



Assessment of Groundwater Potential Using Geospatial Technology and Multi-Criteria Evaluation Techniques of Ibadan Metropolis, Oyo State, Nigeria

Babatunde Adebo¹, Olubusola Stephen Ilugbo^{1*}, Henry Otoberise¹, Kazeem Adekunle Bello², Tinuola Christiana Ekanade³, Adeniyi Afolabi Akinfaderin¹, Olayinka Olanike Alada⁴

1. Department of Physics, Lead City University, Ibadan, Oyo State, Nigeria

2. Department of Physics, Bells University of Technology, Ota, Ogun State, Nigeria

3. Department of Surveying and Geo-informatics, Lead City University, Ibadan, Oyo State, Nigeria

4. Department of Geology, Lead City University, Ibadan, Oyo State, Nigeria

*Corresponding author: ilugbo.stephen@lcu.edu.ng

*ORCID ID: 0000 0002 1001 4815h

ABSTRACT

One of the major challenges facing many nations is the lack of reliable access to an adequate water supply, particularly in areas where people struggle to obtain water for domestic use, agriculture, and industry. Because of this, it is essential to develop dependable methods that can accurately identify and allocate groundwater resources. In this study, we used integrated approaches to map the groundwater prospect zones in the Ibadan metropolis of Oyo State, Nigeria. Eleven distinct thematic parameters were formulated to demarcate areas with groundwater potential: slope (S), proximity to the water table (PSWT), geomorphology (G), drainage density (DD), landuse/landcover (LU/LC), elevation (E), lineament density (LD), soil types (ST), landsurface temperature (LST), geology (GE), and rainfall (R). Each of these eleven layers was assigned a weight through Saaty's Analytical Hierarchy Process (AHP) before being combined and processed within the ArcGIS platform to produce a comprehensive groundwater potential zoning model. The groundwater potential map that was produced was divided into five distinct recharge zones. Areas classified as "very high" and "high" potential were found primarily in the southwestern, northwestern, and part of the northern sections of Ibadan. A "moderate" potential zone stretched across the study area from the southeastern corner up to the northeastern side. The southeastern and northeastern portions of the investigated region exhibited "low" and "very low" potential, respectively. Because the underlying bedrock lacks primary porosity, overall groundwater occurrence in the study area tends to be limited. Nonetheless, the zones identified as having very high to moderate potential can serve as valuable guides for individuals, institutions, governments, and policymakers as they plan sustainable groundwater exploration and management strategies.

Keywords: Groundwater Occurrence; MCDA; Geospatial data; Geoenvironmental factors; Multicollinearity; linear Regression.

Evaluación del potencial de aguas subterráneas a través de tecnología geoespacial y técnicas de evaluación multicriterio en Ibadan, estado de Oyo, Nigeria

RESUMEN

Uno de los principales retos que enfrentan muchas naciones es la falta de acceso confiable a un suministro de agua adecuado para uso doméstico, agrícola e industrial. Por ello, es esencial desarrollar métodos confiables para identificar y asignar con precisión los recursos de agua subterránea. En este estudio se emplearon enfoques integrados para cartografiar las zonas prospectivas de aguas subterráneas en Ibadan, estado de Oyo, Nigeria. Se formularon once parámetros temáticos distintos para delimitar las áreas con potencial de aguas subterráneas: pendiente (S), proximidad al nivel freático (PSWT), geomorfología (G), densidad de drenaje (DD), uso/cobertura del suelo (LU/LC), altitud (E), densidad de lineamientos (LD), tipos de suelo (ST), temperatura superficial terrestre (LST), geología (GE) y precipitación (R). Cada una de estas once capas recibió un peso mediante el Proceso Analítico Jerárquico (AHP) de Saaty, antes de ser combinadas y procesadas en ArcGIS para producir un modelo integral de zonificación del potencial de las aguas subterráneas. El mapa de potencial de aguas subterráneas resultante se dividió en cinco zonas de recarga diferenciadas. Las áreas clasificadas como de "potencial muy alto" y "alto" se localizaron principalmente en las secciones suroeste, noroeste y parte del norte de Ibadan. Una zona de "potencial moderado" se extendió a lo largo del área de estudio, desde la esquina sureste hasta el lado noreste. Las porciones sureste y noreste de la región investigada presentaron potenciales "bajo" y "muy bajo", respectivamente. Debido a que el basamento subyacente carece de porosidad primaria, la ocurrencia general de aguas subterráneas en el área de estudio es limitada. No obstante, las zonas identificadas como de potencial de moderado a muy alto pueden servir de guía valiosa para individuos, instituciones, gobiernos y responsables de políticas al planificar estrategias sostenibles de exploración y gestión de las aguas subterráneas.

Palabras clave: Ocurrencia de aguas subterráneas; MCDA; datos geoespaciales; factores geoambientales; multicolinealidad; regresión lineal.

Record

Manuscript received: 29/04/2025

Accepted for publication: 11/12/2025

How to cite this item:

Adebo, B., Ilugbo, O. S., Otoberise, H., Bello, K. A., Ekanade, T. C., Akinfaderin, A. A., & Olayinka, A. O. (2025). Assessment of Groundwater Potential Using Geospatial Technology and Multi-Criteria Evaluation Techniques of Ibadan Metropolis, Oyo State, Nigeria. *Earth Sciences Research Journal*, 2(4), 469-483. <https://doi.org/10.15446/esrj.v29n4.120079>

1. Introduction

Water is essential for human life and for achieving environmentally sustainable development, because it underpins community health, agricultural productivity, and the integrity of natural ecosystems (Adebiyi et al., 2018; Adebo et al., 2018; Abdekareem et al., 2022; Ozegin & Ilugbo, 2024a). At present, about 40% of the global population experiences substantial water related difficulties, a situation that raises serious concerns for global wellbeing (Unesco, 2015). The preservation of both aquatic and terrestrial habitats, as well as the livelihoods of human societies, depends heavily on groundwater reserves (Abdelouhed et al., 2021). Nevertheless, the growing pressure on groundwater resources driven by expanding populations and intensified agricultural activities has resulted in a decline not only in the quantity of water available but also in its quality (Adebo et al., 2019; Abijith et al., 2020; Arunbose et al., 2021; Ozegin et al., 2024a). Therefore, protecting this indispensable resource and systematically identifying where groundwater is most likely to be found are urgent priorities. In 2017 the WHO/UNICEF Joint Monitoring Programme published findings that 2.1 billion people overwhelmingly in SubSaharan Africa still lack access to safe drinking water. Although Nigeria is endowed with considerable water reserves, successive governments have failed to translate that abundance into reliable, safe supplies for the populace (Malik & Shukla, 2019; Bawallah et al., 2020a; Ozegin et al., 2024b). Within Nigeria's water sector the challenges are stark: roughly 39% of the population about 71 million individuals do not receive high quality water, while only around 61% have access to water that meets basic safety standards. These figures underscore the critical need for better management, exploration, and conservation of groundwater resources (Aggarwal et al., 2019; Abu El-Magd et al., 2021; Abu El-Magd et al., 2022). In Ibadan, Oyo State, a major constraint on the reliability of water supply stems from the crystalline composition of the subsurface bedrock, which inherently lacks primary porosity and therefore cannot store water within its matrix. Consequently, groundwater in this area is confined to the fractures and weathered zones of the basement rocks, meaning that substantial aquifers can only develop where the rock mass has undergone extensive fracturing and deep weathering (Bawallah et al., 2019; Mallick et al., 2019; Adebo et al., 2022; Ilugbo et al., 2023a). This geological setting makes irrigation farming especially problematic, as the scarcity of accessible water bodies limits agricultural productivity, and the prevalence of unproductive boreholes has become a pressing issue for the residents of the Ibadan metropolis (Ahirwar et al., 2020; Ahmed et al., 2021). Identifying potential groundwater sources demands a systematic survey of the study area using a range of geophysical methods, a point emphasized by Ozegin and Ilugbo (2024b). In recent years, the combined use of geographic information systems (GIS) and remote sensing (RS) technologies has become a valuable strategy for spatially modeling hydrological phenomena over large, heterogeneous landscapes (Singha et al., 2024). Traditional, field intensive approaches to regional groundwater exploration are typically time consuming and costly, limiting their practicality (Ozegin et al., 2024). In contrast, GIS and RS based techniques provide a more cost effective and efficient framework for assessing and managing groundwater resources (Al-Shabeeb et al., 2018; Senapati & Das, 2021; Akinluyi et al., 2021).

Creating a reliable groundwater potential map requires that the factors controlling groundwater occurrence in a region be identified, examined, and combined within a GIS framework (e.g., Arabameri et al., 2019; Das, 2019; Maity & Mandal, 2019; Abu ElMagd & Embaby, 2021). Key geoenvironmental parameters such as slope, geomorphology, lineament density, drainage density, elevation, and related attributes exert strong temporal and spatial influence on where groundwater accumulates, with the specific effects often shaped by the local topography (e.g., Bawallah et al., 2020b; Roy et al., 2020; Das, 2021; Ozegin et al., 2023; Ilugbo et al., 2023b; Ozegin et al., 2024c). The use of remote sensing (RS) and geographic information systems (GIS) to delineate groundwater potential zones on both local and regional scales has been widely recognized and adopted by many researchers (AlDjazouli et al., 2020; Akinluyi et al., 2021; Allafta et al., 2021; Senapati & Das, 2021; Bawallah et al., 2024; Singha et al., 2024; Ozegin et al., 2024c). By combining multispectral satellite imagery, digital elevation models, and advanced spatial analysis tools, these approaches have substantially increased the precision with which the boundaries of groundwater bearing areas can be identified and mapped (Arshad et al., 2021). Evaluating and mapping groundwater potential in a region involves bringing together all the factors that influence how water moves through the subsurface (Das, 2019). A practical way to do this is by applying multicriteria decision analysis (MCDA) together with the Analytical Hierarchy Process (AHP) (Brunelli, 2015; Das, 2019;

Makonyo & Msabi, 2012; Ozegin et al., 2023; Ilugbo et al., 2023a). The study has four main goals: (1) identify hydrological characteristics that control how much runoff infiltrates and recharges the unconfined aquifers beneath the study area; (2) assign weights and ratings to each thematic layer according to how strongly it affects groundwater potential; (3) integrate the weighted layers in a GIS to spatially delineate and produce a detailed map of groundwater potential zones; and (4) validate the resulting map by comparing it with borehole data to confirm that the predicted sites match actual groundwater occurrences. The main purpose of this research is to create a workable methodological framework that can be used to locate, map, and evaluate groundwater resources in data scarce areas, thereby facilitating the responsible, long term exploitation of these vital supplies and contributing to overall water security sustainability. By establishing such a structure, the study aims to support sustainable groundwater management even where comprehensive hydrological information is unavailable.

2. Study Area

The research focuses on Ibadan, the capital of Oyo State, which was founded in 1829. It is the largest city in Nigeria and the second largest urban centre in Africa after Cairo, Egypt. Geographically, Ibadan lies between latitudes $7^{\circ}14'27.97''N$ and $7^{\circ}14'50.64''N$ and longitudes $5^{\circ}10'5.03''E$ and $5^{\circ}10'27.95''E$; in Universal Transverse Mercator (UTM) terms this translates to northings ranging from 805,100 to 805,900 and eastings from 740,200 to 740,600. Ibadan's landscape is dominated by an extensive road network that links major highways with countless minor streets (Figure 1), and the most conspicuous geological unit in the study area is a suite of crystalline basement rocks. These rocks are largely impermeable, which normally restricts groundwater storage, but long term tectonic activity has weathered and fractured them, producing pathways that allow limited infiltration and recharge (Rahaman, 1976). The intensity of this weathering is shaped by the local geology, the terrain's topography, and the region's climatic conditions (Oladejo et al., 2015). The area where gneiss, migmatite and granite dominate typically exhibits a relatively thin weathered mantle (Rahaman, 1988). Chemical weathering that creates these shallow zones requires both adequate drainage and a surplus of annual rainfall to drive the breakdown of the crystalline rock. Nevertheless, a transitional layer can often be observed between the deeply weathered regolith above and the unaltered bedrock below (Palacky et al., 1981). This intermediate zone reflects the gradual decrease in weathering intensity with depth, influenced by local lithology, topography and climatic conditions. The area where gneiss, migmatite and granite dominate typically exhibits a relatively thin weathered mantle. Chemical weathering that creates these shallow zones requires both adequate drainage and a surplus of annual rainfall to drive the breakdown of the crystalline rock (Odusanya & Amadi, 1989). Nevertheless, a transitional layer can often be observed between the deeply weathered regolith above and the unaltered bedrock below (Odeyemi, 1981; Obaje, 2009). This intermediate zone reflects the gradual decrease in weathering intensity with depth, influenced by local lithology, topography and climatic conditions.

