region. For this, six parameters (depth, resistivity, thickness, transverse resistance, transmissivity, and hydraulic conductivity) will be used in this modeling investigation. It stands as the first and unique scientific contribution to the sustainable management of groundwater resources in this region. Hence, the outcome will support planners, stakeholders, decision-makers, and municipal authorities in their "Municipal Strategy Document (MSD)" by providing them with thematic maps useful to improve borehole productivity by identifying the priority areas where to concentrate the geological and hydrogeological investigation during groundwater exploration. The novelty in this paper is a matter of producing a sound GWP map that gathers and integrates all major contributing parameters (depth, resistivity, thickness, transverse resistance, transmissivity, and hydraulic conductivity) with respect to their specific weights in the final output.

2. Material and methods

2.1. Study area

The Adamawa region is located between longitudes 11–16° E and latitudes 6–8° N in the heart of Central Africa (Fig. 1), and plays an important hydrogeological role at an international level. With its 150–300 km wide, the Adamawa Plateau stands as the major watershed for Cameroon and its neighboring countries, namely Congo, the Federal Republic of Nigeria, and the Central African Republic (Aretouyap et al., 2021). It extends from the Federal Republic of Nigeria to the Central African Republic with a total area of 6700 km^2. Volcanic highlands constitute the main morphological feature of the region, with an average altitude of 1100 m. This is the result of tectonic subsidence and uplift (Tchameni et al., 2001). The terrain is very rugged, characterized by a huge cliff in the north and an uneven escapement southward. The center of the region is characterized by swampy valleys and a gentle topography scattered with volcanic cones and mountains. One can observe large massifs resulting from tectonic and erosional events in the eastern part, and high hills and mountains westward. A set of basins and plains are also observed in the study region with a plateau sloping gradually from north to south (Toteu et al., 2000).

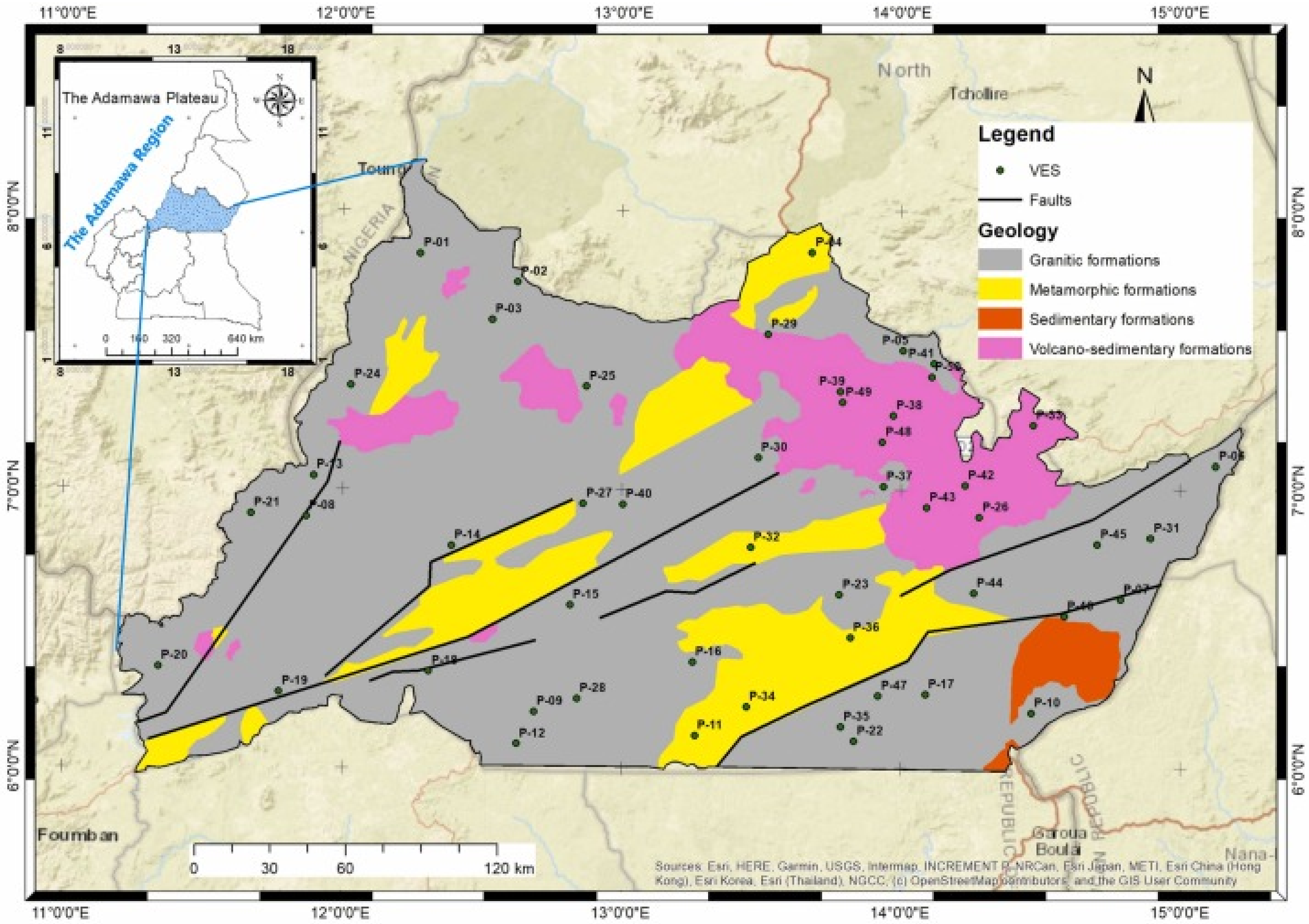

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Fig. 1. The Geological map of the Adamawa region.

