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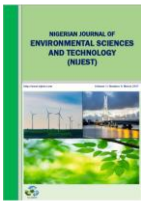

Integration of GIS-based Multi-criteria Analysis Techniques for the Delineation of Groundwater Potential Zones in Oyo state, Nigeria using Bayes' Approach

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ABSTRACT

Groundwater is the world's most extracted raw material due to its incessant need for human consumption. This study was carried out to delineate groundwater potential zones in Oyo state, Nigeria using the integration of two GIS-based multi-criteria analysis techniques – Multi influencing factor (MIF) and Analytic hierarchy process (AHP). The Bayes' integration approach for the recalculation of criteria weights was used. Eight groundwater potential contributing factors such as land cover, drainage density, lineament density, soil texture, geology, geomorphology, slope, and rainfall were processed and the multi-criteria analysis techniques were employed in assigning weights to each thematic layer and sub-classes. The thematic layers were overlaid in ArcGIS 10.4 software environment using the groundwater potential index equation for the generation of groundwater potential maps. The criteria weights of the MIF and AHP techniques were further integrated using Bayes' approach to obtain an optimum groundwater potential map. In this study, the groundwater potential maps from the three techniques were validated using the Receiver Operating Characteristics (ROC) curve methods. The validation of the groundwater potential zonation maps from the MIF, AHP and the Bayes' integration was also executed by evaluating the depths and yields from 1425 boreholes distributed across the study area. The Bayes' approach shows that the groundwater percentage distributions within the study area are: very low (36%), low (34%), Moderate (14%) and high (16%). The maximum yields of 200m^3 were observed in Akinyele, Atisbo and Egbeda LGA with minimum borehole depths of 24.20m, 30.30m and 30.00m. The Area under the Curve (AUC) results are: MIF (69.4%), Bayes' (69.0%) and AHP (67.6%) respectively. The Bayes' integration approach further shows better consistency as the average borehole yields across the groundwater potential zones positively correlates i.e. high potential zone has the highest average borehole yield, followed by the moderate, low and very low.

Keywords: Groundwater potential, Multi influencing factor, Analytic hierarchy process, GIS, Bayes' approach

1.0. Introduction

Amongst the various sources of water, groundwater is the most appropriate because, it often meets the criteria of the quality of water required for human consumption. It is the most widely used source of water in Nigeria and most of the African countries (Fasunwon *et al.*, 2010). Groundwater is defined as that water that lies under ground and the world depends on its freshwater availability as the best quality source of water. It is the water held in the sub-surface within the saturated zone under hydrostatic pressure below water table. In the sedimentary terrain, groundwater exploration is less difficult compared to the areas that fall within the basement complex terrain underlined by crystalline rocks. Where the Basement Complex rocks are fractured and/or weathered, it is possible for the rocks to be porous and permeable. Groundwater occurs in pockets restricted by fractures and weathered zones in Basement Complex rocks (Abdullahi *et al.*, 2016; Oladunjoye and Jekanyinfa, 2016).

The dynamic connections of different natural factors such as: geology, geotectonic structures, overburden thickness, weathering grade, geomorphology, lineament and fracture extent, drainage pattern, permeability of topsoil, land use/cover and climate (rainfall) determine the occurrence, adoption and stream flow of groundwater (Ayoade, 1988; Olorunfemi, 1990, Surrette *et al.*, 2008).

Other factors such as secondary porosity (Sener *et al.,* 2005; Sander, 2007) and vegetation (Shaban *et al.,* 2006) also affects groundwater occurrence and flow. Sometimes, test drilling and stratigraphy analysis are required in the determination of the location of an aquifer and its characteristics. However, these methods are costly and time-consuming (Todd and Mays, 1980; Adiat *et al.*, 2013) and as such, these methods are rarely used. Nowadays, the use of geophysical and hydrogeological techniques such as resistivity sounding for groundwater exploration and water quality evaluations is also very common due to the simplicity of the technique and rapid advances in computer software and other numerical modelling techniques. Oladunjoye *et al.* (2019) opined that the use of vertical electrical sounding technique for exploring groundwater resources overcomes the cost and time limitations (to a certain extent) and makes use of evaluation of electrical resistivity. Paine and Collins (2003) applied the use of airborne electromagnetic induction in groundwater salinization and resource studies. Other methods for groundwater investigation include the use of the electromagnetic waves reflected from the water table and groundwater penetrating radar for groundwater exploration which was carried out at various locations (Beres and Haeni, 1991; Jol and Smith, 1991; Smith and Jol, 1992; Ziaqiang *et al.*, 2009).

In Oyo state groundwater investigation, several authors like Anudu *et al.* (2008), Olayinka *et al*. (1997); Adagunodo *et al.* (2013), Layade *et al.* (2017), Adejumo (2018) have worked on various locations within the state using the resistivity sounding technique. Oladunjoye and Jekanyinfa (2016) worked on and improved Schlumberger area (Hummel –Schlumberger array) to obtain an improved result using Ibadan metropolis as a case study. The author opined that the Hamel-Schlumberger technique for exploring groundwater resources overcomes the limitations of using the conventional Schlumberger array and makes use of evaluation of electrical resistivity (Oladunjoye *et al.*, 2019). Oladejo *et al*. (2013) carried out a groundwater exploration study in Ogbomosho using Very Low Frequency (VLF) method. None of these approaches; integrated the use of satellite remote sensing data, geographic information system (GIS) and hydrogeophysical data. Oladunjoye and Jekanyinfa (2016) and Ndlovu Shakespeare *et al*. (2010) opined that a high degree of accuracy to accurately identify the prospective drilling sites for groundwater are be obtained through the integration of two or more methods. This will help to limit the vulnerability of errors linked with the use of a single method. With respect to the above, Alisiobi and Ako (2012) utilized the integration of seismic refraction and vertical electrical methods in groundwater investigation.

In recent times, several authors such as Magesh *et al.* (2012), Tweed *et al*. (2007), Jha *et al*. (2007), Epuh *et al*. (2018, 2019, 2020), Das and Pardeshi (2018) have all demonstrated the technique of integration of remote sensing data and GIS tool in assessing, monitoring, and conserving groundwater resources. This has become extremely useful for groundwater studies and been a breakthrough in the field of groundwater research. For effective groundwater exploration and exploitation, it is important to study the different parameters in a combined approach. The integration of multiple data sets, with various indications of groundwater availability, can decrease the uncertainty and lead to safer decisions (Sander *et al.,* 1996). None of previous groundwater studies in Oyo state has incorporated the use of multi-influencing factor (MIF) and Analytic Hierarchy Process (AHP) methods for groundwater mapping in the study area. Besides, each of them was localized to their immediate study area. None has been comprehensive to give the perspective of the distribution of groundwater potential zones within Oyo state. With respect to the study area which lies within a basement complex region, a comprehensive groundwater development scheme should include a good knowledge of the groundwater potential zones determined from satellite observations and the hydrogeophysical parameters of the subsurface layers, overlying the crystalline bedrock structures/relief determined using electrical methods. The combination of the MIF and AHP-derived weights using the Bayes' approach is a major contribution of this study following the proposition of Vinogradova *et al.* (2018) on the recalculation of criteria weights from two or more methods using the geometric mean model. This integration is with the purpose of improving the accuracy of weights. Hence, an attempt has been made in this study to delineate groundwater potential zones in Oyo state using the fusion of geospatial-based MIF and AHP techniques considering eight groundwater potential contributing factors which are land cover, drainage density, soil texture, geology, geomorphology, slope, rainfall, and lineament density. The factors have been evaluated to prepare the groundwater potential maps from the MIF, AHP and the combined techniques which will be useful in the management and conservation of groundwater resources in Oyo state, Nigeria. The groundwater potential maps were validated using existing borehole yield data.

2.0. Methodology

2.1. Description of study area

The study area (Oyo state) is located in the south-western part of Nigeria. It lies between latitudes 6^o $55^{'}$N – 9^o 10’N and longitudes 2^o $45^{'}$E – 4^o 40’E as shown in Figure 1. The area is underlain by the Precambrian undifferentiated basement complex rocks of south-western Nigeria. These rocks are inherently characterized by low porosity and permeability (Rahaman, 1976; Oladunjoye and Jekanyinfa, 2016; Adejumo, 2018). Wright (1992) and Adejumo (2018) opined that the basement aquifers are settled within the weathered, overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic (granitic/quartzite suite) origin which are mainly of Precambrian age. Oyo state has a land area of 27, 380 square kilometers (Fajuyigbe *et al*., 2007). The state is bounded in the north by Kwara state, in the south by Ogun state, in the east by Osun state and in the west, partly by Ogun state (Olorunfemi and Fasuyi, 1993; Ariyo and Adeyemi, 2009). The terrain is undulating while the elevation ranges between 30 and 630meters.