3. Methodology

The remotely sensed data for this study were downloaded from the Global Land Cover Facility's website. They consist of Landsat 8 OLI imagery and a Digital Elevation Model (DEM), which were processed and enhanced to produce a suite of thematic layers: lineament density, drainage density, geomorphology, slope, landuse/landcover, proximity to water bodies, landsurface temperature, and elevation. Rainfall information was obtained as a raster dataset from NASA, while soil and geology maps were provided by the Nigeria Geological Survey Agency (NGSA) (see Table 1). Eleven thematic layers were generated for the analysis: Geomorphology (G), Slope (S), Drainage Density (DD), Lineament Density (LD), LandUse/LandCover (LU/LC), Soil Types (ST), Elevation (E), Land Surface Temperature (LST), Proximity to Surface Water Bodies (PWSB), Rainfall (R), and Geology (GE). The overall analytical framework employed in this study is summarized visually in Figure 2. Each of the eleven thematic layers was put through a rigorous preprocessing and statistical workflow that began with a multicollinearity check. Multicollinearity occurs when two or more predictor variables in a model are linearly dependent, which can obscure the true importance of each factor in explaining groundwater potential (Mehravari et al., 2023; Singha et al., 2024). To evaluate this, we fitted a regression model to the full set of layers and computed the coefficient of determination (R^2) for every pair of variables (Dube et al., 2020).

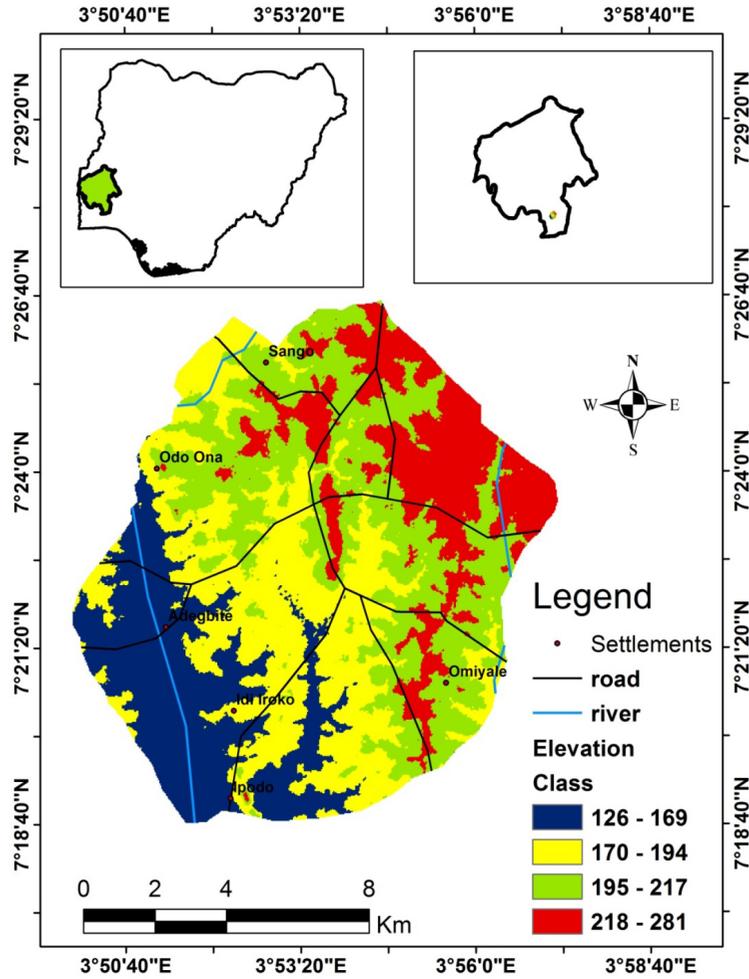


Figure 1. Location Map of the Study Area

Table 1. The source of the geo-environmental variables

S/N	Characteristic	Source
1	Geology, soil type	Nigeria Geological Survey Agency (NGSA)
2	Rainfall	National Aeronautical and Space Administration (NASA)
3	Drainage, Lineament, geomorphology, proximity to surface water bodies, elevation	SRTM DEM, USGS
4	Slopes, Land Surface Temperature land use/landcover	Landsat 8 OLI satellite imagery, USGS
5	Yield of the Boreholes	Ministry of Energy and Water Resources, Oyo State

High R^2 values signaled strong interrelationships, suggesting that some layers were redundant and needed adjustment or removal before the final groundwater prospect analysis. This step ensured that each retained parameter contributed uniquely to the assessment of groundwater prospects (Gyeltshen et al., 2023; Hassaballa & Salih, 2024). To check for multicollinearity, we performed linear regression on each pair of thematic attributes, treating one as the dependent variable and the other as the predictor, and recorded the coefficient of determination (R^2). Variance Inflation Factor (VIF) and Tolerance (TOL) was computed for each parameter, as these are standard metrics for diagnosing multicollinearity (Ozegin et al., 2024). Any attribute with $TOL < 0.10$ and $VIF > 10$ was deemed redundant and excluded from further analysis, as it was considered to be strongly collinear with other variables. The formulas are:

$$TOL_a = 1 - R_a^2 \tag{1}$$

$$VIF_a = 1/TOL_a \text{ i.e. } VIF_a = 1/1 - R_a^2 \tag{2}$$

In the statistical workflow, the tolerance for a particular variable is denoted as TOL_a , and its associated variance inflation factor is expressed as VIF_a . After calculating these two diagnostics for one parameter, the same computation was applied sequentially to each of the remaining variables in the dataset, ensuring that every factor was evaluated for multicollinearity. This systematic repetition produced a complete set of TOL and VIF values for all eleven thematic layers. The resulting metrics were then used to identify and, where necessary, exclude variables that showed excessive collinearity ($TOL < 0.10$ or $VIF > 10$).

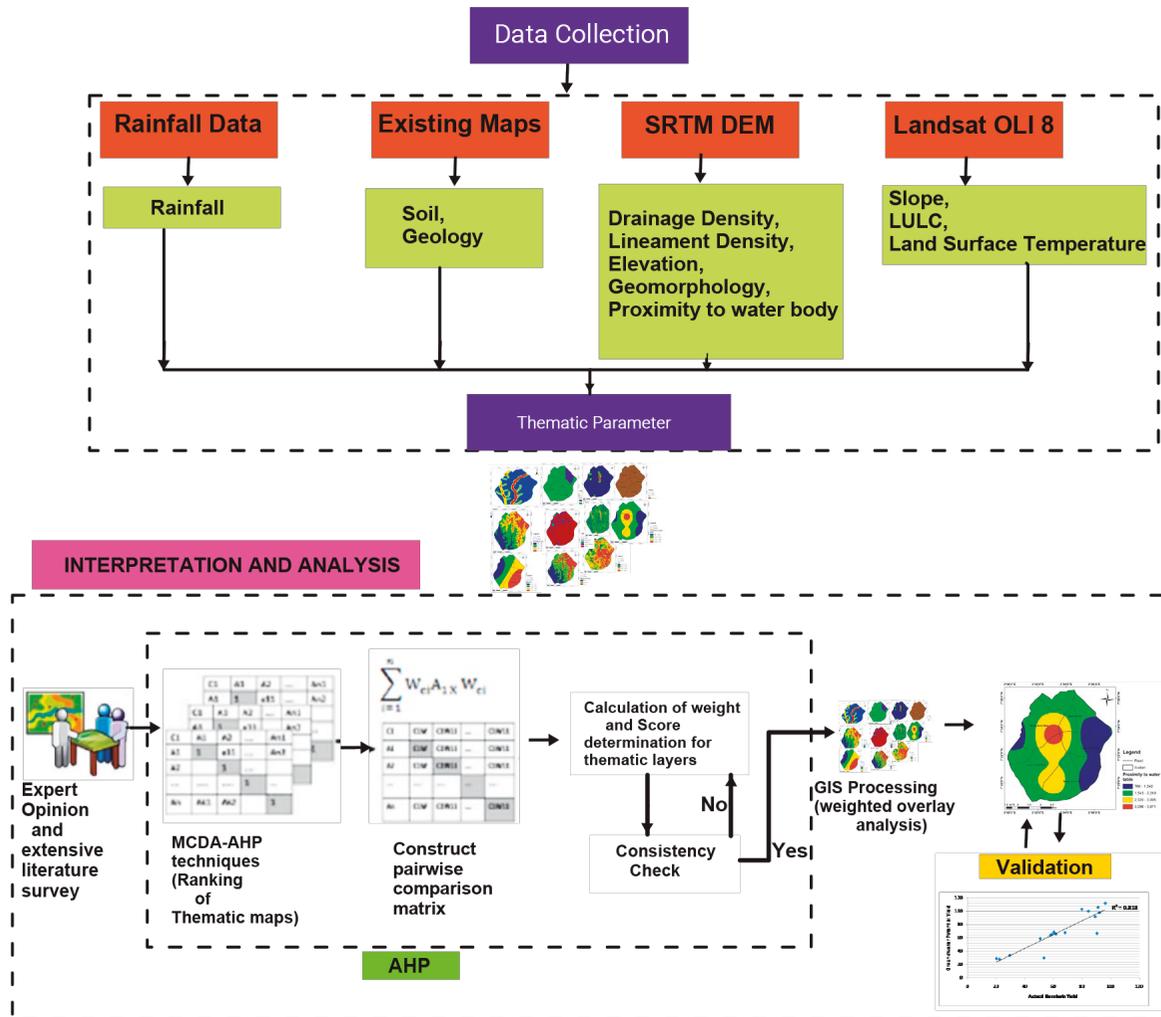


Figure 2. A systematic chart of the approaches depicted in the research

Pairwise Comparison Matrix Analysis

Multicriteria decision analysis (MCDA) using Analytic Hierarchy Process (AHP) is a widely adopted approach for assessing groundwater resource management options and guiding policy decisions (Gyeltshen et al., 2023; Hassaballa & Salih, 2024). In this study, pairwise comparison matrices were built following AHP principles, where each criterion was systematically compared with every other to capture their relative importance, and the resulting comparisons were synthesized to derive weights and rankings for all groundwater potential attributes (Ozegin et al., 2024; Bawallah et al., 2024). In this research the Analytic Hierarchy Process (AHP) was employed to evaluate a comprehensive set of parameters through a pairwise comparison matrix, with the primary aim of calculating each factor's geometric mean and deriving its relative weight. The weighting of every attribute was determined by synthesizing expert judgment, on the ground field experience, and the outcomes of the groundwater prospect analysis (summarized in Table 2), and the resulting weights were checked for internal consistency to ensure they corresponded logically with one another.

Calculating MCDA

The study employed a multi criteria decision analysis (MCDA) framework built on the Analytic Hierarchy Process (AHP) to assign a quantitative weight to each of the groundwater potential variables (Khosravi et al., 2018; Lee et al., 2020). By structuring the problem hierarchically and performing pairwise comparisons, the AHP method makes it possible to translate expert judgments

about the relative importance of each map attribute into numerical scores that reflect how strongly the attribute influences groundwater occurrence (Keenan & Jankowski, 2019; Karimi-Rizvandi et al., 2021; Ozegin et al., 2024; Bawallah et al., 2024). After constructing the comparison matrix, the eigenvectors associated with its principal eigenvalue were calculated; these eigenvectors provide the optimal set of weights for the individual indices, ensuring that the final weighting scheme is mathematically consistent and grounded in the expert assessments. First, the values in each column of the pairwise comparison matrix were added together to obtain column sums. Each entry in the matrix was then divided by its column total, producing a normalized (standardized) matrix. After that, the average of the entries in every row of this normalized matrix was calculated (the results are shown in Table 3). These row averages provide a first order estimate of the relative weights of the parameters being compared. The weights assigned to each factor are obtained by taking the eigenvectors that correspond to the largest (principal) eigenvalue of the reciprocal comparison matrix and then normalizing those eigenvectors so that they sum to one. Because the principal eigenvector captures the dominant pattern of pairwise judgments, this approach minimizes the impact of any unevenness or inconsistencies in the ratio judgments essentially filtering out noise and providing a stable, mathematically sound set of weights. Table 4 presents the dominant recharge mechanisms and the key geological parameters that characterize the study area, together with the normalized eigenvector values that represent the relative importance of each criterion. These numbers reflect how strongly each factor influences groundwater potential after the AHP based consolidation.