The Pan-African granite-gneiss constitutes the local bedrock, with migmatites, Ordovician granites, and gneisses as the major rocks. This is the result of three successive geologic events: a long period of continental erosion from Precambrian to Cretaceous, an onset of volcanism from Cretaceous to Quaternary, and recurrent basement tectonics (Aretouyap et al., 2021). Basalts, metadiorites, trachytes, and trachyphonolites are the main geological units of the region (Toteu et al., 2000, Toteu et al., 2001). There are two main directions of faults: the "Volcanic line of Cameroon" oriented N 30° E, and the "Adamawa shear zone" oriented N 70° E (Njonfang et al., 2008).

At the hydrogeological level, the upper weathered and the fractured portion of the bedrock is the most interesting. A set of investigations (e.g., Chilton and Foster, 1995; Dewandel et al., 2006; Bianchi et al., 2020) established the weathered profile of crystalline basement rocks in tropical Africa. In our study area, this profile is sorted, from the top to the bottom, as follows: topsoil of a few meters made up of laterite and ferritic soils; two components (upper and lower) of saprolite, commonly called saprocks, made up of clay minerals and fractured layer (Bianchi, 2020). Topsoil and saprocks are referred to as regolith. The physical and chemical weathering of the crystalline bedrock controls the lithomineralogical structure and composition of each layer (Fookes, 1997). In general, the topsoil has high hydraulic conductivity. On contrary, an important fraction of the upper portion of saprocks has low values of hydraulic conductivity due to clay minerals, but with maximum values of porosity (Chilton and Foster, 1995). K values of the upper saprolite are so low that this layer cannot sustain groundwater abstractions but does provide an important storage capacity because of its consistent porosity (Chilton n Foster, 1995). The most interesting aquifer generally targeted is the fractured and weathered portion of crystalline bedrock made up of saprocks (Aretouyap et al., 2018, Aretouyap et al., 2019a, Aretouyap et al., 2021). Fracturing and degree of weathering in this layer decreases with depth causing reduction of *K* values until they become representative of the matrix of fresh rock (Bianchi et al., 2020).

2.2. VES technology

Fifty VES points were carried out in the study area. The Schlumberger array was adapted and applied to measure the apparent resistivity data using VES, with a half maximum current electrode spacing (*AB*/2) of 1000 m and potential electrode spacing (*MN*/2) of 25 m.

The Resistance (R_a) was first recorded in the field, and converted later to apparent resistivity (ρ_a) for the Schlumberger configuration using Eq. 1:

$$\rho_a = \left[\frac{(AB/2)^2 - (MN/2)^2}{MN}\right] \times R_a \quad (1)$$

This equation can be written as: $\rho_a = GR_a$ (2)

where G is the geometrical factor (Eq. 3).

$$G = \left[\frac{(AB/2)^2 - (MN/2)^2}{MN} \right] \tag{3}$$

The field apparent resistivity curves were obtained by increasing the electrode spacing *AB/2* around a fixed point. Those vertical electrical sounding curves were thereafter plotted in the next stage for each of the survey locations, and smoothened to remove noisy signatures (Chakravarthi et al., 2007, Ebong et al., 2014). We used the curve matching technique with master curves to interpret the field resistivity curves and to determine an initial model including resistivities and thicknesses of the corresponding layers (initial approximate model) (Orellana and Mooney, 1966). The inversion WINRESIST software program is thereafter used to interpret the parameters of the approximate model to get the final optimum model, in which goodness of fit between the field resistivity curve and the final theoretical regenerated curve was realized (Zohdy, 1989, Zohdy and Bisdorf, 1989). This inversion procedure allows estimating the values of the true resistivity, depth, and thickness of the subsurface after several iterations for each VES point. Fig. 2 shows examples of interpreting VES point P08 and comparison with the lithological description of those points.

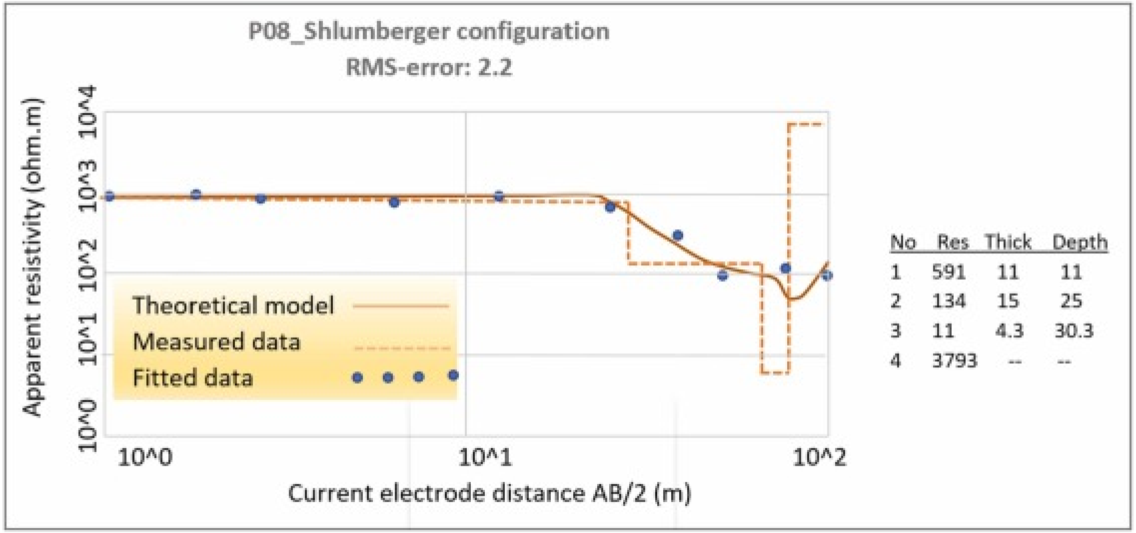

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Fig. 2. An example of inverted electrical resistivity model VES points (P08).

