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Evaluation of Groundwater Potential Zone in Selected Coastal and Non-Coastal Regions of Nigeria

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Abstract

For socioeconomic development, groundwater is a vital resource, especially in areas with limited water supplies. This study assesses groundwater potential zones (GWPZs) in two distinct Nigerian regions, the inland crystalline basement complex of Ile-Ife and the coastal sedimentary basin of Ilaje using integrated geospatial techniques. The novelty of this research lies in its direct comparative analysis of these two disparate hydrogeological and anthropogenic contexts, which fills a critical gap in the existing literature. The study utilized Remote Sensing, GIS, and the Analytical Hierarchy Process (AHP), including a sensitivity analysis to improve methodological robustness. For GWPZ delineation, nine key thematic layers, including geology, land use/land cover, NDWI, NDVI, drainage density, lineament density, rainfall, DEM, and slope, were processed and weighted using AHP. Significant differences were found in the results. Ilaje had a higher percentage of highly available GWPZs (6.15%) than Ile-Ife (4.00%), which was indicative of fundamental variations in hydrogeological, geomorphological, and hydrological controls. Importantly, the results highlight how these differences call for tailored management approaches; Ile-Ife's resources are being depleted by increasing urbanization, while Ilaje's potential is accompanied by serious risks of pollution and saltwater intrusion. This research demonstrates that a "one-size-fits-all'' approach to groundwater management is untenable in diverse environments and offers fresh empirical insights for both hydrogeological theory and practical policy formulation. It is important to note that the resulting GWPZ maps, based on secondary data, should be interpreted as preliminary indicators requiring future validation through borehole logs and pump test data.

Keywords: *Groundwater Potential Zone. Analytical Hierarchy Process (AHP). Remote Sensing (RS). Sensitivity Analysis. Ilaje. Ile-Ife.*

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I. INTRODUCTION

Groundwater is a vital resource for industrial, agricultural, and domestic use that accounts for a third of global freshwater withdrawals, especially in water-stressed regions [1, 2]. Despite the growing demand for groundwater, a critical gap remains in context-specific analyses that synthesize complex hydrogeological factors with prevailing socio-political and economic pressures [5]. This analytical gap is particularly evident in geologically diverse nations like Nigeria [10], where a mosaic of diverse hydrogeological settings and anthropogenic pressures necessitates customized and advanced groundwater management strategies [6, 3, 7].

Traditional methods for groundwater evaluation, such as large-scale geophysical surveys and manual well inventories, are often limited by prohibitive costs, time-consuming processes, and limited coverage [8, 7]. While the introduction of Remote Sensing (RS) and Geographic Information Systems (GIS) has offered scalable and cost-effective alternatives [8, 9], these methods have their own challenges. For instance, data resolution and atmospheric conditions can affect RS-derived indices, potentially introducing classification errors in Nigeria's cloud-prone tropical environments [11]. This underscores the need for robust methodological frameworks that rigorously account for inherent uncertainties [12, 13].

A major challenge in modern groundwater research is the methodological soundness of groundwater potential zone (GWPZ) mapping [14] and the transferability of GWPZ models across different hydrogeological regimes [15, 16]. This study directly addresses these challenges by critically advancing existing frameworks. The primary objective is to conduct a direct comparative analysis of GWPZs in two distinct Nigerian regions: the coastal sedimentary basin of Ilaje and the inland crystalline basement complex of Ile-Ife. This research fills a critical gap, as previous studies have often examined these or similar regions separately, preventing direct insights into how controlling factors behave differently across disparate hydrogeological settings [17, 18].

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The novelty of this research lies in its unique comparative design, which systematically contrasts the groundwater potential between two distinct hydrogeological systems within a unified methodological framework. This approach provides an unprecedented empirical elucidation of context-dependent factor influence, demonstrating how the relative importance of hydrological, geological, and geomorphological elements fundamentally differs between these two systems [19, 20, 16]. By providing empirically derived insights from direct, contrasting comparisons, the study offers a new understanding of localized hydrogeological responses that generic models cannot capture. The findings will significantly advance regional hydrogeological knowledge and policy development by proving that a "one-size-fits-all" approach to groundwater management is not feasible in a country with such diversity as Nigeria.

II. MATERIAL AND METHODS

The integrated geospatial method used to define the groundwater potential zones in the chosen study areas is described in this section. It describes the different kinds of data collected, the pre-processing procedures used to guarantee accuracy and consistency, and the analytical framework used for modeling groundwater potential, including sensitivity analysis. The study's findings are reliable and transferable thanks to its strong methodology.