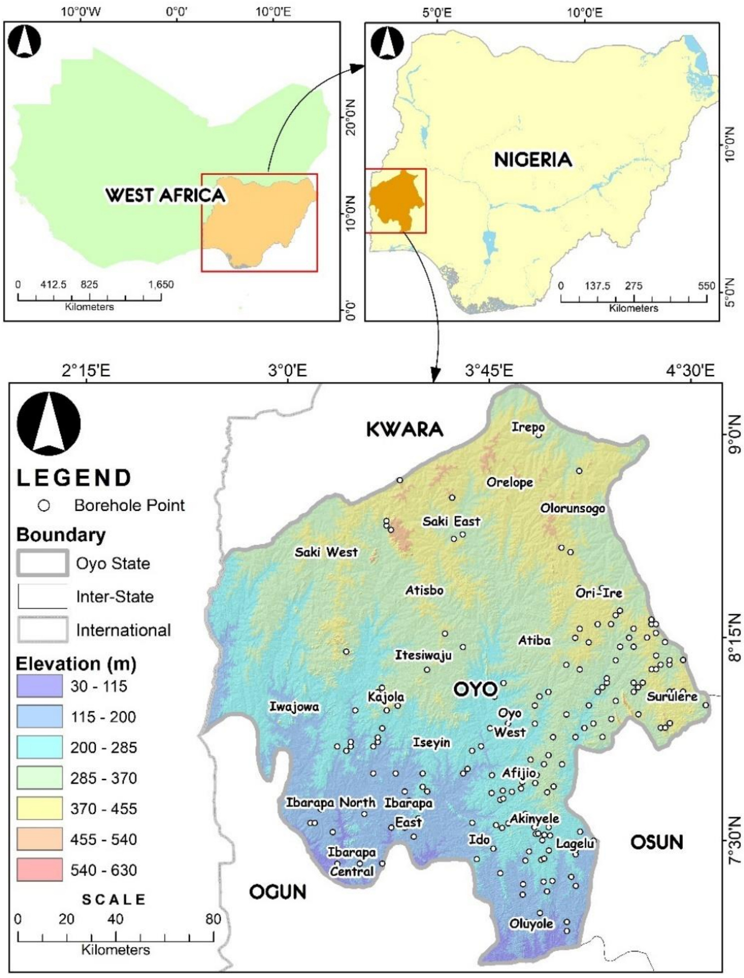

Figure 1: Location map of the study area with reference to Nigeria and West Africa

2.2. Materials and methods

2.2.1. Overview

In this study, the datasets used include Landsat 8 Operational Land Imager (OLI) image and Advanced Land Observation Satellite Digital Elevation Model (ALOS DEM), rainfall data, existing geological and soil data of Nigeria as well as the 178 borehole locations and yield information across the study area. Table 1 shows the details of the datasets. Figure 2 shows the procedure followed through data acquisition, data processing, presentation and validation. The Landsat images scenes covering Oyo state were classified in land cover classes. The lineament features were also extracted from the filtered Landsat image composite. The slope layer and the drainage lines were obtained from the ALOS DEM. The rainfall data was resampled into a rainfall map for the location. The AHP and MIF models were used for the ranking of all the thematic layers and integrated using the groundwater potential index to produce groundwater potential zonation (GWPZ) maps. The weights of the MIF and AHP were aggregated using the Bayes' approach. The new sets of criteria weighted were used for the generation of an optimum result. The borehole data was used for the validation of the groundwater potential maps derived from the MIF and AHP models.

Table 1: Remote sensing, vector, and geophysical datasets

S/N	Dataset	Scale/ Resolution	Source	Coordinate System	Acquisition Date
1	Landsat 8 Imagery (OLI) Path/Row – 191/54, 19054, 191/55, 192/54	30m	United States Geological Survey (USGS) https://earthexplorer.usgs.gov/	WGS 84 UTM Zone 31N	27-12-2019 dd-mm-yyyy
2	ALOS World 3D-30m (AW3D30) Version 3.1	30m	Earth Observation Research Center (EORC) Japan Aerospace Exploration Agency (JAXA) https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm		2014
3	Annual Rainfall data	0.25° x 0.25°	University of California, Center for Hydrometeorology and Remote Sensing (UCI CHRS) Data Portal https://chrsdata.eng.uci.edu	WGS 84 GCS	2001 – 2019
4	Soil data	1:650,000	Federal Department of Agricultural Land Resources, Nigeria		1990
5	Geological data	-	Nigerian Geological Survey Agency, FCT, Abuja		2000
6	Borehole locations and yield data	178 borehole stations	Oyo State Rural Water Supply and Sanitation Agency	WGS 84 UTM Zone 31N	2006 – 2007

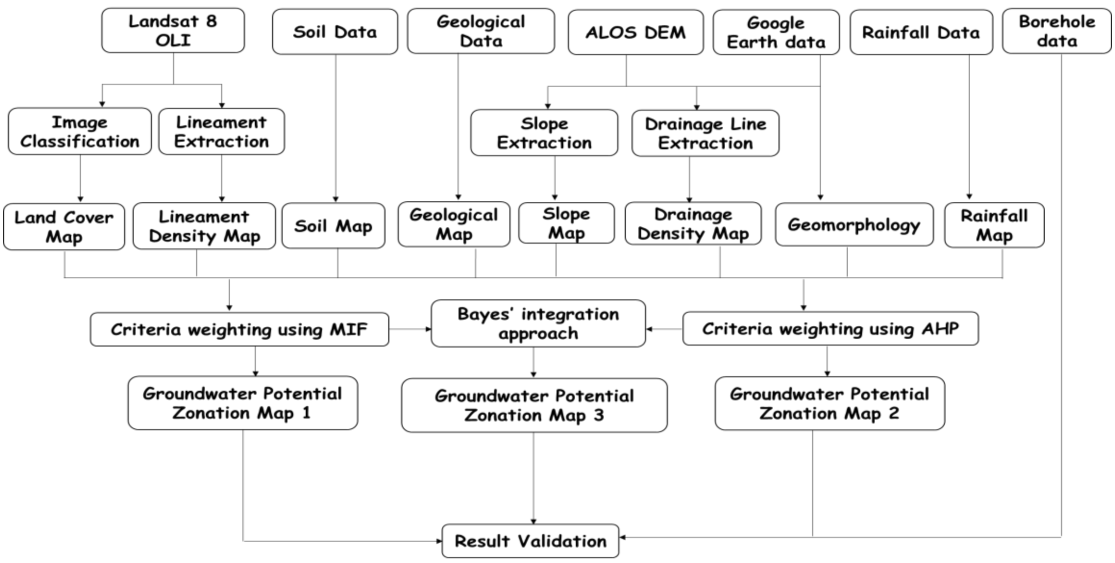

Figure 2: Methodology flowchart

2.2.2. Generation of the thematic layers for the groundwater potential zonation

Eight thematic layers (land cover, drainage density, lineament density, soil texture, geology, geomorphology, slope, and rainfall) were considered from remotely sensed and GIS datasets using GIS techniques. Landsat OLI image scenes covering Oyo State were classified using the maximum likelihood technique into five land cover classes such as built-up, forest land, cultivated area (farmland and grassland), bare land and waterbody. The maximum likelihood image classification algorithm in the ArcGIS environment was used. The Anderson classification scheme level 1 guided the choice of the land cover classes (Anderson *et al.*, 1976). The drainage density map was derived from the drainage lines which were extracted from the ALOS DEM using the watershed generation tool in Global Mapper 13 software. The stream count number was set to 5000 for adequate extraction of drainage lines. The line density tool within the ArcGIS 10.4 software environment was used for the generation of the drainage density raster. The lineaments were derived from the extracted lines representing sharp edges as detected from the Landsat 8 false colour composite of bands 7, 4 and 1 created on ENVI 5.3 software. This was followed by convolution filtering of kernel size 5 by 5 in directions 180^0, 135^0, 225^0 and 270^0. The edges of the filtered image were further extracted in PCI Geomatica v16 software. The line density tool within the ArcGIS environment was used for the generation of the lineament density raster. The acquired soil and geological vector data were rasterised in the ArcGIS software environment. The slope tool in ArcGIS software environment was used to generate slope values in degrees from the ALOS DEM. The annual rainfall raster data for 19 years (2001 – 2019) were averaged to produce the mean annual rainfall input data for the groundwater overlay analysis. The cell statistics tool in ArcGIS software environment was employed in creating the average of the annual rainfall dataset. The averaged raster data was converted into a point vector from which thirty-five (35) rainfall data points covering Oyo state was extracted before a kriging interpolation analysis was performed on the rainfall data points to create a final rainfall raster surface.

2.2.3. Weighting of thematic layers using the multi-influencing factor technique

The multi influencing factor technique basically involves determining interrelationships between factors that influence ground water potential and assigning weights to them as a result of their interrelationship and strength of influence (Das and Pardeshi, 2018).

Eight influencing factors were identified to delineate groundwater potential in the study area. The factors include; geology, geomorphology, slope, land cover, lineament density, drainage density, soil texture, and rainfall. Thematic maps showing the extent and distribution of all these factors have been produced and sampled into raster layers. After the production of the maps, interrelationship between all these factors were determined based on previous studies and reviewed literatures. Figure 3 shows the interrelationships between the factors.