The obtained real thicknesses and resistivities of the corresponding layers of the analyzed VES points in the study area are used to establish the hydraulic parameters of the studied aquifer as shown in Table 1. Those interpretative parameters are used thereafter for interpolating the criteria layers of depth, resistivity, thickness, transverse resistivity, transmissivity, and hydraulic conductivity by using Inverse Distance Weighted (IDW) method.

Table 1. The aquifer's hydrogeophysical data. Primary hydro-parameters namely resistivity (ρ_e), thickness (h), transverse resistance (TR), hydraulic conductivity (K), transmissivity (T), and depth for the fifty VES points are presented with their geographic coordinates X and Y in decimal degrees, WGS-84 datum.

VES locations	X (°)	Y (°)	ρ_e (Ω.m)	h (m)	TR (Ω.m^2)	K (m/day)	T (m^2/day)	Depth (m)
P-01	12.2693333	7.85916667	81.1	2.5	202.75	0.295352	32.2546	21
P-02	12.6206667	7.7535	36.21	4.7	170.187	0.151404	32.0462	22
P-03	12.5263333	7.62016667	47.2	8.4	396.48	0.18398	33.49447	14.5
P-04	13.6745	7.85916667	17.57	4.8	84.336	0.951951	8.367702	43
P-05	14.1171667	7.45933333	60.8	2	121.6	0.136184	31.73524	37.4
P-06	15.1253333	7.087	15.7	6	94.2	0.09952	31.55988	36
P-07	14.7921667	6.60816667	13.7	10	137	0.103768	31.8338	14
P-08	11.86	6.908	13	4.3	55.9	0.101414	31.31476	26
P-09	12.6871667	6.2055	20	1.9	38	0.101166	31.2002	21.8
P-10	14.4713333	6.2055	11.41	1.9	21.679	0.09818	31.09575	20
P-11	13.269	6.12066667	41	4	164	0.623179	13.3945	20

VES locations	X (°)	Y (°)	ρ_e (Ω.m)	h (m)	TR (Ω.m^2)	K (m/day)	T (m^2/day)	Depth (m)
P-12	12.6235	6.09033333	22	3.7	81.4	0.117193	31.47796	22
P-13	11.8903333	7.0565	17.7	4.8	84.96	0.129304	31.50074	16.6
P-14	12.3901667	6.80816667	8	8	64	0.097597	31.3666	29
P-15	12.8205	6.59016667	11	1.7	18.7	0.095796	31.07668	6
P-16	13.2565	6.38733333	46	4.6	211.6	0.214993	32.31124	18
P-17	14.0866667	6.27483333	44.6	3.1	138.26	0.151528	31.84186	24.5
P-18	12.2903333	6.35683333	40.8	4.3	175.44	0.149219	32.07982	40
P-19	11.7723333	6.26933333	26	3.4	88.4	0.140465	31.52276	40
P-20	11.3391667	6.354	18.8	6.1	114.68	0.106148	31.69095	26
P-21	11.6695	6.9205	22.15	1.9	42.085	0.107693	31.22634	79
P-22	13.8353333	6.10266667	34	2.3	78.2	0.149856	31.45748	39.7
P-23	13.7745	6.62633333	48	16.2	777.6	0.123616	35.93364	30
P-24	12.0236667	7.3855	11.29	1.7	19.193	0.109961	31.07984	10
P-25	12.869	7.3745	10	2.2	22	0.097231	31.0978	13.5
P-26	14.2866667	6.90516667	11.08	3.8	42.104	1.191733	33.98835	22
P-27	12.8595	6.95083333	34.1	2.3	78.43	0.158811	31.45895	14
P-28	12.8386667	6.254	39.26	7	274.82	0.125276	32.71585	23
P-29	13.5203333	7.55916667	13	6	78	1.271042	34.3868	17
P-30	13.4898333	7.12033333	82.5	3.8	313.5	0.222574	32.9634	39
P-31	14.8893333	6.83566667	57	4	228	0.14378	32.4162	41