Table 2. paired-by-paired matrix for groundwater recharge

		A	B	C	D	E	F	G	H	I	J	K
R	A	1.00	3.00	3.00	3.00	3.00	3.00	5.00	5.00	5.00	5.00	5.00
LID	B	0.33	1.00	3.00	3.00	3.00	3.00	3.00	3.00	5.00	5.00	5.00
G	C	0.33	0.33	1.00	3.00	3.00	3.00	3.00	3.00	5.00	5.00	5.00
S	D	0.33	0.33	0.33	1.00	3.00	3.00	3.00	3.00	5.00	5.00	5.00
DD	E	0.33	0.33	0.33	0.33	1.00	3.00	3.00	3.00	3.00	5.00	5.00
ST	F	0.33	0.33	0.33	0.33	0.33	1.00	3.00	3.00	3.00	5.00	5.00
LU/LC	G	0.20	0.33	0.33	0.33	0.33	0.33	1.00	3.00	3.00	5.00	5.00
PSWB	H	0.20	0.33	0.33	0.33	0.33	0.33	0.33	1.00	3.00	3.00	5.00
GE	I	0.20	0.20	0.20	0.20	0.33	0.33	0.33	0.33	1.00	3.00	5.00
E	J	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.33	1.00	3.00
LST	K	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	1.00
TOTAL		3.67	6.60	9.27	11.93	14.73	17.40	22.07	24.73	33.53	42.20	49.00

Table 3. Determining Groundwater Recharge Criteria Weight

	R (j=1)	LID (j=2)	G (j=3)	S (j=4)	DD (j=5)	ST (j=6)	LU/LC (j=7)	PSWB (j=8)	GE (j=9)	E (j=10)	LST (j=11)	ΣWij
R (i=1)	0.270	0.450	0.320	0.250	0.200	0.200	0.230	0.200	0.150	0.120	0.100	2.490
LID (i=2)	0.090	0.150	0.320	0.250	0.200	0.200	0.140	0.120	0.150	0.120	0.100	1.840
G (i=3)	0.090	0.050	0.110	0.250	0.200	0.200	0.140	0.120	0.150	0.120	0.100	1.530
S (i=4)	0.090	0.050	0.040	0.080	0.200	0.200	0.140	0.120	0.150	0.120	0.100	1.290
DD (i=5)	0.090	0.050	0.040	0.030	0.070	0.200	0.140	0.120	0.090	0.120	0.100	1.050
ST (i=6)	0.090	0.050	0.040	0.030	0.020	0.060	0.140	0.120	0.090	0.120	0.100	0.860
LU/LC (i=7)	0.050	0.050	0.040	0.030	0.020	0.020	0.050	0.120	0.090	0.120	0.100	0.690
PSWB (i=8)	0.050	0.050	0.040	0.030	0.020	0.020	0.020	0.120	0.090	0.070	0.100	0.610
GE (i=9)	0.050	0.030	0.020	0.020	0.020	0.020	0.020	0.010	0.030	0.070	0.100	0.390
E (i=10)	0.050	0.030	0.020	0.020	0.010	0.010	0.010	0.010	0.010	0.020	0.060	0.250
LST (i=11)	0.050	0.030	0.020	0.020	0.010	0.010	0.010	0.010	0.010	0.010	0.020	0.200
												ΣWij/Σj = 1

Pairwise Matrix Consistency Analysis

The eleven parameters that emerged from the analysis were each given a quantitative weight through the Analytical Hierarchy Process (AHP), a well established multicriteria decision making method that translates expert judgments about the relative importance of factors into a consistent numerical scale (Adebo et al., 2022; Roy et al., 2020; Mehra et al., 2023). In applying AHP, the study first constructed a series of pairwise comparison matrices in which each geoenvironmental parameter was evaluated against every other according to its perceived influence on groundwater storage. The eigenvalues derived from these matrices were then normalized to produce a set of weights that reflect the relative significance of the parameters, with higher weights indicating greater contribution to potential groundwater accumulation (Maity & Mandal, 2019; Mehra et al., 2023). Because the pairwise comparisons of the eleven parameters relied on expert opinion, they are inherently subjective and can introduce bias or logical inconsistencies. To ensure that these judgments are sufficiently reliable, the analysis included a formal consistency check of the comparison matrix. This check involves computing the Consistency Ratio (CR), which is defined as the ratio of the Consistency Index (CI) derived from the matrix's principal eigenvalue to the Random Index (RI) for the same matrix size; a CR below the recommended threshold confirms that the pairwise judgments are acceptably consistent, a key advantage of the Analytic Hierarchy

Process. A perfect level of consistency is attained when the consistency measure equals the total number of criteria (n). In practice, the pairwise judgments are regarded as acceptable when the Consistency Ratio (CR) is ≤ 0.10 (10%); only then can the resulting criteria weights be confidently used. Equation 5 was used to compute the CR, the matrix's consistency improves as the principal eigenvalue λ_{max} approaches the value of n.

- i. The pairwise matrix (A) of each column was multiply by the corresponding weight, W.

$$Aw = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{pmatrix} \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix} = \begin{pmatrix} nw \\ \vdots \\ nw \end{pmatrix} = nw \tag{3}$$

- ii. Determine the largest Eigen value, λ_{max} for matrix A;

$$\lambda_{max} = \frac{1}{n} \sum (\sum ni = \frac{1 \text{ row entry of } Aw}{i \text{th entry of row}}) \tag{4}$$

iii. Determine the consistency index (CI);

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

where n = number of criteria used

iv. Lastly, Determine the consistency ratio, CR,

$$CR = \frac{CI}{RI} \tag{6}$$

where RI, the random index, is obtained from Table 4.

Table 4. RI value (Alonso and Lamata, 2006)

N	RI
1	0
2	0
3	0.5245
4	0.8815
5	1.1086
6	1.2479
7	1.3417
8	1.4056
9	1.4499
10	1.4854
11	1.5141
12	1.5365

The comparison matrix is perfectly consistent only when both the Consistency Index (CI) and the Random Index (RI) are zero, which means there is no deviation from perfect proportionality among the judgments. According to Saaty (1980), a set of judgments is considered acceptable when the Consistency Ratio (CR) is less than 0.1 (i.e., 10%); in that case the weights derived from the matrix can be used with confidence. If the CR exceeds 0.1, the matrix is deemed inconsistent and the pairwise comparisons must be reconstructed and reevaluated (Saaty, 1980).

where $\lambda_{max} = 11.2301$,

$$CI = \frac{11.2301 - 11}{11 - 1}$$

$$CI = \frac{0.2301}{10}$$

$$CI = 0.0230$$

For n = 11, RI = 1.5141 (Table 4); hence

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

$$CR = \frac{0.0230}{1.5141} = 0.0152 \text{ (1.52\%)}$$

In this study the calculated CR is below 0.1, indicating that the weighting scheme is consistent, so the weights reported in Table 5 are valid for subsequent analysis. The weights that were calculated and presented in Table 5 are acceptable for further analysis because the Consistency Ratio (CR) obtained in this study is below the threshold of 0.1 (10%), confirming that the weighting scheme is sufficiently consistent (Rejith et al., 2019; Moodley et al., 2022; Rather et al., 2022; Moharir et al., 2023). Eleven identified thematic variables namely rainfall, lineament density, geomorphology, slope, drainage density, soil type, land use/land cover, proximity to surface water bodies, geology, elevation,

and land surface temperature were combined within the ArcGIS 10.5 platform to generate a groundwater potential map of the study area (Adebo et al., 2019; Alarifi et al., 2022; Ozezin et al., 2023; Ilugbo et al., 2023a; Ozezin & Ilugbo, 2024). The equation for the groundwater potential zone (GWPZ) is as follows:

$$GWPZ = RFW_iRFr_i + Gw_iGr_i + Sw_iSr_i + LDw_iLDr_i + LSTw_iLSTr_i + DDw_iDDr_i + Ew_iEr_i + LU/LCw_iLU/LCr_i + PSWBw_iPSWBr_i + GEw_iGEr_i + STw_iSTr_i \tag{7}$$

Where Geomorphology (G), Slope (S), Drainage Density (DD), Lineament Density (LD), Land Use/Land Cover (LU/LC), soil types (ST), elevation (E), Land Surface Temperature (LST), proximity to water bodies (PSWB), rainfall (R), and Geology (GE) are the parameters used in the analysis.

To evaluate the accuracy of the groundwater potential model, sixteen boreholes distributed throughout the study area was acquired from the Oyo State Ministry of Groundwater and Energy Resources. Each borehole entry was then compared against the corresponding modeled potential value, and the relationship between the observed borehole yields and the predicted potentials was examined through a linear regression analysis. This statistical verification confirmed how well the modeled outputs matched the actual field measurements, thereby validating the groundwater potential map.

Table 5. Assessments of probability for various variable categories

Parameter	Feature/ Class	Unit	Rank	Normalized Weight (W)	Contribution to Groundwater Recharge
Rainfall	1511 – 1517	mm/ year	1	2.49	Very Low Low Moderate High
	1518 - 1522		2		
	1523-1526		3		
	1527-1531		4		
Lineament Density	0 – 761	Km/ Km ²	2	1.84	Low Moderate High
	762 - 3,713		3		
	3,714 – 7,761		4		
Geomorphology	River	-	4	1.53	High Low Very low
	Lowland		2		
	Hill		1		
Slope	0 – 2.8	Degree (°)	4	1.29	High Moderate Low Very low
	2.81 – 5.15		3		
	5.16 – 9.19		2		
	9.2-28.56		1		
Drainage Density	0 -2,0.67	Km/ Km ²	1	1.05	Very Low Low Moderate High
	2,068 – 9.366		2		
	9,367 – 18,246		3		
	18,247 – 31,019		4		
Soil Type	Loamy clay		2	0.86	Very Low
Landuse/ Landcover	National park	-	2	0.69	Low Moderate Low Low Low
	Vegetation		3		
	Built-up		2		
	Bare land		2		
Proximity to Surface Water Bodies	766 – 1542	m	1	0.61	Very Low Low Moderate High
	1543 – 2319		2		
	2322 – 3095		3		
	3096 – 3871		4		
Geology	Basement complex with pebble bids. quartzits schist Complex.	-	2	0.39	Low Moderate
			3		

(Continue)

Parameter	Feature/ Class	Unit	Rank	Normalized Weight (W)	Contribution to Groundwater Recharge
Elevation	126 – 169	m	4	0.25	High Moderate Low Very Low
	170 – 194		3		
	195 – 217		2		
	218 – 281		1		
Land Surface Temperature	29.82 – 30.26	°C	4	0.20	High Moderate Low Very Low
	30.27 – 30.46		3		
	30.47 – 30.59		4		
	30.6 – 30.85		1		

Results and Discussion

The factors impacting groundwater multicollinearity determination

When the tolerance (TOL) values exceed 0.1 and the variance inflation factor (VIF) values remain below 10, the level of multicollinearity among the predictor variables is considered acceptable that is, there is no significant interdependence that would distort the statistical estimates (Abijith et al., 2020; Abu El-Magd et al., 2022; Ozegin et al., 2024a). In the present analysis, every factor that influences groundwater potential exhibited TOL and VIF figures that fell well within these recommended limits. Consequently, the multicollinearity diagnostics confirmed that the predictor set is essentially free of redundancy, which in turn simplifies the validation of the groundwater occurrence model and strengthens confidence in the resulting predictions. The tolerance (TOL) and variance inflation factor (VIF) statistics for the selected variables spanned 0.540–0.890 and 1.30–1.852, respectively (Table 6). Lineament density showed the highest tolerance at 0.890, while proximity to surface water bodies (PWSB) recorded the maximum VIF of 2.852.

Table 6. Collinearity check statistics of the groundwater potential variables

Parameters	TOL	VIF
RF	0.885	1.130
LD	0.890	1.124
G	0.814	1.229
S	0.616	1.623
DD	0.826	1.211
ST	0.829	1.206
LU/LC	0.645	1.550
PWSB	0.542	1.845
GE	0.815	1.227
C	0.540	1.852
E	0.636	1.572

Parameters Influencing Groundwater Potential

Drainage Density and Groundwater Potential

Drainage density refers to the total length of streams per unit area. High drainage density indicates a high runoff rate, low infiltration rate, and potentially low groundwater recharge, leading to lower groundwater potential (Abijith et al., 2020; Abu El-Magd et al., 2022; Bawallah et al., 2024). Low drainage density suggests a low runoff rate, high infiltration rate, and potentially high groundwater recharge, leading to higher groundwater potential. In areas with high drainage density, groundwater potential is often lower due to increased surface runoff and reduced infiltration. Conversely, areas with low drainage density tend to have higher groundwater potential due to increased infiltration and recharge. The drainage density analysis for the study area reveals values that stretch from 0 to 31,019 km/km² (Figure 3a). To interpret these data, the

values were partitioned into four distinct classes: very low, low, moderate, and high drainage density. The very low class occupies the range 18,247–31,019 km/km², and the low class spans 9,367–18,246 km/km². Areas with very low and low categories are characterized by gentle relief, dense vegetation, and soils that are both highly permeable and coarse textured. In contrast, the portions of the study area with moderate drainage density class (2,068–9,366 km/km²) and the high drainage density class (0–2,067 km/km²) are typified by fine textured, relatively impermeable soil horizons, a rugged topography with pronounced relief, and a comparatively sparse vegetative cover. These characteristics promote rapid surface runoff and limit the amount of rainwater that can infiltrate into the underlying aquifer. Consequently, drainage density serves as a key control on the balance between runoff and groundwater recharge, directly influencing how much precipitation ultimately contributes to subsurface storage (Ahmed et al., 2020; Arunbose et al., 2021). In regions where the drainage network is densely developed, the subsurface is often dominated by fine textured, low permeability sediments that inhibit water from infiltrating, so a larger proportion of precipitation runs off as surface flow rather than recharging the aquifer; consequently, these areas tend to exhibit reduced groundwater storage. In contrast, zones characterized by a sparse drainage pattern are usually underlain by coarser, more permeable materials that allow greater infiltration and retention of rainwater, leading to higher aquifer replenishment and larger groundwater reserves. This inverse relationship between drainage density and groundwater storage is therefore driven primarily by the contrasting hydraulic properties of the underlying geologic materials (Baghel et al., 2023).