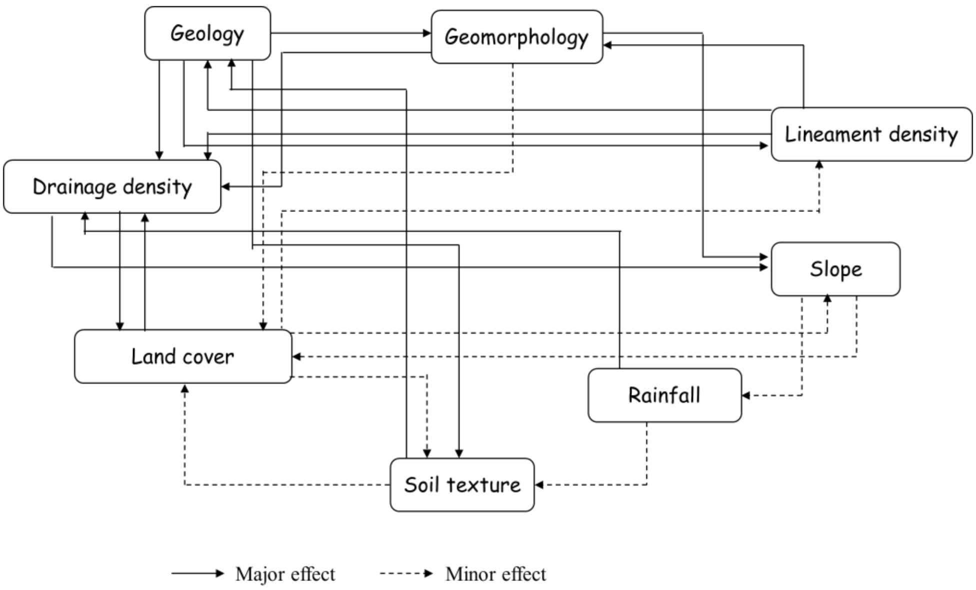

Figure 3: Interrelationship between factors which influence groundwater potential.
(Modified after Magesh *et al.*, 2012; Das and Pardeshi, 2018)

Based on the interdependence of factors as seen in Figure 3 above, factors that have primary influences on other factors as regards groundwater availability are considered to have major effects and factors that have secondary influences on other factors are considered to have minor effects. Also, the minor effects of any factor are represented as dotted lines while the major effects of any factor are represented as the regular lines as seen in Figure 3. The major effect and minor effect of any factor is assigned a value of 2.0 and 1.0 respectively. The cumulative values of both major and minor effects are considered for calculating the relative rates. This rate is further used to calculate the score of each influencing factor. For instance, geomorphology which has a direct (primary) influence on two factors and indirect (secondary) influence on just one factor of ground water occurrence is assigned a value of

5 as seen in Table 2. Table 3 shows the normalised weights of the thematic layers and the sub–classes. The ranking of the thematic layers is in line with the study of Algaydi *et al.* (2019) carried out in similar terrain. The sub-classes were ranked according to Arulbalaji *et al.* (2019) and Jesiya and Gopinath (2020). The proposed score for each influencing factor is calculated by using Equation 1. (Magesh, 2012; Das and Pardeshi, 2018):

$$\left[\frac{M_j + M_i}{\sum(M_j + M_i)}\right] \times 100 \quad (1)$$

M_j stands for major effects of a factor and M_i stands for minor effects of a factors

The internal features of the thematic layers were ranked by dividing the previous scores (P_i) by the number of internal features in each factor. But the feature that is perceived to have the highest influence in that thematic layer will be assigned the proposed score/ weight (P_i) previously assigned to the thematic layer. The method of calculating the ranks of the internal features of the layers is explained further below:

W_i of the most important class/feature of the thematic layer = P_i of the thematic layer
W_i of the next important class of the thematic layer= W_i of first class $- \frac{P_i}{n}$
Where P_i is the weight of thematic layer, W_i is the rank value of the individual class/feature and n is the total number of features in each factor (Das *et al.*, 2017).

Table 2: Calculation of weights based on interrelationships between the groundwater factors

Factors	Major effect (M_j)	Minor effect (M_i)	$M_j + M_i$	Proposed score of each factor (P_i)
Geology	8	0	8	22
Lineament density	6	0	6	17
Geomorphology	4	1	5	14
Land cover	2	3	5	14
Drainage density	4	0	4	11
Soil texture	2	1	3	8
Rainfall	2	1	3	8
Slope	0	2	2	6
Total			**36**	100

2.2.4. Weighting of thematic layers using the analytic hierarchy process technique

Individual class weights and map scores were assessed according to Saaty and Vargas (1991) on AHP. It was used to identify the themes with their rank and priority as it helps to arrange the criteria in hierarchical order through pair-wise comparison matrix. AHP makes judgments and calculations easy because of pairwise comparisons of matrices of the identified criteria and demonstrates the compatibility and incompatibility of decisions which is the recompense of multi-criteria decision making (Lee, 2007). The principle of AHP has been established and deployed in literature (Saaty, 1988; Brunelli, 2015; Reisi *et al.,* 2018; Hamid-Mosaku *et al.,* 2020). In this study, eight groundwater potential contributing factors were identified and adopted from literature. They include drainage density, lineament density, land cover, soil texture, annual rainfall, slope, geomorphology and geology. According to Vinogradova *et al.* (2018), decisions regarding the individual theme and class weight were taken from their ranking obtained through administered questionnaire to experts from which ten responses were retrieved. The ranking is based on the Saaty's scale of relative importance value that reveals that value of 9 indicates extreme importance, 8 very, very strong, 7 very extreme importance, 6 strong plus, 5 strong importance, 4 moderate plus, 3 moderate importance, 2 weak and 1 equal importance (Arulbalaji *et al.,* 2019).

Table 3: The assigned weights and scores to different themes and features respectively

Theme layer	Priority weight (%)	Class	Assigned weight	Normalized weight
Geology	22	Basement complex, undifferentiated	8	0.1778
		Older Granites, undifferentiated	15	0.3333
		Metasediments, Schists, Quartzites	22	0.4889
Lineament density (km/km^2)	17	0 – 0.62	3	0.0588
		0.62 – 1.25	7	0.1373
		1.25 – 1.87	10	0.1961
		1.87 – 2.49	14	0.2745
		2.49 – 3.12	17	0.3333
Geomorphology	14	Flood plain	14	0.3333
		Valley fill	11	0.2619
		Lower plateau	8	0.1905
		Ridge	6	0.1429
		Inselberg	3	0.0714
Land cover	14	Waterbody	14	0.3333
		Mixed forest	11	0.2619
		Agricultural land	8	0.1905
		Built-up area	6	0.1429
		Rock outcrop	3	0.0714
Drainage density (km/km^2)	11	13 – 23	2	0.0606
		23 – 33	4	0.1212
		33 – 43	7	0.2121
		43 – 53	9	0.2727
		53 – 63	11	0.3333
Soil texture	8	Sandy	8	0.2162
		Loamy sand	8	0.2162
		Sandy loam	8	0.2162
		Silty loam	5	0.1351
		Clay loam	4	0.1081
		Sandy clay	4	0.1081
Rainfall (mm)	8	1520 – 1650	2	0.0833
		1650 – 1780	3	0.1250
		1780 – 1910	5	0.2083
		1910 – 2040	6	0.2500
		2040 – 2170	8	0.3333
Slope (degree)	6	0 – 2	6	0.3333
		2 – 5	5	0.2778
		5 – 10	4	0.2222
		10 – 20	2	0.1111
		20 – 64	1	0.0556

According to Hamid-Mosaku *et al*. (2017), pairwise comparison matrices (D) of decisions take the form shown in Equation 2 where the element $\{x_{ij}\}$ of the matrix is the degree of preference of the ith criterion over the jth criterion or vice versa for the determination of the relative priorities of all the criteria. An arithmetic mean of the experts' responses in favour of each layer was calculated to derive the importance levels to be used in the pairwise comparison based on the AHP model. The geometric means of the averaged experts' responses for the layers were determined row-wise after which the normalised comparison values (priority weights) of the layers were computed (Equation 3). The pairwise comparison matrix was computed in ArcGIS software using the AHP extension integrated into ArcGIS software. Table 4 shows the pairwise comparison matrix while Table 5 shows the final weights and ranks of the layers utilized in the development of the groundwater potential using the AHP model. The sub–classes of thematic layers such as rainfall, lineament density, drainage density and slope were reclassified using equal classification method in ArcGIS symbology panel for the purpose of assigning the normalised weights.

Comparison matrices

$$D = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & C_2 & C_3 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \cdots & x_{2n} \\ x_{31} & x_{32} & x_{33} & \cdots & x_{3n} \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ x_{n1} & x_{n2} & x_{n3} & \cdots & x_{nn} \end{bmatrix} \end{array} \tag{2}$$

$$\breve{x}_i = \left(\prod_{j}^{n} \breve{x_{ij}} \right)^{1/n}, \quad i = 1, 2, \dots, n \tag{3}$$

Where n is the number of criteria/thematic layers

The consistency index (CI) was computed using Equation. 4 and the consistency ratio (CR), using Eq. 5 (Hamid-Mosaku *et al.,* 2017). The random index (RI) value which is a direct function of the number of criteria considered was obtained from a lookup table of random indices according to Saaty and Kearns (1985). The RI value for n equals 8 is 1.41. The CR value being less than 0.1 shows the acceptability of both the survey and the experts' judgement.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

where λmax represents the principal eigenvalue of the matrix D having an order of n which is the number of the criteria considered.

$$CR = \frac{CI}{RI} \tag{5}$$

Table 4 is the pairwise comparison matrix for the criteria as presented in Equation 2. Table 5 shows the normalized weights of the final selected thematic layers and sub-classes. The sub-classes were ranked and the normalised (Kumar *et al.,* 2020; Jesiya and Gopinath, 2020).