VES locations	X (°)	Y (°)	ρ_e (Ω.m)	h (m)	TR (Ω.m^2)	K (m/day)	T (m^2/day)	Depth (m)
P-32	13.4593333	6.80233333	25	3.3	82.5	0.112439	31.485	27
P-33	14.4713333	7.2355	48	4.2	201.6	0.151013	32.24724	37.45
P-34	13.4508333	6.2235	10	11	110	0.7949	9.9871	48
P-35	13.7868333	6.15683333	38.7	1.4	54.18	0.172516	31.30375	43.45
P-36	13.823	6.472	53	6.2	328.6	0.561178	23.78076	29.75
P-37	13.9381667	7.0175	42.2	2.8	118.16	0.141243	31.71322	24
P-38	13.9715	7.27166667	4	2.1	8.4	1.397987	33.61424	32
P-39	13.784	7.3565	28	11.8	330.4	0.363315	37.18844	38
P-40	13.0023333	6.95383333	40	6	240	0.704915	36.185	22.9
P-41	14.0076667	7.50216667	20	3.8	76	0.117992	31.4434	28.25
P-42	14.2256667	7.0175	10.4	3.3	34.32	0.10303	31.17665	16
P-43	14.0895	6.95083333	21	5.2	109.2	1.134088	34.73312	28
P-44	14.259	6.63583333	61	9.3	567.3	0.170854	34.58772	30
P-45	14.7045	6.80816667	3	8	24	0.088019	31.1106	25
P-46	14.5893333	6.55966667	20	7	140	0.138088	31.853	37
P-47	13.923	6.25683333	21.61	1.5	32.415	0.125857	31.16446	42.9
P-48	13.9228333	7.17466667	64	3	192	0.52027	35.6522	32.5
P-49	13.784	7.32316667	27.04	3.2	86.528	0.121267	31.51078	21.45
P-50	14.102	7.405	47	8.5	399.5	0.2433	37.95545	17

2.3. Fuzzy algebraic sum model

Fuzzy set theory and fuzzy logic, which were first developed by Zadeh (1965), have been widely applied to the modeling of ambiguity and uncertainty in decision-making. Fuzzy logic's fundamental idea is relatively straightforward: statements indicate each input's degree of truth or falseness in addition to being either "true" or "false." The fundamental element of the idea is that fuzzy sets are defined by their membership functions.

2.3.1. Factor standardization

By applying a fuzzy membership function, the crisp input boundaries were transformed into a degree of membership, with a value between 0 representing no membership zone and 1 denoting the entire membership zone (Zhang et al., 2015). This process is known as Fuzzification. In other meaning, Fuzzification of the input variables, application of the fuzzy operator in the antecedent (degree of fulfillment), the implication from the antecedent to the consequent (inference), aggregation of the consequents across the rules, and defuzzification are the typical steps in a fuzzy rule-based model. The goal of the fuzzy membership function is to combine the criterion layers into a single scale. All classes in this inquiry were standardized using the fuzzy liner membership technique. The fuzzy membership method works well when you want the fuzzy membership to be within a certain range and any negative or positive divergence from that range decreases the desirability. The fuzzy linear Eq. (4) is as follows, according to Benz et al. (2004).

$$\mu(X) = \left\{ \begin{array}{c} 0 \text{if } x < \min \\ 1 \text{if } x > \max \\ \frac{(x - \min)}{(\max - \min)} \text{otherwise} \end{array} \right\} \quad (4)$$

2.3.2. Fuzzy overlay

We must overlay the criteria after scaling each criterion and utilizing fuzzy membership methods to translate values between the 0 and 1 interval. Criteria can be overlaid using fuzzy operators. The choice of an operator depends on how the variables interact or how the operator's final impact (incremental or decreasing) is on the criteria. All of the fuzzified raster inputs were combined using the fuzzy overlay technique (Lee, 2007). The literature (Raines et al., 2010, Baidya et al., 2014, Lewis et al., 2014, Mallik et al., 2021, Raad et al., 2022) lists five different fuzzy combination operators (fuzzy OR, fuzzy AND, fuzzy Product, fuzzy Sum, and fuzzy Gamma).

2.3.2.1. Fuzzy AND

This operator completely disregards the high weights of the pixels and only takes into account the minimal degree of membership of the pixels to create the final map, producing an extremely conservative outcome.

2.3.2.2. Fuzzy OR

The degree of membership in the final map is entered using this operator as the maximum pixel membership value across all combined maps. As a result of ignoring low pixel weights, an extremely optimistic output is produced.

2.3.2.3. Fuzzy product

The degree of membership of a pixel in various maps is multiplied by the fuzzy product. The final membership is reduced by this operator. Each pixel typically has very little weight assigned to it, and if there are several input maps, this weight tends to be zero.

2.3.2.4. Fuzzy sum

The ultimate membership value of the pixels in the final map will tend to be 1 if there are numerous input maps. This operator is appropriate for modeling and is employed when parameters reinforce one another.

2.3.2.5. Fuzzy gamma operator

The product and sum operators are combined to create the gamma fuzzy operator. By choosing the appropriate gamma value, growing and decreasing criteria can be combined concurrently, and the product and sum operators' increasing and decreasing inclinations will be combined.

According to Baidya et al. (2014) and Raad et al. (2022), the generic function (Eq. 5) is as follows:

$$\mu_{combinaison} = \left\{ \begin{array}{cc} \prod_{i=1}^{n} \mu_i & (for \quad Fuzzy \quad algebraic \quad product) \\ \prod_{i}^{n} = (\mu_i - 1) & (for \quad Fuzzy \quad algebraic \quad product) \\ (Fuzzy \quad algebraic \quad sum)^{\lambda} \times (Fuzzy \quad algebraic \quad product)^{(1-\lambda)} & (For \quad Fuzzy \quad gamma) \end{array} \right\} \tag{5}$$

In this equation, μ_i is the fuzzy membership function for the i^{th} map. Maps i = 1, 2,., n are to be combined. λ is a constant chosen in the range [0,1]. A judicious choice of λ may control eventual abrupt variation of output values derived from sum and product operators.