Elevation and Groundwater Potential

Elevation can significantly influence groundwater potential. Higher elevations were associated with lower groundwater potential due to increased runoff and reduced infiltration and thicker unsaturated zones, increasing travel time for recharge (Baghel et al., 2023; Bawallah et al., 2024). Lower elevations were associated with higher groundwater potential due to increased accumulation of water and shallower water tables and increased recharge (Moharir et al., 2023). However, elevation's impact can be complex and site-specific, depending on factors like topography, geology, and climate (Das, 2019, 2021; Ilugbo et al., 2023a; Ozegin et al., 2024a; 2024b). Figure 3b presents the elevation map of the study area, a factor that strongly governs groundwater recharge by determining how surface water runs off and where it can infiltrate. The elevations have been divided into four classes: very low (126–169 m), low (170–194 m), moderate (195–217 m), and high (218–281 m). In the portions of the study area where elevation is very low (126/169 m) and low (170/194 m), the terrain is relatively flat, which reduces the hydraulic gradient and slows surface water movement; as a result, rainwater remains on the land surface longer, giving it more time to infiltrate through the permeable soils and thereby increasing groundwater recharge and storage. Conversely, in zones of moderate (195/217 m) and high (218/281 m) elevation the steeper slopes create a greater hydraulic gradient that speeds up runoff, limiting the duration that water is in contact with the ground and consequently reducing infiltration, recharge, and overall groundwater accumulation.

Geology and Groundwater Potential

Figure 3c presents the geological map of the study area, highlighting the spatial distribution of the various lithologic units. The pebbled deposits, which are composed of fragmented and heavily weathered rock fragments, are characterized by a network of fractures that permit some water movement; however, the overall storage capacity of these beds is only moderate to low because the interconnected voids are limited and the material's permeability does not allow large volumes of water to be retained. In contrast, the quartzites schist complex tends to hold a larger proportion of groundwater because the quartzite component is essentially impermeable; its dense, low porosity matrix restricts the movement of water through the rock mass, effectively creating a barrier that forces infiltrating precipitation to be stored in the fractures, joints, and weathered zones of the surrounding schist rather than draining away quickly (Baghel et al., 2023; Bawallah et al., 2024). This combination of a relatively impervious quartzite backbone with a more fractured schist envelope promotes longer residence times for water within the formation, enhancing high groundwater storage in that portion of the study area.

Geomorphology and Groundwater Potential

Geomorphology significantly influences groundwater potential by shaping the landscape's ability to capture, store, and transmit water (Das, 2019, 2021; Ilugbo et al., 2023a; Ozegin et al., 2024a; 2024b). Figure 3d presents the geomorphology map of the study area, which divides the terrain into three primary landform categories; river, lowland, and hills. The hill zones are characterized by steep slopes that accelerate surface runoff and limit water infiltration, so they contribute relatively little to groundwater recharge and exhibit low accumulation of subsurface water. In contrast, river corridors act as conduits that allow surface water to move quickly into the underlying sediments, boosting recharge rates and giving those zones a moderate to high groundwater potential. Lowland areas, with their gentle gradients and highly permeable soils, capture and retain large amounts of infiltrating water, leading to substantial groundwater storage that supports both human extraction and the water needs of vegetation (Moodley et al., 2022).

Lineament Density and Groundwater Potential

Lineament density is a measure of how many linear features like fractures, faults, and joints are present in an area (Ilugbo et al., 2023b). These features can significantly impact groundwater flow and storage. Areas with high lineament density have increased secondary porosity, enhanced permeability, and improved groundwater recharge (Das, 2021; Ilugbo et al., 2023a; Ozegin et al., 2024b). Lineament density is a key factor in groundwater potential mapping, helping identify areas with higher potential for groundwater accumulation (Makonyo & Msabi, 2021; Rather et al., 2022). Figure 4a presents a lineament density map that visualizes the spatial distribution of fractures, faults, and other linear geological features across the study area; because these structures act as conduits for water, their density offers valuable clues about how groundwater is stored in the subsurface and how it moves through the rock matrix. By classifying the mapped lineaments into distinct categories, the map delineates three separate zones that correspond to low, moderate, and high groundwater potential areas, to pinpoint regions where the subsurface is most likely to accumulate and transmit water. The lineament density indicating high (3714–7761 km/km²) or moderate (762–3713 km/km²), the abundance of fractures creates pathways that encourage infiltration and channel water through the subsurface, leading to medium to high groundwater storage and retention. In the extensive areas where lineament density is low (0–761 km/km²), the sparse fracture network limits water entry and movement, resulting in reduced infiltration, slower groundwater flow, and consequently lower accumulation of subsurface water.

Land Surface Temperature and Groundwater Potential

Land surface temperature (LST) is another important factor influencing groundwater potential (Gyeltshen et al., 2023). LST helps identify potential groundwater targets, especially in arid and semi-arid regions (Makonyo & Msabi, 2021; Rather et al., 2022). Figure 4b displays the land surface temperature (LST) map for the study area, showing surface temperatures that vary from a minimum of 29.82°C to a maximum of 30.85°C. The LST values are grouped into four distinct classes: the high varies from 30.6°C–30.85°C, the moderate spans from 30.47°C–30.59°C, the low ranges from 30.27°C–30.46°C, and the very low ranges from 29.82°C–30.26°C. This classification highlights the spatial pattern of thermal variation across the landscape. Higher land surface temperatures boost the energy available for evaporation, causing more water to leave the soil and shallow subsurface as vapor rather than infiltrating downward. This intensified evaporative loss dries the near surface materials, diminishes the amount of water that can percolate into the underlying aquifers, and ultimately curtails the replenishment of groundwater reserves, leading to a reduction in overall groundwater accumulation.

Landuse/Landcover and Groundwater Potential

Land use and land cover (LULC) significantly influence groundwater potential. Different LULC types affect infiltration, runoff, and recharge rates (Gyeltshen et al., 2023). Landuse/landcover map was classified into vegetation, water bodies, agriculture, and builtup (Figure 4c). In particular,

zones covered by dense natural vegetation and protected parklands exhibit the highest groundwater potential because canopy interception and leaf litter reduce runoff, allowing more water to percolate into the soil. Deep root systems create macropores that increase soil permeability and retain moisture for longer periods. Shaded ground and higher humidity beneath forest canopies limit evaporative losses, promoting deeper recharge. These combined effects make vegetation and national park areas the most favorable locations for groundwater occurrence. Builtup zones and bareland/outcrop areas offer far less opportunity for groundwater accumulation because the surfaces are largely impermeable. Paved streets, concrete buildings, and compacted soils prevent rainwater from soaking into the ground, while the lack of vegetation eliminates the root mediated pathways that would otherwise channel water downward (Malik & Shukla, 2019). As a result, most of the precipitation quickly runs off into drainage networks, leaving little to percolate into the subsurface. The combination of reduced infiltration and accelerated runoff means these landscapes typically support only modest, if any, groundwater reserves.

Rainfall and Groundwater Potential

Rainfall is a crucial factor in groundwater recharge. Areas with high rainfall rates tend to have higher groundwater potential, as more water is available to infiltrate the soil and recharge aquifers (Mallick et al., 2019; Ilugbo et al., 2023a; Ozegin et al., 2024b). Conversely, areas with low rainfall may have limited groundwater recharge, making them more vulnerable to over extraction and decreased water tables (Mehravara et al., 2023). Figure 4d presents the rainfall map, which serves as a primary indicator of groundwater storage and recharge potential. In the study area, annual precipitation spans from 849 mm to 1,692 mm and is partitioned into four classes: very low (1,511–1,517 mm), low (1,518–1,522 mm), moderate (1,523–1,526 mm), and high (1,527–1,531 mm). The relationship between groundwater recharge and rainfall intensity is pronounced: as the amount of precipitation falling over a given period increases, the volume of water that can infiltrate the soil and percolate down to the water table also rises (Hassaballa & Salih, 2024). Consequently, areas that receive higher rainfall typically exhibit larger recharge rates and, over time, develop more substantial groundwater reserves than regions with lower precipitation.

Slope Analysis and Groundwater Potential

Slope analysis is a crucial factor in assessing groundwater potential. Slope angle affects runoff and infiltration rates and influencing recharge. Steep slopes (high gradients) increased runoff, reduced infiltration and low groundwater potential (Hassaballa & Salih, 2024). Gentle slopes (moderate gradients) balanced runoff and infiltration and medium groundwater potential (Bawallah et al., 2024; Ozegin et al., 2024c). Flat areas (low gradients) reduced runoff, increased infiltration, and high groundwater potential. Figure 5a displays the slope map of the study area, showing that ground inclination varies from 0° to 28.56°. The slopes are divided into four gradient classes: high (9.2°–28.56°), moderate (5.16°–9.19°), low (2.81°–5.15°), and very low (0°–2.8°). In regions where the land surface is steep characterized by high gradients rainfall tends to flow quickly downhill as surface runoff, leaving little time for water to infiltrate the soil and recharge the underlying aquifer, which consequently limits groundwater potential. In contrast, areas with moderate slopes allow a portion of the precipitation to linger on the surface long enough to percolate into the subsurface, resulting in a moderate level of groundwater availability. Low gradient and very low gradient zones with slopes ranging from 0° to 2.8° and from 2.81° to 5.15° tend to promote the slow movement of rainwater across the land surface. Because the terrain is relatively flat, water lingers long enough to percolate into the soil, where it can travel downward and recharge the underlying aquifers. The gentle topography also reduces the velocity of runoff, allowing more precipitation to be stored within the pore spaces of the subsurface materials (Ozegin & Ilugbo 2024b). As a result, these areas typically show higher rates of infiltration and longer retention times within the aquifer system, which translates into a greater likelihood of finding exploitable groundwater resources. In other words, the flatter the landscape, the more favorable it is for groundwater accumulation and prospecting.