Table 4: Pairwise comparison matrix of the criteria

Layer	Gl	Ld	Gm	S	ST	Dd	LC	AR	Geometric mean, $\breve{x}_i$	Normalised weight, w_i
Gl	1	3	3	3	3	3	5	5	2.9713	0.2875
Ld	0.333	1	3	3	3	3	5	5	2.2577	0.2185
Gm	0.333	0.333	1	3	3	3	3	5	1.6094	0.1557
S	0.333	0.333	0.333	1	3	3	3	5	1.2228	0.1183
ST	0.333	0.333	0.333	0.333	1	3	3	3	0.8717	0.0843
Dd	0.333	0.333	0.333	0.333	0.333	1	3	3	0.6623	0.0641
LC	0.200	0.200	0.333	0.333	0.333	0.333	1	3	0.4429	0.0429
AR	0.200	0.200	0.200	0.200	0.333	0.333	0.333	1	0.2962	0.0287
Sum, a_i	3.067	5.733	8.533	11.200	14.000	16.667	23.333	30.000	10.3343	
$a_i w_i$	0.882	1.253	1.329	1.3253	1.181	1.068	1.000	0.860	$\lambda_{max} = \sum_{i=1}^{n} w_i\, a_i$ =8.897	
Consistency Index (CI) = 0.1282; Random Index (RI) =1.41, Consistency Ratio = 0.0909										

Gl is geology, Ld is lineament density, S is slope, ST is soil texture, Dd is drainage density, LC is land cover, AR is annual rainfall and Gm is geomorphology

Table 5: Normalized weights of the final selected thematic layers and sub-classes

Thematic layer	Normalized priority weight	Class	Assigned weight	Normalized sub-class weight
Geology	0.2875	Basement complex, undifferentiated	1	0.1667
		Older Granites, undifferentiated	2	0.3333
		Metasediments, Schists, Quartzites	3	0.5000
Lineament density (km/km^2)	0.2185	0 – 0.62	1	0.0667
		0.62 – 1.25	2	0.1333
		1.25 – 1.87	3	0.2000
		1.87 – 2.49	4	0.2667
		2.49 – 3.12	5	0.3333
Geomorphology	0.1557	Flood plain	5	0.3333
		Valley fill	4	0.2667
		Lower plateau	3	0.2000
		Ridge	2	0.1333
		Inselberg	1	0.0667
Slope (degree)	0.1183	0 – 2	5	0.3333
		2 – 5	4	0.2667
		5 – 10	3	0.2000
		10 – 20	2	0.1333
		20 – 64	1	0.0667
Soil texture	0.0843	Sandy	4	0.2500
		Loamy sand	4	0.2500
		Sandy loam	4	0.2500
		Silty loam	2	0.1250
		Clay loam	1	0.0625
		Sandy clay	1	0.0625
Drainage density (km/km^2)	0.0641	13 – 23	1	0.0667
		23 – 33	2	0.1333
		33 – 43	3	0.2000
		43 – 53	4	0.2667
		53 – 63	5	0.3333
Land cover	0.0429	Waterbody	5	0.3333
		Mixed forest	4	0.2667
		Agricultural land	3	0.2000
		Built-up area	2	0.1333
		Rock outcrop	1	0.0667
Annual rainfall (mm)	0.0287	1520 – 1650	1	0.0667
		1650 – 1780	2	0.1333
		1780 – 1910	3	0.2000
		1910 – 2040	4	0.2667
		2040 – 2170	5	0.3333

2.2.5. Delineation of groundwater potential zones

Groundwater potential zones (GWPZs) are a dimensionless quantity that predicts the groundwater potential zones in an area (Rahmati *et al.,* 2015; Kumar *et al.*, 2020). The weights derived for the layers and the sub-classes were overlayed or aggregated using the groundwater potential index (GWPI) formula as shown in Equation 6 (Kumar *et al.*, 2020). The formula was deployed through the raster calculator tool in the ArcGIS environment. The output of the overlay process which is the groundwater potential zonation map was reclassified into three classes namely high, moderate, and low groundwater potentials.

$$GWPI = \sum_{i=1}^{n} \sum_{w=1}^{m} (W_i \times X_j) \quad (6)$$

Where W_i is the normalised weight of the j thematic layer, X_j is the rank value of each class with respect to the j layer, m is the total number of thematic layers, and n is the total number of classes in a thematic layer. The GWPI for each grid was calculated using Equation 7 (Kumar *et al.*, 2020):

$$\mathrm{GWPI} = \mathrm{Gl_w Gl}_r + \mathrm{Ld_w Ld_r} + \mathrm{Gm_w Gm}_r + \mathrm{S_w S}_r + \mathrm{ST_w ST_r} + \mathrm{Dd_w Dd_r} + \mathrm{LC_w LC_r} + \mathrm{AR_w AR_r} \quad (7)$$

Where Gl is geology, Ld is lineament density, S is slope, ST is soil texture, Dd is drainage density, LC is land cover, AR is annual rainfall and Gm is geomorphology. The subscripts 'w' and 'r' represent the weight of a feature and that of the individual subclasses of the feature based on their relative importance for groundwater potentiality. The sub-classes were ranked between 1 and 5 where the rates of 1, 2, 3, 4 and 5 represent very poor, poor, moderate, good and very good, respectively, with respect to groundwater storage potential. The groundwater potential zonation maps from the MIF and AHP-weighted layers were combined

2.2.6. Integration of criteria weights from MIF and AHP techniques using the Bayes' approach

In this study, the criteria weights obtained from both multi-criteria analysis techniques were further integrated and recalculated to obtain new weights using the Bayes' approach. The combination of the MIF-derived weights and the AHP-derived weights makes a robust set of new weights for nthe delineation of groundwater potential. The application of the Bayes' theorem or approach for the combination of multi-criteria weights was suggested by Vinogradova *et al.* (2018) and has been repeatedly used in the investigation for combining the objective (MIF) and subjective (AHP) weights for recalculating the criteria weights. According to Jeffreys (1973), the Bayes' equation for recalculating criteria weights is mathematically expressed in Equation 8.

$$\omega(R_j/X) = \frac{\omega(R_j)\omega(X/R_j)}{\sum_{j=1}^{m} \omega(R_j)\omega(X/R_j)} \quad (8)$$

Where $\omega(R_j) = \omega_j$ is the initial weight of the *j*-th criterion R_j; X denotes the event, when new criteria weights are obtained; $\omega(X/R_j) = W_j$ denotes new weights of the criteria calculated by a different method or by another group of experts; $\omega(R_j/X)$ denotes the recalculated criteria weights.

Equation 8 applied to the weights of the criteria in this study has the form:

$$\alpha_j = \frac{\omega_j W_j}{\sum_{j=1}^{m} \omega_j W_j} \quad (9)$$

Where α_j denotes the recalculated weights of the criteria.

Equation 9 is based on the concept of the geometric mean for integrating weights. It was applied to criteria weights and the sub-classes to obtain the new weights as shown in Table 6.

Table 6: The recalculated criteria weights using Bayes' equation

Theme layer	Priority weight	Class	Normalized weight
Geology	0.4178	Basement complex, undifferentiated	0.0769
		Older Granites, undifferentiated	0.2884
		Metasediments, Schists, Quartzites	0.6346
Lineament density (km/km^2)	0.2454	0 – 0.62	0.0160
		0.62 – 1.25	0.0745
		1.25 – 1.87	0.1596
		1.87 – 2.49	0.2979
		2.49 – 3.12	0.4521
Geomorphology	0.1440	Flood plain	0.4574
		Valley fill	0.2876
		Lower plateau	0.1569
		Ridge	0.0784
		Inselberg	0.0196
Land cover	0.0397	Waterbody	0.4574
		Mixed forest	0.2876
		Agricultural land	0.1569
		Built-up area	0.0784
		Rock outcrop	0.0196
Drainage density (km/km^2)	0.0466	13 – 23	0.0164
		23 – 33	0.0656
		33 – 43	0.1721
		43 – 53	0.2951
		53 – 63	0.4508
Soil texture	0.0445	Sandy	0.6957
		Loamy sand	0.6957
		Sandy loam	0.6957
		Silty loam	0.2174
		Clay loam	0.0870
		Sandy clay	0.0870
Rainfall (mm)	0.0152	1520 – 1650	0.0230
		1650 – 1780	0.0690
		1780 – 1910	0.1724
		1910 – 2040	0.2759
		2040 – 2170	0.4597
Slope (degree)	0.0469	0 – 2	0.4477
		2 – 5	0.2986
		5 – 10	0.1791
		10 – 20	0.0597
		20 – 64	0.0149