The criteria have been overlaid in this study using the fuzzy Sum operator because we believe that the parameters reinforce one another. Admittedly, each parameter has a significant contribution to groundwater occurrence or yield. But their combination gives a clear overview of the groundwater potential in the region and leads to an important decision-making tool which is the GWP map. Hence, the fuzzy Sum stands as the most appropriate operator. In addition, this operator does not bias the final result in the case of repetition or redundancy of a parameter. The suitability analysis was created using GIS technologies and was based on multiple criterion layers. In ArcGIS 10.8, all criterion layers were combined to provide a map with a fuzzy overlay showing the ideal spot for drilling new groundwater wells. Fig. 3 depicts the appropriateness model's flowchart. The fuzzy overlay tool can be used in a multi-criteria superposition analysis to analyze the likelihood that a phenomenon falling under many categories will occur.

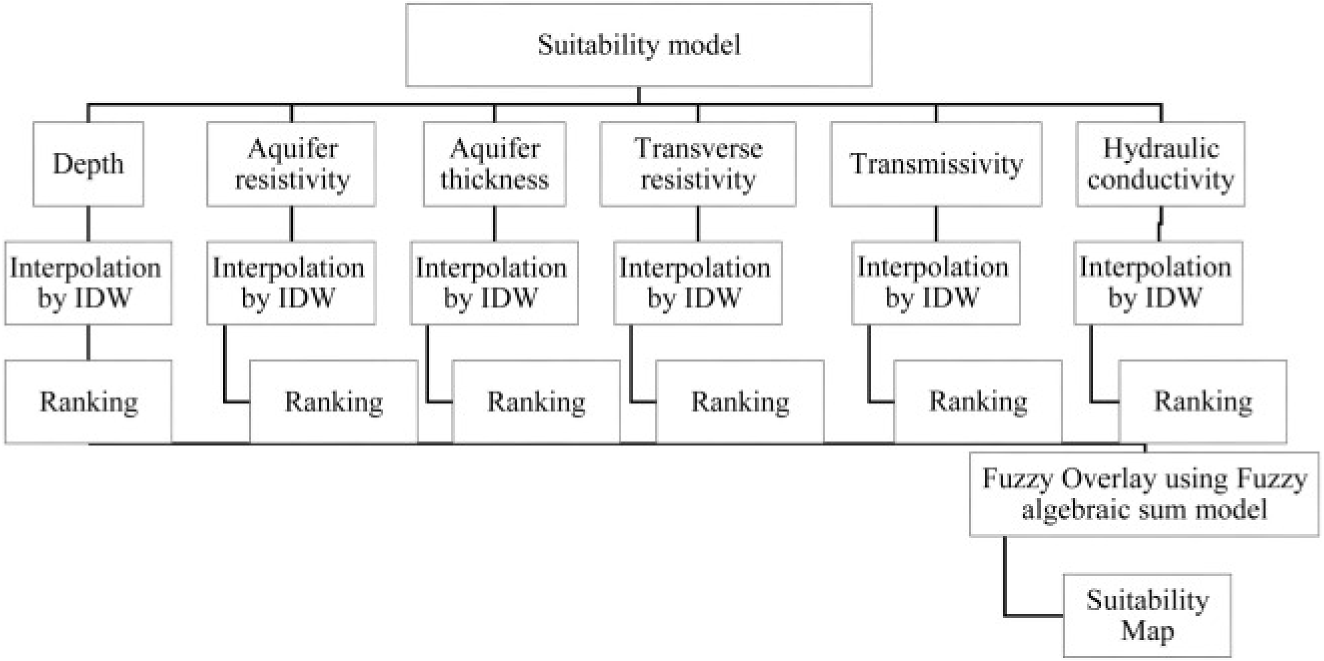

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Fig. 3. Flowchart of the Suitability model.

3. Results and discussion

Key findings are presented and discussed in this section. Hydrogeophysical data used in this analysis are presented in Table 1.

3.1. 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, transverse resistivity, transmissivity, and hydraulic conductivity). As indicated in Fig. 3, the IDW interpolation method was applied to interpolate layers of hydro-geoelectric parameters (Fig. 4). Depth values range from 6 to 80 m, resistivity values range between 3 and 90 Ω.m, the thickness ranges from 1.4 to 18 m, transverse resistivity values ranging between 8.5 and 777.6 $\Omega.m^2$, transmissivity values range from 8.4 to 40 m^2/day, and hydraulic conductivity values vary from 0.0002 to 1.5 m/day.