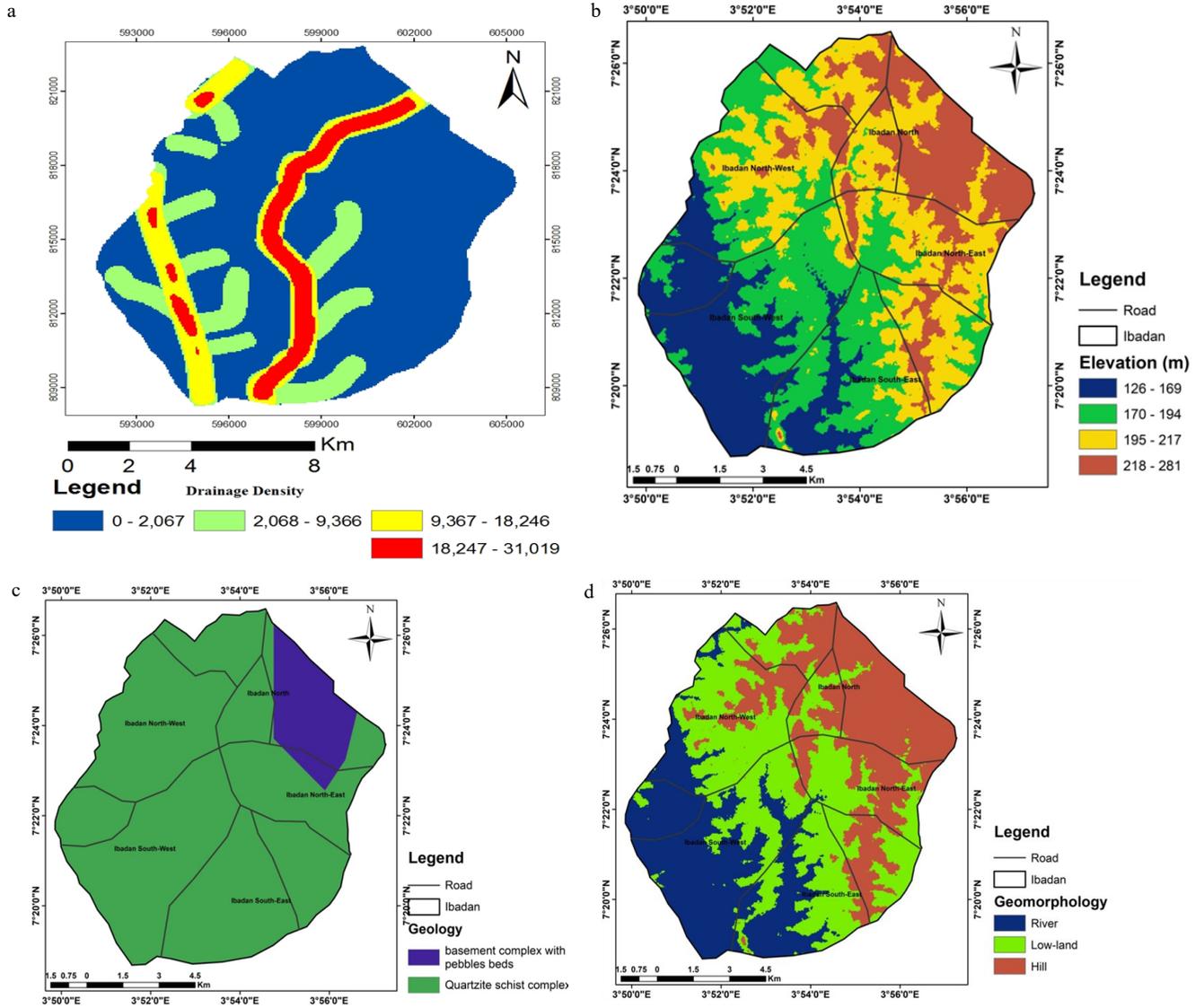


Figure 3. (a) Drainage density (b) Elevation (c) Geology (d) Geomorphology

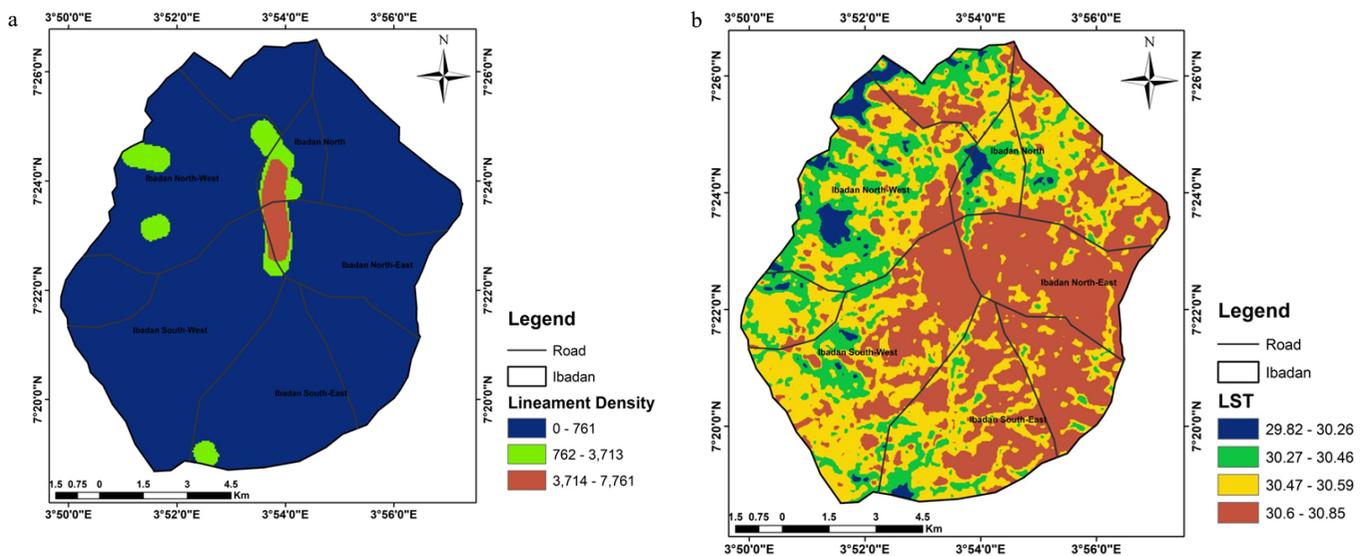


Figure 4. (a) Lineament density (b) Land surface temperature (c) Landuse/landcover (d) Rainfall

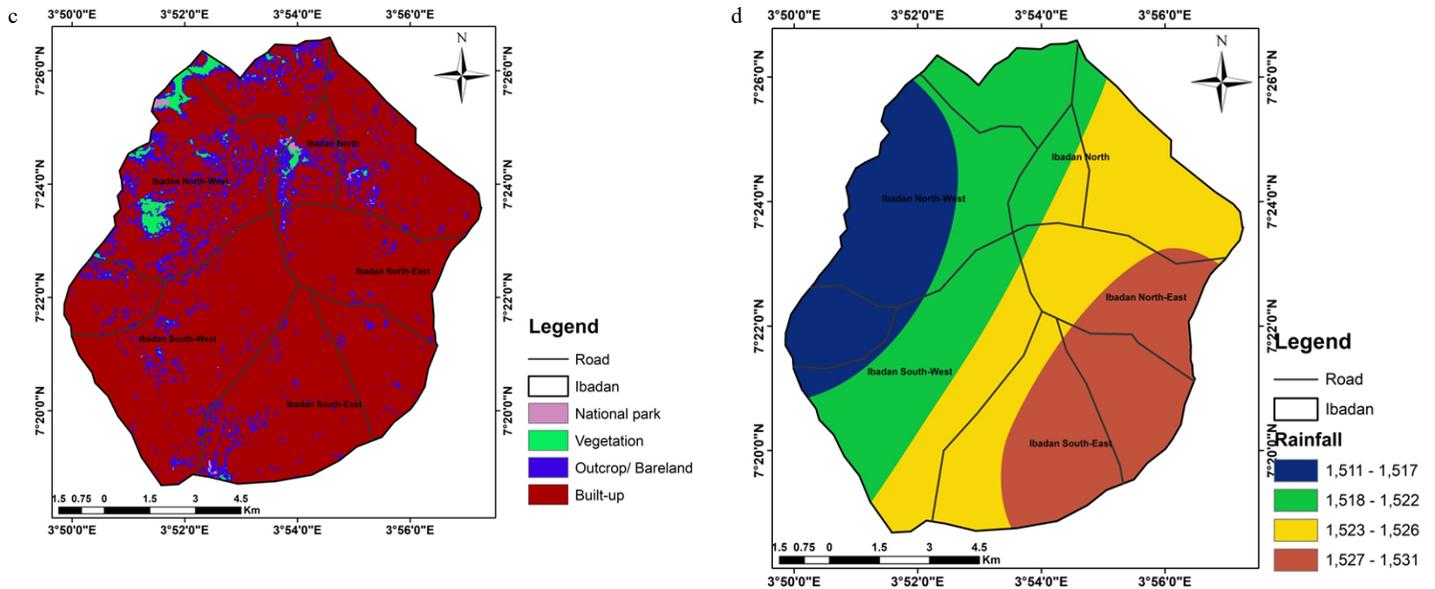


Figure 4. (a) Lineament density (b) Land surface temperature (c) Landuse/landcover (d) Rainfall

Soil Type and Groundwater Storage

Soil type significantly influences groundwater potential. Different soil textures and structures affect infiltration, permeability, and water-holding capacity, impacting recharge rates (Ozegin and Ilugbo 2024a). Soil analysis helps identify areas with suitable conditions for groundwater accumulation (Roy et al., 2020; Senapati & Das, 2021). Figure 5b shows that the loamy soils in the study area have an intermediate capacity to store and release water, giving them a relatively modest groundwater potential. While loam is highly permeable, its comparatively low porosity lets water pass through quickly, limiting the amount that can be retained in the soil profile. As a result, rapid drainage and limited water holding capacity together restrict significant recharge and keep groundwater accumulation relatively low. The fine clay fraction within the loamy soil matrix holds water tightly, so the soil's water holding capacity is high. This strong retention slows the downward movement of infiltrating water, causing it to linger near the surface. As a result, the soil is more likely to become saturated during rain events, which can lead to localized flooding. Because water moves slowly through the profile, less of it reaches the deeper aquifer, diminishing the soil's effectiveness for groundwater recharge.

Proximity to Surface Water Bodies

Proximity to surface water bodies like rivers, lakes, and wetlands can significantly impact groundwater potential. These water bodies can recharge groundwater aquifer, influence local hydrology and water tables, and affect water quality and availability (Khosravi et al., 2018; Ozegin et al., 2023). Areas near surface water bodies may have higher groundwater potential due to increased recharge and connectivity (Roy et al., 2020; Senapati & Das, 2021). The Proximity to Surface Water Bodies (PSWB) map (Figure 5c) divides the landscape into four distance-based classes reflecting how water bodies influence the surrounding groundwater system: high (3096-3871 m), moderate (2320-3095 m), low (1543-2319 m), and very low (766-1542 m) of rivers, lakes, and wetlands. Regions that fall into the high Proximity to Surface Water Bodies (PSWB) class often underlain by crystalline basement rocks tend to accumulate more subsurface water because these hard rock formations can store and transmit water through fractures (Lee et al., 2020; Ozegin et al., 2024a). When both drainage capacity and lineament density are high, water infiltrates readily and moves quickly through the subsurface, leading to greater groundwater accumulation; when they are low, water movement is restricted and accumulation diminishes. Boreholes situated close to rivers, lakes or wetlands often benefit from a strong hydraulic connection to surface water, which can enhance recharge rates and raise the water table in the immediate vicinity; as a result, these wells frequently produce groundwater volumes that

are up to fourteen times greater than those drilled in more distant locations where infiltration is limited and the aquifer receives less lateral inflow (Mehrarvar et al., 2023). This marked increase in yield reflects the combined effects of greater water availability at the surface, reduced travel distance for infiltrating water, and the presence of permeable pathways that facilitate rapid transmission to the borehole.

Determination of Groundwater Potential Zones

Determining groundwater potential involves assessing various factors that influence the occurrence, availability, and quality of groundwater (Ilugbo et al., 2023a; Moharir et al., 2023; Mehravar et al., 2023; Ozegin et al., 2024a; Bawallah et al., 2024). The groundwater potential zones in the study area were delineated by applying the weighted overlay method, which combines a set of hydrogeological attributes after assigning each a rating and a relative weight. Eleven thematic layers that control groundwater occurrence: slope, soil type, geology, lineament density, drainage network, rainfall distribution, landuse/landcover, aquifer thickness, hydraulic conductivity, depth to water table, and proximity to surface water were prepared, weighted, and overlaid in ArcGIS environment to producing the final potential map shown in Figure 5d. The final groundwater potential map divides the study region into five distinct recharge categories: very high, high, moderate, low, and very low, each indicating a progressively lower likelihood of substantial groundwater accumulation. The zones classified as very high and high potential are clustered in the southwestern and northwestern parts of Ibadan, as well as in several sectors of northern Ibadan. These locations, therefore, represent the most promising areas for groundwater extraction within the mapped area. The high and very high potential zones are distinguished by a suite of hydro-geomorphic traits: they admit water readily because the soils and weathered rock have strong infiltration and storage capacities; they sit close to rivers, streams or lakes, which enhances recharge; the terrain is gently undulating with low elevations and mild slopes that slow runoff; fracture networks are abundant, giving a high lineament density that provides pathways for subsurface flow; and the surface drainage network is sparse, so water is not quickly whisked away. In contrast, the moderate potential belt stretches across the study area from the southeastern corner up through the northeastern region, where these favorable conditions are present but less pronounced. Conversely, the portions of the study area that fall into the low and very low groundwater potential categories are concentrated mainly in the southeastern and northeastern districts of Ibadan. However, the prevailing clay rich soils, hilly terrain and ridge lines, a sparse network of fractures (low lineament density), and relatively steep slopes all promote rapid surface runoff and inhibit the downward percolation of rainwater, limiting recharge to the underlying aquifers. The analysis underscores that lineament

density, geomorphology, and rainfall are pivotal for groundwater targeting in crystalline basement settings. The study area’s groundwater prospect map aligns with those reported by Akinluyi et al., (2021), Dar et al. (2021), Moodley et al., (2022), Rather et al., (2022); Kumar et al. (2022), Ozegin et al. (2023), Baghel et al., (2023), Ilugbo et al. (2023a), Moharir et al., (2023), Mehravar et al., (2023), Singha et al. (2024), and Ozegin et al. (2024), which classify groundwater potential into very low, low, medium, and high categories.