2.2.7. Validation of the groundwater potential zonation maps

This study employed the Receiver Operating Characteristics (ROC) validation technique for the accuracy assessment of the groundwater potential maps. ROC curves are able to discriminate between observed and predicted variables based on the logistic regression S-shaped curve (Zhang *et al.*, 2015). The ROC curve is also free of parametric assumptions (Brown and Davis, 2006). The ROC curve technique follows a binary classification rule which results in four possible classifications depending on whether the positive or negative test result is correct or whether the positive or negative test result is not correct. A true positive occurs when a correct result correctly tests positive, while a false positive identifies a negative result incorrectly tests positive. On the other hand, a true negative occurs when a negative result is identified correctly as being negative, and a false negative identifies incorrectly a true result as being negative (Schwenke and Schering, 2007; Carter *et al.*, 2016). ROC curves are created by plotting the true positive rate (sensitivity) on the y axis against the false-positive rate (1 – specificity) on the x axis while the area under the curve (AUC) depicts the accuracy of the predicted results. Sensitivity is defined as the proportion of positives which are identified correctly, also known as the true-positive rate (Equation 10). Specificity is defined as the proportion of negatives which are identified correctly, also known as the true-negative rate. The false positive rate (1 – specificity), as shown in Equation 11, is defined as the proportion of incorrect positive results that are in fact negative (Nelson *et al.*, 2005). The ROC curve tool in the statistical package for the social sciences (SPSS) software environment was used to generate the ROC curve.

$$\text{True positive rate} = \frac{\text{True positives}}{\text{True positives} + \text{False negatives}} \quad (10)$$

$$\text{False positive rate} = \frac{\text{True negatives}}{\text{True negatives} + \text{False positives}} \quad (11)$$

The accuracy of the GWPI values was assessed based on the yield rate of 1425 boreholes well distributed across the study area. According to the ROC curve model, the dependent variable also known as the state variable is a binary data type while the independent variable known as the test variable can be categorical or quantitative (dis. For the validation of the GWPI maps in this study, the borehole yield which was used as the state variable was divided into a binary group of 0 and 1. The boreholes with no yield per day were assigned zero while boreholes with yield were assigned one (1). The GWPI being a quantitative variable was used as the test variable (See Table 9).

3.0. Results and Discussion

This section entails the presentation of the groundwater potential contributing factors as thematic layers, presentation, discussion and the validation of the groundwater potential maps.

3.1. Thematic layers of the groundwater potential contributing factors

3.1.1. Soil texture

Soil texture is a significant element in the delineation of groundwater potential zones in any region. Soil Porosity and permeability are direct function of soil texture. The nature of soil texture determines its infiltration intensity. The movement and infiltration of water in fine-grained soil is low compared to coarse-grained soil because these types of soils are not the same (Das and Pardeshi, 2018). The study area is mainly characterized by sandy clay in the south-eastern part, clay loam in the south-western part, sandy loam in the western part and loamy sand in the northern part of the study area. There are patches of other soil textures across the study area which include silty loam, and sandy soils. According to the hydrological soil group by the United States of Department of Agriculture (USDA, 2007), sandy, loamy sand and sandy loam belong to category A, silt loam belongs to category B while clay loam and sandy clay belong to category D. Category A has the highest infiltration level, followed by B and D respectively. The soil map of the study area is shown in Figure 4a.

3.1.2. Drainage density map

Drainage density refers to the total length of streams per unit area (Avtar *et al.,* 2011; Das and Pardeshi, 2018). Studies have shown that areas with low drainage density tend to have high ground water potential due to high run off on rocks that are impermeable. Drainage pattern indicates the joints and faults in the bedrock which in turn indicates the presence or absence of groundwater. The drainage map shows that the study area has many zones of high drainage density (Figure 4b).

3.1.3. Geomorphology

Geomorphology shows a major influence on occurrence, percolation and recharging of water into the subsurface of the earth (Balamurugan *et al.*, 2016; Etikala *et al.*, 2019). The geomorphic features were delineated from DEM and digitization from the satellite image (Fashae *et al.*, 2014). In this study area, high topography is seen in the northern parts while the southern parts show nearly plain to gentle plains (Figure 4c). Based on structural and depositional origins, a total of five geomorphological features were identified such as inselberg, ridge, lower plateau, valley fill and flood plain. The highest weight was assigned to the geomorphological class of flood plain, followed by valley fill, lower plateau, ridge, and inselberg respectively.

3.1.4. Geology

Geologically, Oyo state falls in the undifferentiated basement complex and older granites regions. The metasediments, schists and quartzites also exist in the study area as shown in Figure 4d. Geology is also another factor that majorly influences groundwater potential. Rocks found in basement complex terrains are usually hard rocks which are high in porosity and low in permeability. This impedes their ability to store groundwater efficiently. Hydrogeological investigation of lithologies has shown that the schists and quartzites have more groundwater yield than the migmatite gneiss biotite granite undifferentiated and the older granite undifferentiated (Fashae *et al.,* 2014; Akinluyi *et al.,* 2018). In this study, the metasediments, schists, quartzites class was assigned the highest weight.

3.1.5. Lineament density map

Lineaments are basically the results of as joints, cracks, shears fault and fractures. Areas showing high lineament density tend to have high levels of porosity and permeability and this allows for more percolation of water which could signify reasonable ground water potential. According to Mogaji *et al.* (2011), the zones of high lineament intersection density are feasible zones for groundwater prospecting in the study area. The high density exists at the centre (Oyo west, Iseyin, Shaki west, and Ogbomosho north). Figure 4e shows the lineament density map of the study area.

3.1.6. Slope map

Slope is one of the most essential terrain derivatives used in expressing the steepness from ground surface, providing information on the nature of geologic and geodynamic processes operating at the regional scale (Epuh *et al.,* 2020a, b). It is a key factor which influences the penetration of surface water into the subsurface. The slope of the study area has been calculated in degrees (^{o}) based on the Digital Elevation Model (DEM) which was extracted from the ALOS DEM data. The slope has been classified into five categories varying from 0 – 64 degrees. Based on natural jenks classification interval, they were classified as follows: very low: 0 – 2, low: 2 – 5, moderate: 5 – 10, high: 10 – 20 and very high: 20 – 64^o. According to Chowdhury *et al.* (2009), in relation to groundwater, flat areas in the Oyo state slope map that depict low slope percentage are most capable of containing rainfall, which in turn enhances recharge. However, elevated regions depicting very high slope (20^o – 64^o), will experience high run-off and low infiltration will be observed. Figure 4f shows the slope map of Oyo state.

3.1.7. Land cover layer

The land cover distribution is one of the major factors that influence the occurrence of groundwater in any region. Their effect on availability of groundwater in any area varies based on the land cover type dominant in the area. Different types of land cover act differently on run-off and infiltration capacities. Areas covered with forests tend to reduce infiltration rate while regions that are highly urbanized can impede ground water availability as a result of more surface run off. Lands dominated by agriculture are also good sites for possible ground water occurrence because of loose top soil on the surface. The study area, Oyo state has more of vegetation areas than it has built up areas, rock outcrop and water bodies as shown in Figure 4g. According to Ashaolu *et al.* (2019), vegetation contributes mostly groundwater recharge, followed by built-up and rock outcrop respectively. The land cover distribution also shows that mixed forest has the largest coverage of about 24846.687km^2 (90.9%), agricultural land, 1489.585 km^2 (5.4%), built-up area, 724.807km^2 (2.6%), rock outcrop, 255.410 km^2 (0.9%) and waterbody, 39.482km^2(0.1%).

3.1.8. Rainfall map

The amount of rainfall is one of the major factors that contribute to groundwater recharge. Rainfall distribution alongside slope gradient primarily affects the infiltration rate of runoff water which in turn increases the possibility of groundwater occurrence. In Figure 4h, the mean annual rainfall ranges between 1520 – 1650mm in the western part of the study area as it increases eastwards up to 2170mm. The rainfall distribution was classified into five classes of 130mm interval rainfall. Higher weights were assigned to higher rainfall amounts, suggesting good groundwater potentiality.