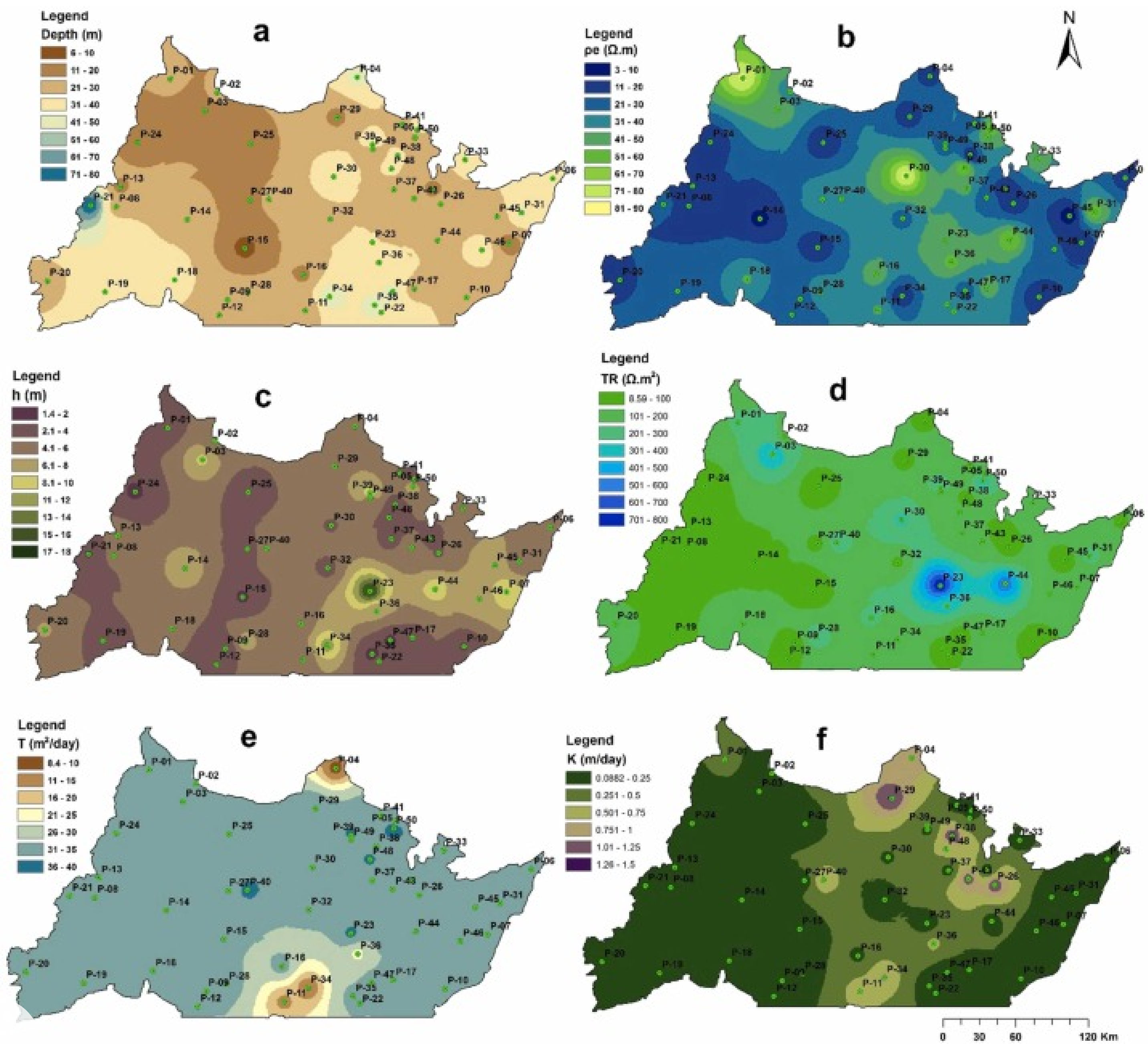

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Fig. 4. Interpolation of the criteria layers (**a-**Depth, **b**-Resistivity, **c**-Thickness, **d**- Transverse resistivity, **e**-Transmissivity, **f-** Hydraulic conductivity) using IDW method**.**

3.2. 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 six criterion layers employed in this investigation is shown in Fig. 5. Finally, using a fuzzy Sum operator, these factors are integrated to create a suitability map, as illustrated in Fig. 6. 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.