Validation of Groundwater Potential Map

To validate the groundwater potential map, the study likely used existing borehole data, such as yield or water level, to test the map’s accuracy. This involves: Comparing predicted potential zones with actual borehole performance, assessing the map’s ability to identify productive aquifers, and evaluating the overall reliability of the map for groundwater exploration. The validation process helps to refine the map and increase confidence in its predictions, making it a useful tool for groundwater management and development. To verify the methodology employed, the research overlaid a set of existing borehole data onto the groundwater potential (GWP) map (Figure 6), allowing a direct visual and statistical comparison between predicted potential zones and actual well yields. Confirming the map’s accuracy is essential,

because without such validation the geospatial output would remain uncertain and its practical value for water resource planning could be significantly constrained (Moharir et al., 2023; Mehravar et al., 2023; Singha et al. 2024; Ozegin and Ilugbo, 2024). Sixteen boreholes were randomly selected across the study area and overlaid on the groundwater potential map to test its predictive power. The data show that two boreholes are located in very high GWP zones, five in high GWP zones, three in moderate GWP zones, four in low GWP zones, and two in very low GWP zones. The validation exercise shows that the borehole observations line up closely with the mapped groundwater potential categories. Out of the sixteen wells examined, fifteen (93.75%) produced yields that matched the expected output for their respective zones, confirming a strong statistical agreement between the model and the field data. The remaining one borehole (6.25%) fell outside the predicted class, representing a small deviation that does not undermine the overall reliability of the map (Table 7). The strong agreement between the borehole observations and the predicted groundwater potential categories demonstrates that the model reliably identifies where exploitable aquifers are most likely to occur. Consequently, future exploration and resource development activities should prioritize the areas mapped as very high, high, and moderate potential, as these zones have been shown to yield the greatest returns on investment in terms of water supply and drilling success.

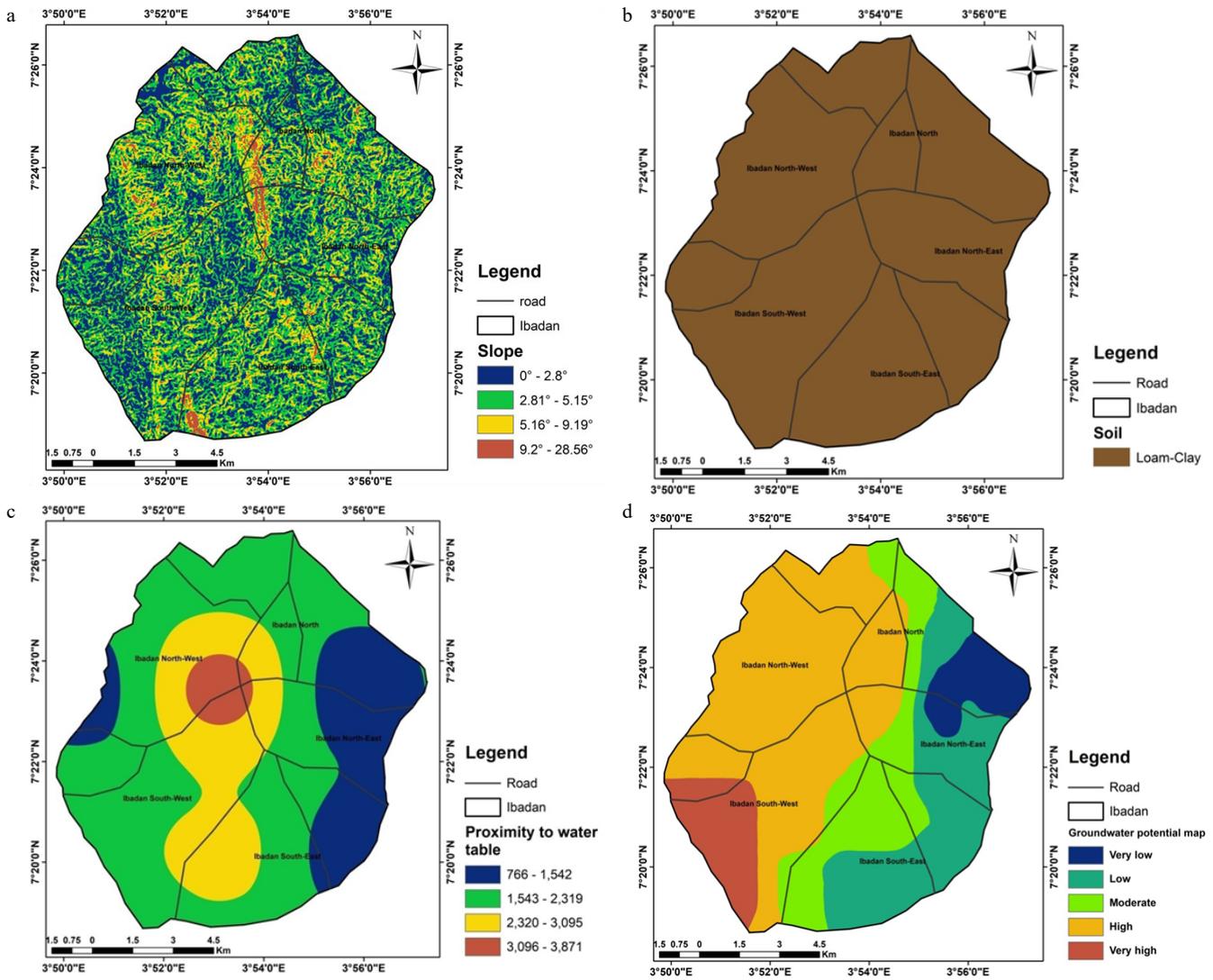


Figure 5. (a) Slope (b) Soil type (c) Proximity to surface water bodies (d) Groundwater potential Map

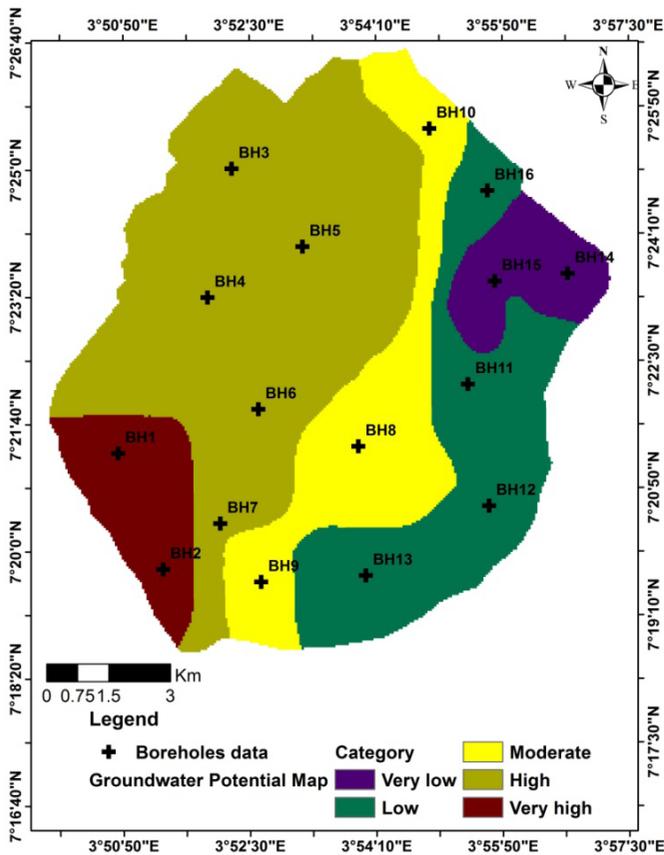


Figure 6. Validation map

Table 7. Validation of borehole data for the GW potential map

Borehole Number	Borehole Yield Class	GWPZ Yield Class	conformity between borehole and GWPZ yield
BH1	Very High	High	Conform
BH2	Very High	High	Conform
BH3	High	High	Conform
BH4	High	High	Conform
BH5	High	High	Conform
BH6	High	High	Conform
BH7	Moderate	High	Not Conform
BH8	Moderate	Moderate	Conform
BH9	Moderate	Moderate	Conform
BH10	Moderate	Moderate	Conform
BH11	Low	Moderate	Conform
BH12	Low	Moderate	Conform
BH13	Low	Moderate	Conform
BH14	Low	Moderate	Conform
BH15	Very low	Low	Conform
BH16	Very low	Low	Conform

Regression Analysis

Regression analysis is a statistical method used to establish a relationship between two or more variables (Moodley et al., 2022; Rather et al., 2022;

Kumar et al. 2022). To verify the reliability of the methodology, the researchers carried out a linear regression analysis that directly compared the groundwater potential values predicted by the map with the actual yields recorded at the validation boreholes; the resulting regression line showed a strong correspondence, confirming that the map accurately represents the spatial distribution of groundwater resources (Moharir et al., 2023; Mehravar et al., 2023; Bawallah et al., 2024; Singha et al. 2024; Ozegin and Ilugbo, 2024). This statistical test therefore substantiates the validity of the adopted approach. The validation procedure involves a direct comparison between the actual discharge rates recorded at each borehole and the groundwater potential zone (GWPZ) values assigned by the model. By plotting the observed yields against the predicted potential categories, the analysis demonstrates that the final model reliably distinguishes areas where groundwater is likely to occur, as illustrated in Figure 7. This close correspondence confirms that the model is effective for identifying and delineating zones of groundwater occurrence across the study area. The comparison reveals that the MultiCriteria Decision Analysis–Analytic Hierarchy Process (MCDAAHP) framework yields results that are markedly more reliable, precise, and robust than those obtained from the linear regression model, as reflected by a higher coefficient of determination (R^2). In other words, while the regression analysis provided a basic statistical fit, the MCDAAHP method captured the complex interplay of the influencing factors more effectively, leading to superior predictive accuracy for groundwater potential across the study area.

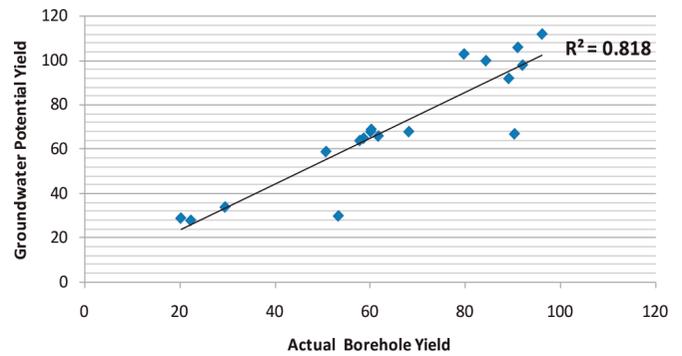


Figure 7. Relationship between actual borehole yield and groundwater potential value

Research Drawback

One potential drawback of the research is that it relies on a limited number of borehole data points (16) for validation, which may not be representative of the entire study area. Although the research was carried out with a thorough and systematic approach, it is important to acknowledge that it is not free of constraints. One notable limitation is the inherent susceptibility of the adopted methodology to the selection and weighting of criteria. Because the process relies on subjective decisions about which factors to include and how heavily to value them, there is a risk that the resulting assessments could be skewed or inconsistent, potentially leading to contradictory findings that reflect the analysts’ biases rather than an objective depiction of groundwater potential. Moreover, the Analytic Hierarchy Process (AHP) is founded on the premise that each decision criterion can be treated as an isolated factor, which means it does not account for any synergistic or antagonistic interactions among the various components that control groundwater occurrence. In reality, groundwater influencing elements such as lineament density, soil texture, topography, and rainfall often interact with one another (for example, high lineament density may amplify the effect of rainfall infiltration). By ignoring these interrelationships, AHP can produce an oversimplified assessment that may miss important nuances in the hydrogeological system. The intrinsic heterogeneity of the original datasets may have been concealed by the standardization and normalization procedures, which compress the natural variability of the variables and can therefore overlook subtle but meaningful differences among them. Additionally, because the Analytic Hierarchy Process depends on fixed pairwise comparisons, it struggles to accommodate uncertainty or evolving conditions; this rigidity limits the method’s ability to

adapt to ambiguous information or to temporal changes in the hydrogeological environment. Even though the AHP method has its drawbacks, it can still serve as a valuable component of a broader analytical framework, complementing techniques such as machine learning models or GIS-based spatial analysis to refine the delineation of groundwater potential zones. By integrating AHP with these supplementary approaches, the overall predictive accuracy and reliability of regional groundwater assessments are markedly improved.