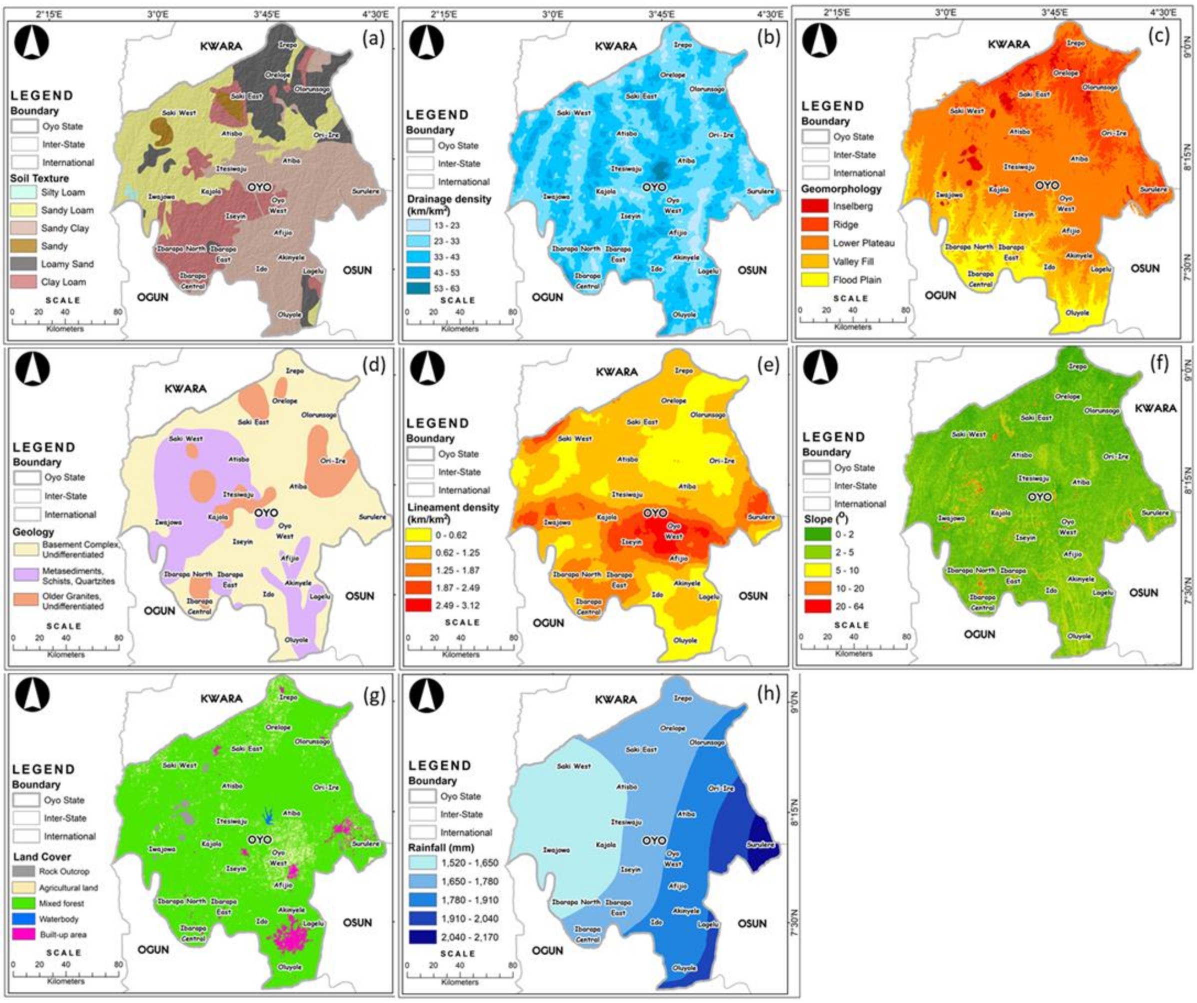

Figure 4: Thematic layers (a) Soil texture (b) Drainage density (c) Geomorphology (d) Geology (e) Lineament density (f) Slope (g) Land cover (h) Rainfall

3.2. Generation of the groundwater potential map

The groundwater prospect zones were evaluated based on the integration of all groundwater influencing thematic layers: geology, lineament density, soil texture, drainage density, rainfall, slope, land cover. Figure 6a and b show the groundwater potential zones of Oyo state as defined using the MIF and AHP methods respectively. The criteria weights of both methods were combined using the Bayes' equation to obtain the optimum result for groundwater potential zone map (Figure 6c). Figure 5 shows high groundwater potential in the western and south-southern parts of the study area (Iwojowa and Oluyole local government areas), moderate groundwater potential outlining the high zone in the western part and the south-southern part (Saki West and Oyo West local government areas), low groundwater potential towards the eastern, south-western and northern parts of the area (Irepo, Surulere and Ori-ire local government area) while the very low groundwater potential towards the northern part of the area (Atiba and Orelope local government areas). Figure 6 reveals high groundwater potential in the western and south-southern parts of the study area (Iwojowa, Lagelu and Atisbo local government areas), moderate groundwater potential outlining the high zone in the western part and the south-southern part (Saki West, Akinyele and Oyo West local government areas), low groundwater potential towards the eastern, south-western and northern parts of the area (Irepo, Surulere and Ori-ire local government area) while the very low groundwater potential towards the central and northern part of the area (Atiba, Akinyele and Orelope local government areas). Figure 6 reveals high groundwater potential in the western and south-southern parts of the study area (Iwojowa and Ibarapa East local government areas), moderate groundwater potential outlining the high zone in the western part and the south-southern part (Saki West, Akinyele and Oyo West local government areas), low groundwater potential towards the eastern, southern and northern parts of the area (Irepo, Surulere, Ido, Iseyin and Ori-ire local government area) while the very low groundwater potential towards the central and northern part of the area (Atiba, Akinyele and east of Orelope local government areas).

By implementing MIF, it is observed in Table 7 that about 11%, 55%, 28% and 6% areas fall under very low (GWPI: 477.00 – 670.25), low (GWPI: 670.25 – 863.50), moderate (GWPI: 863.50 – 1056.75) and high (GWPI: 1056.75 – 1250.00) groundwater potential zones respectively. In case of AHP, it shows that about 7%, 57%, 23% and 13% areas fall under very low (GWPI: 0.12 – 0.17, low (GWPI: 0.17 – 0.22), moderate (GWPI: 0.22 – 0.28) and high (GWPI: 0.28 – 0.33) groundwater potential zones respectively. Both methods show that the low groundwater zone in dominant in the study area. The groundwater potential map from the integrated multi-criteria technique (Bayes' approach) shows that 36%, 34%, 14% and 16% areas fall under very low (GWPI: 0.12 – 0.18), low (GWPI: 0.18 – 0.25), moderate (GWPI: 0.25 – 0.31) and high (GWPI: 0.31 – 0.37) groundwater potential zones respectively. This reveals the dominance of low and very low groundwater potential zones in the area.

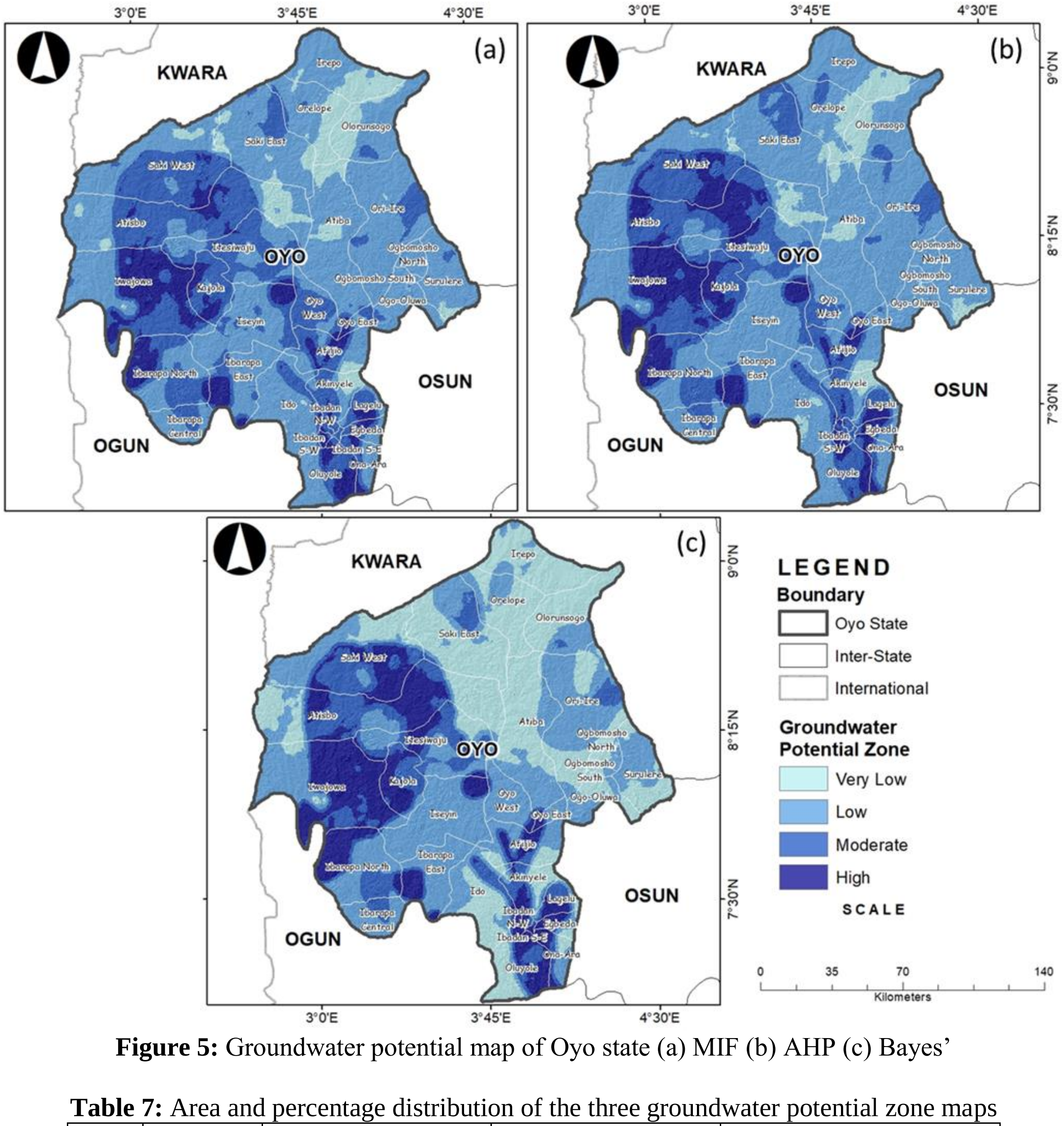

Figure 5: Groundwater potential map of Oyo state (a) MIF (b) AHP (c) Bayes'