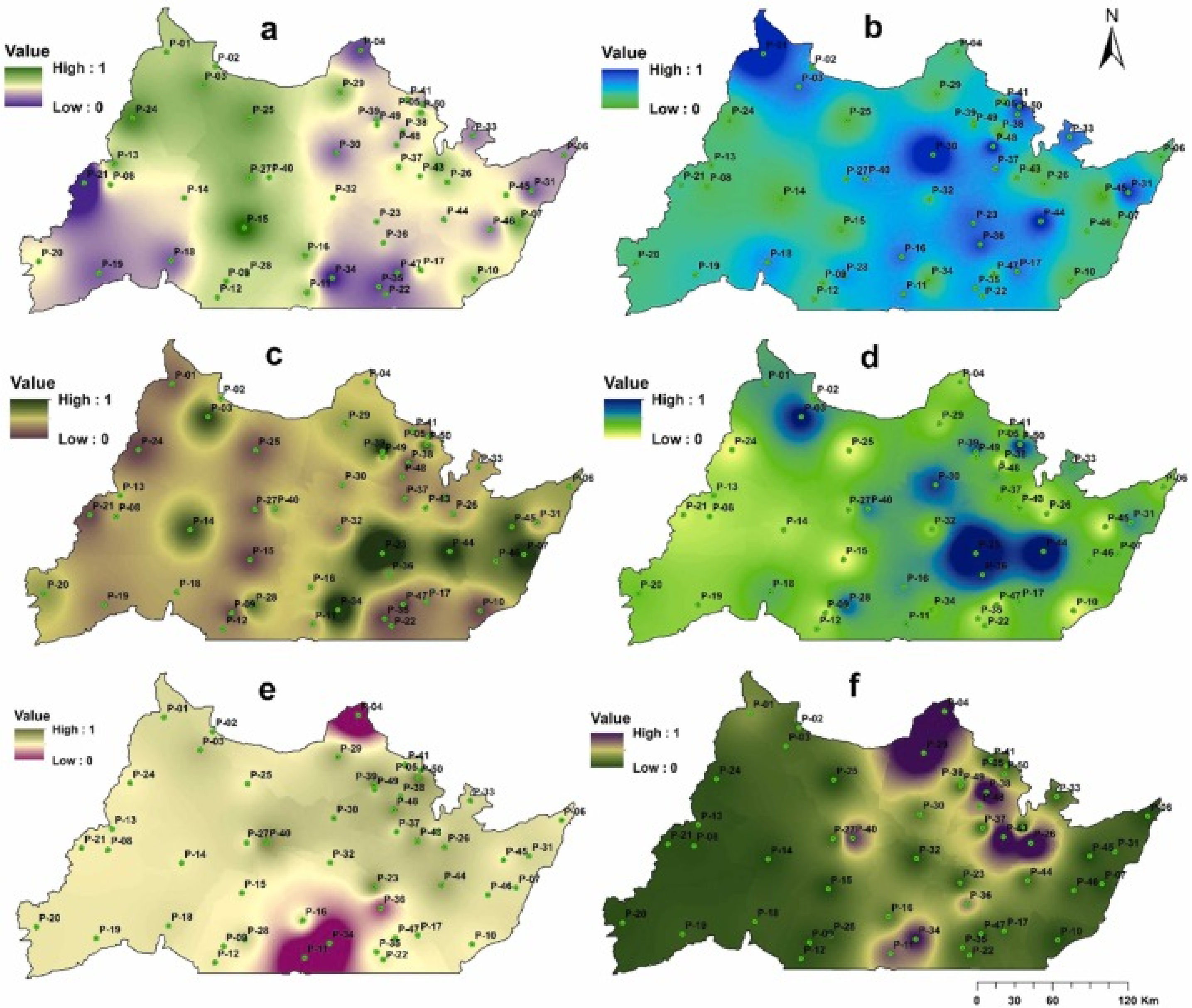

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Fig. 5. Liner membership of the criteria layers (a-Depth, b-Resistivity, c-Thickness, d- Transverse resistivity, e-Transmissivity, f- Hydraulic conductivity) using fuzzy method.

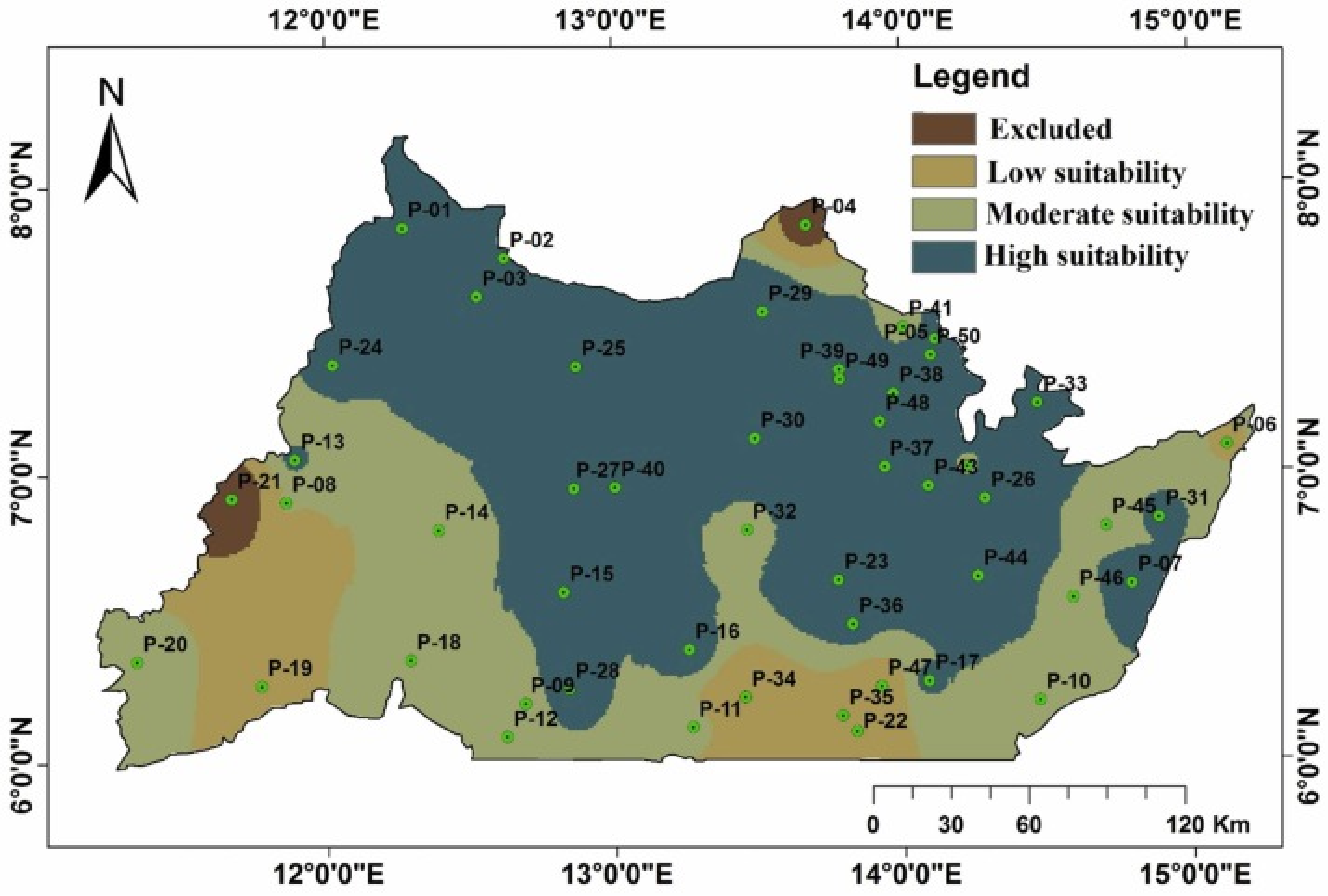

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Fig. 6. Site suitability map using fuzzy algebraic sum model.