Conclusions

Achieving sustainable development and effective management of groundwater requires a clear understanding of where the most promising aquifers lie; therefore, it is essential to systematically evaluate and delineate the spatial patterns of groundwater potential across a given area. To meet this need, the study applied a GIS based MultiCriteria Decision Analysis (MCDA) that integrates the Analytical Hierarchy Process (AHP) with advanced geospatial tools, thereby providing a rigorous, spatially explicit framework for monitoring and preserving groundwater supplies at the regional level. To pinpoint locations within the study area that are likely to host viable groundwater, the research employed a GIS based MultiCriteria Decision Analysis (MCDA) that incorporates the Analytical Hierarchy Process (AHP). This approach allowed the team to combine a suite of geoenvironmental factors, each weighted according to its relative influence on groundwater occurrence. The variables examined were: Geomorphology, Slope, Drainage density, Lineament density, Land use/land cover, Soil types, Elevation, Land surface temperature, Proximity to surface water bodies, Rainfall, Geology. Each factor was assigned a rating that reflected its suitability for groundwater development, and the ratings were combined using AHP derived weights to produce a spatially explicit map of groundwater potential across the region. This integrated analysis provides a robust foundation for targeting sustainable groundwater exploration and management efforts. In the ArcGIS environment the suite of geo-environmental variables was merged through a weighted overlay procedure, allowing the creation of a spatially explicit groundwater potential map. This map was then reclassified into five recharge categories that span from very low to very high potential. The analysis revealed that the most favorable zones those rated as very high and high potential are concentrated in the southwestern and northwestern sectors of Ibadan, as well as in several locales within the northern part of the city. Moderate potential groundwater zones were found scattered throughout the study area, extending from the southeastern sector up to the northeastern sector. These zones exhibit a combination of attributes that promote recharge: they possess soils and subsurface materials with high infiltration and water holding capacity, lie close to rivers, lakes or other surface water bodies, display landforms that facilitate water accumulation, occur at relatively low elevations, contain a dense network of lineaments that act as conduits, have a sparse drainage network that reduces rapid runoff, and are characterized by gentle slopes that encourage infiltration rather than overland flow. Collectively, these conditions make the moderate potential areas well suited for groundwater recharge. Conversely, the analysis revealed that the southeastern and northeastern parts of Ibadan are dominated by low and very low potential groundwater zones, especially in areas where clayey soils, hills, and ridges prevail. These locales are typified by a sparse network of fractures (low lineament density), a dense surface drainage pattern that quickly routes water away, and steep gradients that together accelerate runoff and sharply limit the amount of water that can infiltrate into the subsurface. As a result, recharge in these regions is minimal, making them the least favorable for sustainable groundwater development. The investigation's results affirm that, in the crystalline basement complex that underlies the study area, three variables lineament density, geomorphology, and rainfall exert the strongest control on where groundwater is likely to accumulate and be extractable; lineaments provide fracture pathways that enhance permeability, the shape and origin of landforms dictate where water can pond and infiltrate, and the amount and distribution of precipitation supply the recharge needed to sustain aquifers. To verify the reliability of the groundwater potential map generated from these and other criteria, the research team compared its predictions with an extensive set of borehole observations collected across the entire region, and the comparison revealed a statistically significant correspondence between the mapped potential zones and the actual water bearing intervals encountered in the wells, confirming that the model accurately captures the spatial patterns of groundwater availability. Effective groundwater resource management and

planning in any region hinge on a clear understanding of the key parameters and methodological approaches demonstrated in this study. By systematically integrating geoenvironmental variables such as lineament density, geomorphology, rainfall, and related factors within a GIS based MCDA/AHP framework, the research provides a robust, reproducible decision support tool that can be adapted to diverse hydrogeological settings, thereby enhancing the reliability of groundwater potential mapping and supporting sustainable water use strategies. The results of this investigation offer a solid foundation for both the sustainable development and the day to day management of groundwater within the investigated basin, because they delineate where aquifers are most abundant and where they are scarce. By pinpointing zones of very high and high groundwater potential, the study provides actionable guidance for future exploration campaigns, infrastructure planning, and extraction projects, enabling policymakers and water resource professionals to prioritize investments, mitigate over exploitation risks, and design targeted interventions that align with long term water security objectives.

Acknowledgements:

The Authors are grateful to the two anonymous reviewers who provided valuable feedback on a previous draft of the work, greatly enhancing its quality.

Author contribution:

All sections of this manuscript were written by all authors.

Funding:

This research was conducted without the support of any governmental or non-governmental funding sources.

Availability of data and material:

Not applicable. The corresponding author should be contact for the availability of the data used.

Declarations

Conflicts of interest: There is no conflict of interest, according to the authors.

References

- Abdekareem, M., Al-Arifi, N., Abdalla, F., Mansour, A., & El-Baz, F. (2022). Fusion of Remote Sensing Data Using GIS-Based AHP-Weighted Overlay Techniques for Groundwater Sustainability in Arid Regions. *Sustainability*, 14, 7871.
- Abdelouhed, F., Ahmed, A., Abdellah, A., Yassine, B., & Mohammed, I. (2021). Using GIS and remote sensing for the mapping of potential groundwater zones in fractured environments in the CHAOUIA-Morocco area. *Remote Sensing Applications: Society and Environment*, 23, 100571. <https://doi.org/10.1016/j.rsase.2021.100571>
- Abijith, D., Saravanan, S., Singh, L., Jennifer, J. J., Saranya, T., & Parthasarathy, K. S. S. (2020). GIS-based multicriteria analysis for identification of potential groundwater recharge zones - a case study from Ponnaniyar watershed, Tamil Nadu, India. *HydroResearch*, <https://doi.org/10.1016/j.hydres.2020.02.002>.
- Abu El-Magd, S. A., Amer, R. A., & Embaby, A. (2020). Multi-criteria decision-making for the analysis of flash floods: A case study of Awlad Toq-Sherq, Southeast Sohag, Egypt. *Journal of African Earth Sciences*, 162, 103709. <https://doi.org/10.1016/j.jafrearsci.2019.103709>
- Abu El-Magd, S. A., & Embaby, A. (2021). To investigate groundwater potentiality, a GIS-based model was integrated with remote sensing data in the Northwest Gulf of Suez (Egypt). *Arabian Journal of Geosciences*, 14, 2737. <https://doi.org/10.1007/s12517-021-08396-2>
- Adebiyi, A. D., Ilugbo, S. O., Bamidele, O. E., & Egunjobi, T. (2018). Assessment of aquifer vulnerability using multi-criteria decision analysis around akure industrial estate, Akure, Southwestern Nigeria. *Journal of Engineering Research and Reports*, 3(3), 1–13. DOI: 10.9734/jerr/2018/v3i316874

- Adebo, B. A., Ilugbo, S. O., Jemiriwon, E. T., Ali, A. K., Akinwumi, A. K., Adeniken, N. T. (2022). Hydrogeophysical Investigation Using Electrical Resistivity Method within Lead City University Ibadan, Oyo State, Nigeria. *International Journal of Earth Sciences Knowledge and Applications*, 4(1), 51–62.
- Adebo, B. A., Layade, G. O., Ilugbo, S. O., Hamzat, A. A., Otobrise, H. K. (2019). Mapping of Subsurface Geological Structures using Ground Magnetic and Electrical Resistivity Methods within Lead City University, Southwestern Nigeria. *Kada Journal of Physics*, 2(2), 64–73.
- Adebo, A. B., Ilugbo, S. O., Oladetan, F. E. (2018). Modeling of groundwater potential using Vertical Electrical Sounding (VES) and multi-criterial analysis at Omitogun Housing Estate, Akure, Southwestern Nigeria. *Asian Journal of Advanced Research and Reports*, 1(2), 1–11
- Al-Djazouli, M. O., Elmorabiti, K., Rahimi, A., Amellah, O., & Fadil, O. A. M. (2020). Delineating of Groundwater Potential Zones based on RS, GIS and AHP: A case of Waddai, eastern Chad. *GeoJournal*, 86, 1881–1894. <https://doi.org/10.1007/s10708-020-10160-0>
- Aggarwal, M., Saravanan, S., Jennifer, J. J. & Abijith, D. (2019). Delineation of groundwater potential zones for hard rock region in Karnataka using AHP and GIS. In: El-Askary, H., Lee, S., Heggy, E., Pradhan, B. (eds). *Advances in Remote Sensing and Geo Informatics Applications*. Springer, Cham, 315–317. https://doi.org/10.1007/978-3-030-01440-7_71
- Ahirwar, S., Malik, M. S., Ahirwar, R., & Shukla, J. P. (2020). Application of remote sensing and GIS for groundwater recharge potential zone mapping in upper Betwa watershed. *Journal of the Geological Society of India*, 95, 308–314. <https://doi.org/10.1007/s12594-020-1430-3>
- Ahmed, A., Alrajhi, A., Alquwaizany, A. S., Ahmed, A., Alrajhi, A., & Alquwaizany, A. S. (2021). Identification of Groundwater Potential Recharge Zones in Flinders Ranges, South Australia Using Remote Sensing, GIS, and MIF Techniques. *Water*, 13(18). <https://doi.org/10.3390/w13182571>
- Allafta, H., Opp, C., & Patra, S., (2021). Identification of groundwater potential zones using remote sensing and GIS techniques: A case study of the Shatt Al-Arab Basin. *Remote Sens*, 13(1), 112. <https://doi.org/10.3390/rs13010112>
- Allafta, H., Opp, C., & Patra, S. (2020). Identification of Groundwater Potential Zones Using Remote Sensing and GIS Techniques: A Case Study of the Shatt Al-Arab Basin. *Remote Sensing*, 13(1). <https://doi.org/10.3390/rs13010112>
- Alonso, J. A., & Lamata, M.T. (2006). Consistency in the Analytic Hierarchy Process: A New Approach. *International Journal of Uncertainty, Fuzziness and Knowledge-based Systems*, 14(4), 445–459.
- Al-Shabeeb, A. A. R., Al-Adamat, R., Al-Fugara, A., Al-Amoush, H., & AlAyyash, S. (2018). Delineating groundwater potential zones within the Azraq Basin of Central Jordan using multi-criteria GIS analysis. *Groundwater for Sustainable Development*, 7, 82–90. <https://doi.org/10.1016/j.gsd.2018.03.011>
- Arshad, A., Zhang, Z., Zhang, W., & Dilawar, A. (2020). Mapping favorable groundwater potential recharge zones using a GIS-based analytical hierarchical process and probability frequency ratio model: A case study from an agro-urban region of Pakistan. *Geoscience Frontiers*, 11(5), 1805–1819. <https://doi.org/10.1016/j.gsf.2019.12.013>
- Arunbose, S., Srinivas, Y., Rajkumar, S., Nair, N. C., & Kaliraj, S. (2021). Remote sensing, GIS and AHP techniques based investigation of groundwater potential zones in the Karumeniyar river basin, Tamil Nadu, southern India. *Groundwater for Sustainable Development*, 14, 100586. <https://doi.org/10.1016/j.gsd.2021.100586>
- Baghel, S., Tripathi, M. P., Khalkho, D., Kumar, A., & Elbeltagi, A. (2023). Delineation of suitable sites for groundwater recharge based on groundwater potential with RS, GIS, and AHP approach for Mand catchment of Mahanadi Basin. *Scientific Reports*, 13(1), 9860. <https://doi.org/10.1038/s41598-023-36897-5>
- Bawallah, M. A., Adebayo, A. E., Ilugbo, S. O., Adewumi, O. A., Ayodele, T., & Olutomilola, O. O. (2024). Ground Water Sustainability in a Crystalline Rock Environment Using Electrical Resistivity and MCDA Approach in the Federal Polytechnic Ado-Ekiti, Ekiti State, Nigeria. *Earth Sciences Pakistan*, 8(1), 05–18. <http://doi.org/10.26480/esp.01.2024.05.18>
- Bawallah, M. A., Adiat, K. A. N., Akinlalu, A. A., Ilugbo, S. O., Akinluyi, F. O., Ojo, B. T., Oyedele, A. A., Bamisaye, O. A., Olutomilola, O. O., & Magawata, U. Z. (2021a). Resistivity contrast and the phenomenon of geophysical anomaly in ground water exploration in a crystalline basement environment Southwestern Nigeria. *International Journal of Earth Sciences Knowledge and Applications*, 3(1), 23–36.
- Bawallah, M. A., Adiat, K. A. N., Akinlalu, A. A., Ilugbo, S. O., Akinluyi, F. O., Benjamin, O. O., Oyedele, A. A., Omosuyi, G. O., & Aigbedion, I. (2021b). Groundwater sustainability and the divergence of rock types in a typical crystalline basement complex region Southwestern Nigeria. *Turkish Journal of Geosciences*, 2(1), 1–11. <https://doi.org/10.48053/turkgeo.777217>
- Bawallah, M. A., Ilugbo, S. O., Aina, A. O., Olufemi, B., Akinluyi, F. O., Ojo, B. T., Oyedele, A. A., & Olasunkanmi, N. K. (2020a). Hydrogeophysical studies of central Kwara state basement complex of Nigeria. *International Journal of Earth Sciences Knowledge and Applications*, 2(3), 146–164.
- Bawallah, M. A., Ofomola, M. O., Ilugbo, S. O., Aina, A. O., Olaogun, S. O., Olayiwola, K. O., & Awoniran, D. R. (2020b). Effect of Lineament and Drainage Orientation on Groundwater Potential of Moro Area Central Kwara State Nigeria. *Indian Journal of Science and Technology*, 13(10), 1124–1134. DOI: 10.17485/ijst/2020/v13i10/147567
- Bawallah, M. A., Aina, A. O., Ilugbo, S. O., Ozegin, K. O., & Olasunkanmi, K. N. (2018). **Evaluation of Groundwater Yield Capacity Using Dar-Zarrouk Parameter of Central Kwara State, Southwestern Nigeria.** *Asian Journal of Geological Research*, 1(1), 1–13. DOI: 10.9734/AJOGER/2018/42053
- Brunelli, M. (2015). *Introduction to the Analytic Hierarchy Process*. SpringerBriefs in Operations Research. Springer Cham. <https://doi.org/10.1007/978-3-319-12502-2>
- Das, S. (2019). Comparison among influencing factor, frequency ratio, and analytical hierarchy process techniques for groundwater potential zonation in Vaitarna basin, Maharashtra, India. *Groundwater for Sustainable Development*, 8, 617–629. <https://doi.org/10.1016/j.gsd.2019.03.003>
- Das, S. (2021). Hydro-geomorphic characteristics of the Indian (Peninsular) catchments: Based on morphometric correlation with hydro-sedimentary data. *Advances in Space Research*, 67(8), 2382–2397. <https://doi.org/10.1016/j.asr.2021.01.043>
- Dube, T., Shoko, C., Sibanda, M., Baloyi, M. M., Molekoa, M., Nkuna, D., Rafapa, B., & Rampheri, B. M. (2020). Spatial modelling of groundwater quality across a land use and land cover gradient in Limpopo Province, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 115, 102820. <https://doi.org/10.1016/j.pce.2019.102820>
- Gyeltshen, S., Kannaujiya, S., Chhetri, I. K., & Chauhan, P. (2023). Delineating groundwater potential zones using an integrated geospatial and geophysical approach in Phuentsholing, Bhutan. *Acta Geophysica*, 71, 341–357. <https://doi.org/10.1007/s11600-022-00856-x>
- Hassaballa, A., & Salih, A. (2024). Mapping Groundwater Potential (GWP) in the Al-Ahsa Oasis, Eastern Saudi Arabia Using Data-Driven GIS Techniques. *Water*, 16, 194. <https://doi.org/10.3390/w16020194>
- Ilugbo, S. O., Aigbedion, I., Ozegin, K. O., & Bawallah, M. A. (2023a). Assessment of Groundwater Occurrence in a Typical Schist Belt Region in Osun State, Southwestern Nigeria using VES, Aeromagnetic Dataset, Remotely Sensed data and MCDA Approaches. *Sustainable Water Resources Management*, 9, 29. <https://doi.org/10.1007/s40899-022-00810-1>
- Ilugbo, S. O., Aigbedion, I., & Ozegin, K. O. (2023b). Structural mapping for groundwater occurrence using remote sensing and geophysical data in Ilesha Schist Belt, Southwestern Nigeria. *Geology, Ecology, and Landscapes*, 9(1), 199–216. <https://doi.org/10.1080/24749508.2023.2182063>