Table 7: Area and percentage distribution of the three groundwater potential zone maps

S/N	Zone	MIF		AHP		Bayes' integration approach	
		Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
1	Very low	2905.926	10.616	1824.134	6.664	9894.163	36.147
2	Low	15117.416	55.229	15604.101	57.007	9244.083	33.772
3	Moderate	7718.552	28.198	6254.601	22.850	3759.815	13.736
4	High	1630.330	5.956	3689.387	13.479	4474.164	16.346
	Total	27372.224	100	27372.224	100	27372.224	100

3.3. Validation of results

It is imperative to assess the accuracy of any model after design in preparation for implementation. In this study, the validation of the groundwater potential zonation maps from the MIF, AHP and the Bayes' integration was executed by evaluating the depths and yields from 1425 boreholes distributed across the study area as shown in Table 8 and Figure 7. The shallowest borehole depth is 10m, located in Ibarapa Central LGA (Moderate zone classification) with a maximum yield of 150m^3 and average yield of 57.37m^3. The deepest borehole depth is 130m located in Ogbomosho south LGA (moderate zone classification) with a maximum yield of 150m^3 and average yield of 64,08m^3. The maximum yields of 200m^3 were observed in Akinyele, Atisbo and Egbeda LGA with minimum borehole depths of 24.20m, 30.30m and 30.00m and maximum borehole depths of 72.70m, 45.50 and 45.50m respectively (Figure 7). The high yield boreholes all exist within the high groundwater potential zones (Figure 6). The descriptive statistics of the borehole yield data is shown in Table 9. From the table, it is observed that there are boreholes with zero daily yield based on the minimum daily yield and this could infer that these boreholes are seasonal or no longer functional. The maximum yield appears to be 200m^3/day across the groundwater potential zones except the "moderate" zone from the AHP technique as well as the "very low" and "moderate" zones of the Bayes' integration approach. The average borehole yield in the "high" zone is higher than other zones from all the techniques which validates the delineation of the high zone. Higher yield of an aquifer indicates higher groundwater potential. Areas with high yield in this study are extremely suitable for artificial groundwater recharge. The existence of boreholes is used as representation of the groundwater yield as generally a very large number of boreholes can be found in regions having high groundwater yield (Das and Pardeshi, 2018). The relationship between the borehole yield and the GWPI was established using the ROC curve. The area under the curve (AUC) was calculated to assess the accuracy of the model. The AUC shows 69.4% accuracy when the model is generated using multi-influencing factor technique. This accuracy gives a standard error of 0.039 with the significance value of 0.000 at 99% confidence interval. The null hypothesis which says that the true area is 0.5 is rejected at probability value less than 0.01. The AUC shows 67.6% accuracy when the model is generated using analytic hierarchy process technique. This accuracy gives a standard error of 0.040 with the significance value of 0.000 at 99% confidence interval. The AUC shows 69.0% accuracy when the model is generated using Bayes' integration approach to MIF and AHP. This accuracy gives a standard error of 0.040 with the significance value of 0.000 at 99% confidence interval (Figure 6). The accuracy values (AUC) of the three techniques are considerably good but it is recommended to follow the MIF technique with the highest AUC and standard error values of 69.4% and 0.039 respectively. The MIF follows a less subjective criteria weighting technique. The positive correlation between the average borehole yield and the groundwater potential zonation from Bayes' integration approach also confirms the consistency of the integration above the MIF and AHP techniques.

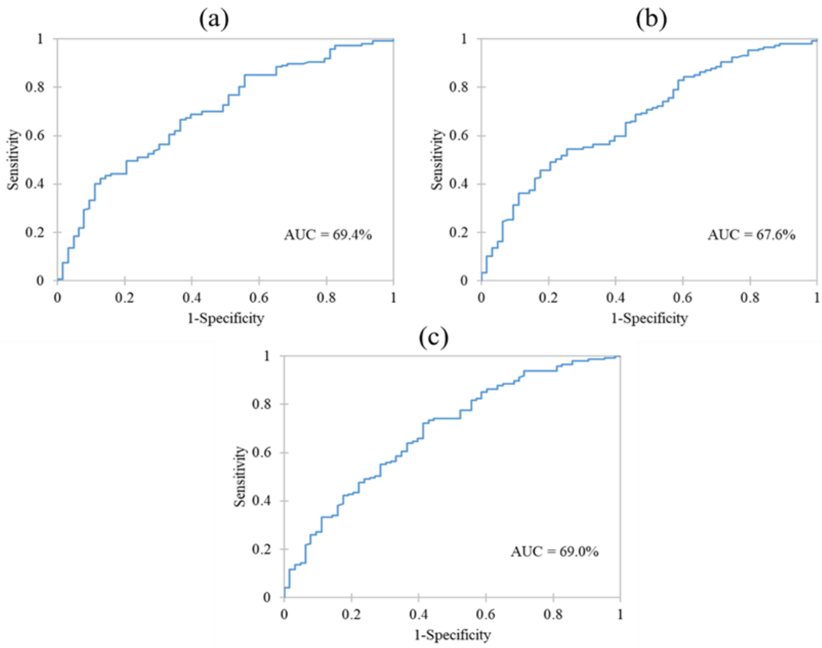

Figure 6: The ROC technique validation result (a) AHP (b) MIF (c) Bayes' integration approach.

Table 8: Borehole statistics and location classification

S/N	LGA	No. of Boreholes	Depth			Yield			Groundwater Classification		
			Min	Max	Average	Min	Max	Average	MIF	AHP	Bayes
1	Afijo	49	27	59	40	35	160	72	Moderate/ High	Moderate/ High	Moderate/ High
2	Akinyele	86	24.2	72.7	44.4	32.14	200	94	Moderate/ High	Moderate/ High	Moderate/ High
3	Atiba	16	27	50.6	38.7	32.14	120	63.3	Very Low/ Low	Very Low/ Low	Very Low/ Low
4	Atisbo	8	30	45	36.75	75	200	120	Moderate/ High	Moderate/ High	Moderate/ High
5	Egbeda	24	30.3	45.5	37.8	35	200	105.65	Moderate/ High	Moderate/ High	Moderate/ High
6	Ibadan North	125	30	56.14	38.23	35	140	93.58	Low/ Moderate	Low/ Moderate	Low/ Moderate
7	Ibadan North East	19	30	52	39.37	40	150	107.11	Low/ Moderate	Low/ Moderate	Low/ Moderate
8	Ibadan North West	17	36	92	50.54	0	180	89.67	Moderate/ High	Moderate/ High	Moderate/ High
9	Ibadan South East	20	30.3	66.7	44.72	0	150	88	Low/ Moderate	Low/ Moderate	Low/ Moderate
10	Ibadan South West	52	27.3	78.2	41.36	0	180	80.74	Moderate/ High	Moderate/ High	Moderate/ High
11	Ibarapa Central	138	10	79.2	41.31	0	150	57.37	Low/ Moderate	Low/ Moderate	Low/ Moderate
12	Ibarapa East	96	27	75	41.35	0	150	52.51	Low/ Moderate	Moderate/ High	Moderate/ High
13	Ibarapa North	93	30	107	42.49	30	62	40.72	Low/ Moderate	Low/ Moderate	Low/ Moderate
14	Iddo	35	30	87	38.9	0	150	67.42	Low/ Moderate	Low/ Moderate	Low/ Moderate
15	Iseyin	83	23	72.7	45.67	0	130	67.34	Low /Moderate	Low	Low
16	Itesiwaju	21	30	60.6	42.17	0	110	64.29	Low/ Moderate	Low/ Moderate	Low/ Moderate
17	Iwajowa	31	30	63.14	49.6	0	150	47	Moderate/ High	Moderate/ High	Moderate/ High
18	Kajola	71	24	60	39	0	150	64.65	Low/ Moderate	Moderate/ High	Moderate/ High
19	Lagelu	31	27	68.4	40.81	0	150	89.52	Moderate/ High	Moderate/ High	Moderate/ High
20	Ogbomosho	42	30	120	44.29	0	150	61.83	Moderate/ High	Moderate/ High	Moderate/ High
21	Ogbomosho South	33	30.3	130	46.66	0	150	64.08	Moderate/ High	Moderate/ High	Moderate/ High
22	Olorunsogo	14	24	60	36.85	0	150	84.52	Low/ moderate	Low/ moderate	Low/ moderate
23	Oluyole	28	30	51	38.15	30	140	67.48	Moderate/ High	Moderate/ High	Moderate/ High
24	Oorelope	24	26.14	60	43.53	30	120	60.09	Moderate	Moderate	Moderate
25	Orire	142	21	66	42.52	0	150	57.41	Moderate/ High	Moderate/ High	Moderate/ High
26	Oyo East	19	24	55	40.94	38.49	120	57.44	Moderate/ Low	Moderate/ Low	Moderate/ Low
27	Oyo West	19	24.2	56.7	43.63	30	150	57.02	Moderate/ Low	Moderate/ Low	Moderate/ Low
28	Saki East	19	27	60	40.33	0	150	85.8	Moderate/ High	Moderate/ High	Low/ Moderate
29	Saki West	45	27	66	42.36	0	195	78.07	Moderate/ High	Moderate/ High	Moderate/ High
30	Surulere	25	32.14	51.51	41.07	32.14	51.51	41.47	Very Low/ Low	Very Low/ Low	Very Low/ Low