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

Category	Value range	Area (km^2)	Percentage (%)
Excluded	0.84 – 0.92	848	1.319
Low suitability	0.93 – 0.96	7866	12.242
Moderate suitability	0.97 – 0.98	20353	31.675
High suitability	0.99–1.00	35187	54.762
Total		64254	100

Areas with high suitability are mainly located in the northern, southern, eastern, and central parts of the region; they cover an area of 35187 km^2 for 54.76 % of the study area. Areas with moderate suitability are found in the West, South, East, and a tiny part of the North. They occupy an area of 20353 km^2 and represent a percentage of 31.68 %. Areas with low suitability are located in the West, South, and a small part of the East and North. They cover an area of 7866 km^2 and represent a proportion of 12.24 %. Unsuitable areas, with almost inexistent groundwater potential, are located in the West and North; they occupy an area of 848 km^2 for a proportion of 1.32 %.

Firstly, each parameter was mapped individually and then processed in a GIS environment using the fuzzy algebraic model to map GWP from which is derived the suitability map. Higher is GWP on a site, the more the site is suitable to bear a borehole or a well. A visual similarity of the parameters distribution reveals some correlations between the suitability map and hydro-parameters distribution. Areas with the lowest aquifer depth are included in the zone with the highest suitability. Raad et al. (2022) with the resistivity where a higher resistivity-areas match with the lower suitability zone.

A more suitable zone covers most of the areas with low transverse resistance values. areas with lower transmissivity perfectly fit with the less suitable zone. This observation is also true for the hydraulic conductivity where the lowest values are found in the zone excluded according to its very low suitability. The strong correlation between the above-mentioned parameters (generally determined by geophysical or hydrogeological methods) and the suitability distribution confirms the significance of the hydrogeophysical approach in groundwater exploration in the region (Gupta, 1997; Jones, 2000; Anomohanran, 2013; Nshagali et al., 2014; Aretouyap et al., 2018; Aretouyap et al., 2019b; Bisso et al., 2019). However, there is no clear relationship between aquifer thickness variability and sustainability distribution.

In the Adamawa region and the whole of Central Africa, there is growing interest in the exploitation of groundwater resources by households, schools, health centers, etc. The lack of appropriate geophysical investigations generally leads to unproductive wells and boreholes. Even when a geophysical survey is envisaged, the extent of the area to be investigated is so high that an important financial resource is required. The outcome of this study addresses both issues by demarcating the most suitable zone where to focus the geophysical survey or to directly drill boreholes or wells in case of the absence of geophysics material or professional.

With a clear demarcation of the GWP zones in the Adamawa Plateau, the fuzzy algebraic model is a very useful tool for groundwater exploration. Its appropriate application may considerably reduce the time and costs of groundwater exploration while increasing the rate of successful and productive wells and boreholes. It can be successfully applied to any other region worldwide. However, its accuracy depends on a prior hydrogeophysical survey that may determine parameters to be processed in a GIS environment.

4. Conclusions

While groundwater is becoming the main source of water in most towns and villages in Central Africa, the number of unproductive wells continues to grow. Previous attempts to improve the wells and boreholes yield in the Adamawa region felt because related investigations addressed various hydro-parameters individually and separately. Fifty VES points were interpreted in this article using the Schlumberger configuration. Contributing parameters (aquifer depth, resistivity, thickness, transverse resistivity, transmissivity, and hydraulic conductivity) to GWP derived from this interpretation are combined using the fuzzy algebraic model on a GIS environment to demarcate GWP zones. According to the GWP category, the study area is classified into four suitability levels: high, moderate, low, and null covering 54.76 % (35187 km^2), 31.66 % (20353 km^2), 12.24 % (7866 km^2), and 1.32 % (848 km^2) of the total study area respectively. This approach provides key information on the suitability of a site to bear a productive borehole for lasting and sustainable exploitation. The fuzzy algebraic model demonstrates its ability to demarcate suitable zone to implement productive wells and boreholes in the Adamawa region. This article is a strategic document to support planners, stakeholders, decision-makers, and municipal authorities in their MSD. However, the approach used cannot stand alone without prior classical geophysical and hydrological surveys for determining hydro-parameters to be processed. Ideally, a minimum of six independent parameters are needed for a reliable assessment. Although the approach is reported to be effective, swift, universal, and advised for the analytical hierarchy process, it is strongly recommended to densify investigation sites. More VES points may lead to a more accurate GWP map.

CRediT authorship contribution statement

Zakari Aretouyap: Conceptualization, Investigation, Data curation, Writing – original draft preparation. **Jamal Asfahani:** Investigation, Methodology, Supervision. **Zaidoon Abdulrazzaq:** Software, Methodology. **Sandra Tchato**: Visualization, Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Compliance with ethical standards

- Authors declare that there are no conflicts of interest;
- This research does not involve human participants nor animals;
- All authors participated, approved the final manuscript and agreed for the submission to ***Journal of Hydrology: Regional Studies***.

Recommended articles

Data Availability

Data will be made available on request.

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