- Karimi-Rizvandi, S., Goodarzi, H. V., Afkouseh, J. H., Chung, I.-M., Kisi, O., & Kim, S. (2021). Groundwater-potential mapping using a self-learning bayesian network model: a comparison among metaheuristic algorithms. *Water*, 13, 658. <https://doi.org/10.3390/w13050658>
- Keenan, P. B., & Jankowski, P. (2019). Spatial Decision Support Systems: Three decades on. *Decision Support Systems*, 116, 64-76. <https://doi.org/10.1016/j.dss.2018.10.010>
- Khosravi, K., Sartaj, M., Tsai, F. T. C., Singh, V. P., Kazakis, N., Melesse, A. M., Prakash, I., Tien Bui, D., & Pham, B. T. (2018). A comparison study of DRASTIC methods with various objective methods for groundwater vulnerability assessment. *Science of The Total Environment*, 642, 1032-1049. <https://doi.org/10.1016/j.scitotenv.2018.06.130>
- Lee, S., Hyun, Y., Lee, S., Lee, J., Lee, S., Hyun, Y., Lee, S., & Lee, J. (2020). Groundwater Potential Mapping Using Remote Sensing and GIS-Based Machine Learning Techniques. *Remote Sensing*, 12(7). <https://doi.org/10.3390/rs12071200>
- Maity, D. K., & Mandal, S. (2019). Identification of Groundwater Potential Zones of the Kumari River Basin, India: An RS & GIS Based Semi-Quantitative Approach. *Environment, Development and Sustainability*, 21(2), 1013-1034. <https://doi.org/10.1007/s10668-0170072-0>
- Makonyo, M., & Msabi, M. M. (2021). Identification of groundwater potential recharge zones using GIS-based multi-criteria decision analysis: A case study of semi-arid midlands Manyara fractured aquifer, North-Eastern Tanzania. *Remote Sensing Applications: Society and Environment*, 23, 100544. <https://doi.org/10.1016/j.rsase.2021.100544>
- Malik, M. S., & Shukla, J. (2019). GIS modeling approach for assessment of groundwater vulnerability in parts of Tawa river catchment area, Hoshangabad, Madhya Pradesh, India. *Groundwater for Sustainable Development*, 9, 100249. <https://doi.org/10.1016/j.gsd.2019.100249>
- Mallick, J., Khan, R. A., Ahmed, M., Alqadhi, S. D., Alsubih, M., Falqi, I., Hasan, M. A., Mallick, J., Khan, R. A., Ahmed, M., Alqadhi, S. D., Alsubih, M., Falqi, I., & Hasan, M. A. (2019). Modeling Groundwater Potential Zone in a Semi-Arid Region of Aseer Using Fuzzy-AHP and Geoinformation Techniques. *Water*, 11(12). <https://doi.org/10.3390/w11122656>
- Mehravar, S., Razavi-Termeh, S. V., Moghimi, A., Ranjgar, B., Foroughnia, F., & Amani, M. (2023). Flood susceptibility mapping using multi-temporal SAR imagery and novel integration of nature-inspired algorithms into support vector regression. *Journal of Hydrology*, 617, 129100. <https://doi.org/10.1016/j.jhydrol.2023.129100>
- Moharir, K. N., Pande, C. B., Gautam, V. K., Singh, S. K., & Rane, N. L. (2023). Integration of hydrogeological data, GIS and AHP techniques applied to delineate groundwater potential zones in sandstone, limestone and shales rocks of the Damoh district, (MP) central India. *Environmental Research*, 228, 115832. <https://doi.org/10.1016/j.envres.2023.115832>
- Moodley, T., Seyam, M., Abunama, T., & Bux, F. (2022). Delineation of groundwater potential zones in KwaZulu-Natal, South Africa using remote sensing, GIS and AHP. *Journal of African Earth Sciences*, 193, 104571. <https://doi.org/10.1016/j.jafrearsci.2022.104571>
- Obaje, N. G. (2009). *Geology and Mineral Resources of Nigeria*. London: Springer Dordrecht Heidelberg, 5-14.
- Odeyemi, I. (1981). A review of the orogenic events in the Precambrian basement of Nigeria, West Africa. *Geologische Rundschau*, 70(3), 897-909. <https://doi.org/10.1007/BF01820170>
- Odusanya, B. O., & Amadi, U. M. P. (1989). An Empirical Resistivity Model for Predicting Shallow Groundwater Occurrence in the Basement Complex. *Water Resources Journal*, 2, 77-87.
- Oladejo, O. P., Sunmonu, L. A., & Adagunodo, T. A. (2015). Groundwater Prospect in a Typical Precambrian Basement Complex Using Karous-Hjelt and Fraser Filtering Techniques. *Journal of Industrial Engineering Research*, 1(4), 40-49.
- Ozegin, K., Ilugbo, S., & Ogunseye, T. (2023). Groundwater exploration in a landscape with heterogeneous geology: An application of geospatial and analytical hierarchical process (AHP) techniques in the Edo north region, in Nigeria. *Groundwater for Sustainable Development*, 20, 100871. <https://doi.org/10.1016/j.gsd.2022.100871>
- Ozegin, K. O., & Ilugbo, S. O. (2024). A triangulation approach for groundwater potential evaluation using geospatial technology and multi-criteria decision analysis (MCDA) in Edo State, Nigeria. *Journal of African Earth Sciences*, 209, 105101. <https://doi.org/10.1016/j.jafrearsci.2023.105101>
- Ozegin, K. O., & Ilugbo, S. O. (2025). Evaluation of potentially susceptible flooding areas leveraging geospatial technology with multicriteria decision analysis in Edo State, Nigeria. *Natural Hazards Research*, 5(1), 109-133. <https://doi.org/10.1016/j.nhres.2024.07.002>
- Ozegin, K. O., Ilugbo, S. O., & Adebo, B. (2024). Spatial evaluation of groundwater vulnerability using the DRASTIC-L model with the analytic hierarchy process (AHP) and GIS approaches in Edo State, Nigeria. *Physics and Chemistry of the Earth, Parts A/B/C*, 134, 103562. <https://doi.org/10.1016/j.pce.2024.103562>
- Ozegin, K. O., Ilugbo, S. O., & Akande, O. N. (2024b). Leveraging geospatial technology and AHP for groundwater potential zonation in parts of south and north-Central Nigeria. *Sustainable Water Resources Management*, 10, 146. <https://doi.org/10.1007/s40899-024-01124-0>
- Ozegin, K. O., Ilugbo, S. O., Alile, O. M., & Iluore, K. (2024). Integrating in-situ data and spatial decision support systems (SDSS) to identify groundwater potential sites in the Esan plateau, Nigeria. *Groundwater for Sustainable Development*, 26, 101276. <https://doi.org/10.1016/j.gsd.2024.101276>
- Palacky, G. J., Ritsema, I. L., & De Jong, S. J. (1981). Electromagnetic prospecting for groundwater in pre-cambrian terrains in the republic of Upper Volta (Burkina Faso). *Geophysical Prospecting*, 29(6), 932-955. <https://doi.org/10.1111/j.1365-2478.1981.tb01036.x>
- Rahaman, M. A. (1976). Review of the basement geology of southwestern Nigeria. In: C. A. Kogbe (ed). *Geology of Nigeria*. Elizabethan press, Lagos, 41-58.
- Rahaman, M. A. (1988). Recent advances in the study of the basement complex of Nigeria. *Precambrian geology of Nigeria*, Geological survey of Nigeria, Kaduna South, 11-43.
- Rather, A. F., Ahmed, R., Wani, G. F., Ahmad, S. T., Dar, T., Javadi, S., & Ahmed, P. (2022). Mapping of Groundwater Potential Zones in Pohru Watershed of Jhelum Basin-Western Himalaya, India Using Integrated Approach of Remote Sensing, GIS and AHP. *Earth Science Informatics*, 15, 2091-2107. <https://doi.org/10.1007/s12145-022-00824-5>
- Rejith, R. G., Anirudhan, S., & Sundararajan, M. (2019). Delineation of groundwater potential zones in hard rock terrain using integrated remote sensing, GIS and MCDM techniques: A case study from vamanapuram river basin, Kerala, India. In: S. Venkatraman, M. V. Prasanna, & S. Y. Chung. (Eds). *GIS and Geostatistical Techniques for Groundwater Science*. Elsevier: Amsterdam, the Netherlands, 349-364.
- Roy, S., Hazra, S., Chanda, A., & Das, S. (2020). Assessment of Groundwater Potential Zones Using Multi-Criteria Decision-Making Technique: A Micro-Level Case Study from Red and Lateritic Zone (RLZ) of West Bengal, India. *Sustainable Water Resources Management*, 6, 4. <https://doi.org/10.1007/s40899-020-00373-z>
- Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill Book Co, New York, 287.
- Senapati, U., & Das, T. K. (2021). Assessment of basin-scale groundwater potentiality mapping in drought-prone upper Dwarakeshwar River basin, West Bengal, India, using GIS-based AHP techniques. *Arabian Journal of Geosciences*, 14(11), 1-22. <https://doi.org/10.1007/s12517-02107316-8>
- Singha, C., Swain, K. C., Pradhan, B., Rusia, D., Moghimi, K. A., & Ranjgar, B. (2024). Mapping groundwater potential zone in the Subarnarekha basin, India, using a novel hybrid multi criteria approach in Google earth Engine. *Heliyon*, 10, e24308. <https://doi.org/10.1016/j.heliyon.2024.e24308>
- Unesco. (2015). *The United Nations World Water Development Report 2015: Water for a sustainable world*. Paris, France.