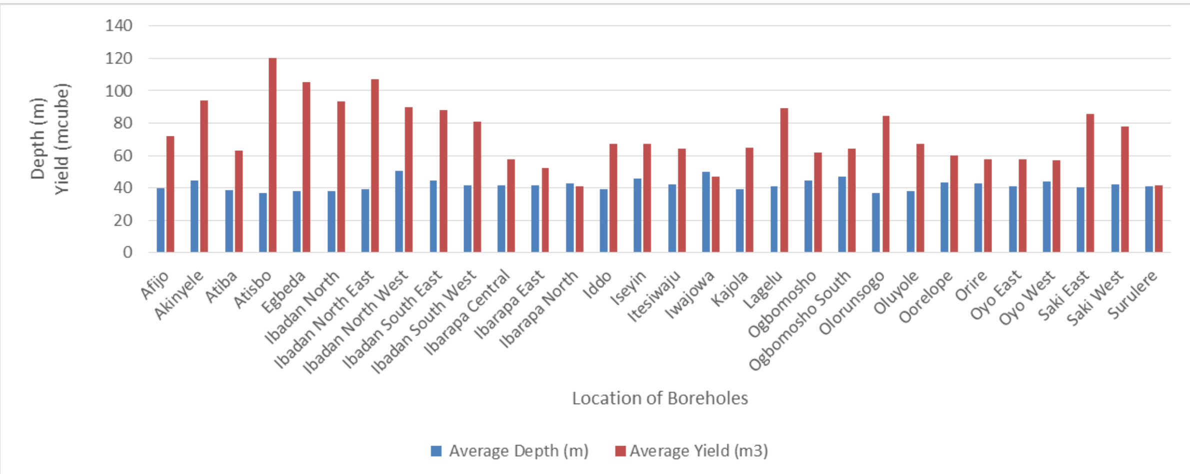

Figure 7: Chart showing Borehole average depth and yields

Table 9: Statistics of borehole distribution across the groundwater potential maps

MIF				
	Very low	Low	Moderate	High
Min (m^3/day)	0	0	0	0
Max (m^3/day)	200	200	200	200
Mean (m^3/day)	87.69	68.20	82.42	109.28
N	8	102	49	19
AHP				
	Very low	Low	Moderate	High
Min (m^3/day)	0	0	0	0
Max (m^3/day)	200	200	187.2	200
Mean (m^3/day)	76.14	73.29	68.02	111.30
N	104	8	48	18
Bayes' integration				
	Very low	Low	Moderate	High
Min (m^3/day)	0	0	0	0
Max (m^3/day)	172.8	200	187.2	200
Mean (m^3/day)	71.94	74.63	76.26	98.86
N	43	83	29	23

3.4. Discussion

In this study, eight groundwater influencing factors have been determined, presented and analysed for the zonation of groundwater potential zones in Oyo state. The integrated groundwater potential zone map (Figure 14) shows that Afijo, Akinyele, Atisbo, Egbeda, Iwajowa, Kajola, Itesiwaju, Ibarapa west, Lagelu, Oluyole and Saki west Local Government Areas (LGAs) are all located in the high groundwater potential zone within the state. While Atiba, Iddo, Iseyin, Ibarapa North, Itesiwaju and Surulere are located in the moderate and low groundwater potential zones. It is revealed that the Oyo west, Oyo east, Saki west and Iseyin local government area are characterized by relatively high lineament density closures. The north-western part and south-eastern flanks have low lineaments densities. The high lineaments density areas correspond to the area with undifferentiated basement complex within the study (Figure 11). This corroborates the opinion of Mabee *et al*. (1994), Edet *et al*. (1994, 1998), Kresic (1995), and Sander *et al.* (1996) that high lineament density correlates with areas where basement rocks outcrop are close to the source. A correlation between the slope map (Figure 6) and the lineament density map (Figure 7) shows that the basement rock outcrop areas with high slope correlates with the zones of high lineament density whereas areas with low lineament frequencies coincide with the low (relatively) flat plains. The slope map shows that the groundwater flows into the various collecting converging centres e.g. Oyo west, Iseyin, Saki west, Asa, Oshogbo north and Ibarapa as shown in the integrated groundwater potential map (Figures 15). Kann and Glenn (2006), Meijerink *et al.* (2007) and Mogaji *et al*. (2011) opined that the principal groundwater flow directions must have structural trends of the geology. The drainage density map (Figure 8) shows that the major rivers and their tributaries will help to recharge the groundwater resource zones within the study area. Based on the AUC values of the three techniques used, it shows that they are significantly reliable for groundwater prediction. These results corroborate the findings of Joshua *et al.* (2017). Previous study (Adagunodo *et al.*, 2013) showed that the nature of the overlying weathered layer determines to a significant extent the yield of the borehole, irrespective of the thickness of the underlying fractured basement column. The study area lies within the tropics with a mean annual rainfall of between 1520mm and 2170mm (Figure 10). The high annual rainfall as shown in Figure 10, favours recharge of basement aquifers through surface precipitation (Olorunfemi and Okhue, 1992; Akinlalu *et al.*, 2017; Akinluyi *et al.*, 2018). The discontinuities nature of basement aquifer reduces the influence of recharges through lateral groundwater flow (Figure 8). The drainage map and slope map show that the rivers and their surface tributaries could be significantly recharged by groundwater flow from the basement aquifer.

The groundwater potential maps from the three techniques reflect the predominance of the geology of the study area which has the highest influence on groundwater recharge potential among the criteria considered. The results are in accordance with the work of Fashae *et al.* (2014) which affirms the variation of borehole yield is based on the geological structure in the south-western states of Nigeria. Their study revealed the highest borehole yield in the meta-sediments, schists and quartzite’s region, followed by granitic rocks and undifferentiated basement complex respectively. The high and moderate groundwater potential zones coincide mainly with the meta-sediments, schists and quartzite’s region. The study area is dominated by the low and very low groundwater potential zones which reflects the dominance of the basement complex. From the estimation of the transmissivity and other properties of the aquifer by Agbede *et al.* (2019) in the study, there is relatively medium yields with low to very low groundwater potentials across the study area due to the underlying rocks. The methods used in this study have proven considerably accurate for the delineation of groundwater potential zones. The Bayes' approach has helped optimise the AHP technique with the MIF and can further be used for the fusion of both objective and subjective criteria weighting techniques in groundwater potential zonation. The integrated approach has also shown some consistency above the MIF and AHP techniques due to the positive correlation between the average borehole yield and the groundwater potential zonation.

4.0. Conclusions

The GIS-based integration of the MIF and AHP using the Bayes' approach has been found to be efficient in the delineation of groundwater potential zones of Oyo state, Nigeria for medium scale modeling of groundwater potential. In this study, space-based earth observation data and vector datasets have been used for the generation of eight thematic layers which influence groundwater potential and occurrence in an area. The factors considered in the delineation of the groundwater potential zones are geology, geomorphology, soil texture, drainage density, lineament density, slope, rainfall and land cover and these were weighted using the MIF, AHP and the Bayes' integration approach. The factors in form of thematic layers were overlaid using the groundwater potential index model in the GIS software environment and three groundwater potential maps were generated. The maps were categorized into four potential zones. The groundwater potential maps from the three techniques were validated using the ROC curve methods. Indication shows that the MIF technique and the Bayes' integration approach have higher accuracy and efficiency of AUC, 69.4% and 69.0% respectively. The Bayes' integration approach further shows better consistency as the average borehole yields across the groundwater potential zones positively correlates. The high potential zone has the highest average borehole yield, followed by the moderate, low and very low.

The study is highly valuable in urban planning as it would guide in future groundwater exploration in an area. This study provides geospatial multi-criteria analysis methods as well as the Bayes' criteria weight integration approach for the delineation of groundwater potential zones. However, this study needs to be replicated in hard terrain regions, semi-arid and arid regions.

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Declarations

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Availability of data and material: The data used in this study are made available in https://drive.google.com/file/d/12Udu_F8y_tRZuV6FQPBwmoyoNtTVrLWe/view?usp=sharing.

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