A. Area of Study

The Ilaje Local Government Area in Ondo State and the Ile-Ife Local Government Area in Osun State are two starkly different parts of Nigeria where this study was carried out. These sites were chosen because of their notable environmental and hydrogeological differences. Figure 1 displays the Ilaje and Ile-Ife locations used in this investigation.

Ilaje located in what is known as a coastal region in southwest Nigeria. With recorded annual precipitation ranging from 2586 to 4163 mm, the region has a tropical rainforest climate. Elevations ranging from -18 m to 26.01 m above sea level indicate that Ilaje is primarily low-lying with generally flat terrain. Its geology is mainly defined by layers of silt and unconsolidated sand that are dominated by Gleysols. A thick layer of clay is also present. In Ilaje, lineament density varies throughout the region, with northern regions experiencing values as high as 1.4 km^{-1}.

Ile-Ife is a non-coastal, inland area in southwest Nigeria that is part of the crystalline basement complex. With an average yearly rainfall of between 2383 and 3433 mm, it enjoys a tropical climate. Ile-Ife's terrain is undulating, with elevations typically falling between 160 and 245.01 meters. Hard, crystalline basement rocks, such as ferric lutesols, lithosols, and eutric nittosols, are what define the geology. Ile-Ife has a more dispersed lineament distribution, with a peak value of 1.30 km^{-1}. In southwest Nigeria, the area is also a well-known urban center. The study area is presented in Figure 1.

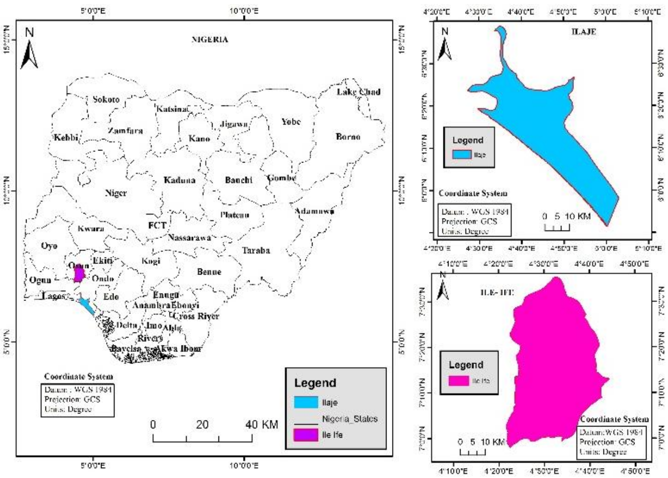


Fig. 1. Study area maps, Nigeria map association with boundary, Study area of Ile-Ife, Study area of Ilaje.

B. Data Collection and Sources

This study utilized only secondary datasets to assess groundwater potential zones in the selected coastal (Ilaje) and non-coastal (Ile-Ife) regions. A total of nine parameters were integrated: Land Use/Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Rainfall, Digital Elevation Model (DEM), Slope, Lineament Density, Drainage Density, and Soil Geology. These parameters were chosen based on their established influence on groundwater recharge and distribution. The details of the datasets, their sources, and resulting products are summarized in Table I.

TABLE I. DESCRIPTION OF DATASETS, THEIR SOURCES, AND PURPOSE

S/N	Dataset	Source	Scale/ Resolution	Epoch	End Product
1	Landsat 9 imagery, path 190 rows 56	USGS	30m	2023	LULC NDWI and NDVI maps
2	SRTM DEM (version 3.0)	USGS	30 m (1 arc-second)	2000	Elevation, Slope, Lineament Density and Drainage density maps
3	CHRS data portal	CHRS	79 km (T255 spectral)	2000-2020	Rainfall map across the study area
4	FAO (Food Agriculture Organisation) portal	DSMW	-	1990	Soil Geology map

C. Data Pre-processing

Prior to the AHP analysis, the following pre-processing steps were applied to the datasets:

- Landsat 9 Imagery: The Landsat 9 imagery was radiometrically and atmospherically corrected using the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) algorithm in ENVI 5.6. LULC classification was performed using the Support Vector Machine (SVM) algorithm, with training data collected from field surveys and high-resolution Google Earth imagery. NDWI and NDVI were calculated using the following equations:

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (2)$$

  Where Green, NIR, and Red represent the spectral bands corresponding to green, near-infrared, and red wavelengths, respectively.

- SRTM DEM**:** The Shuttle Radar Topography Mission (SRTM) DEM data were preprocessed prior to analysis. Sink filling was performed to eliminate spurious depressions and errors in the raw data, thereby ensuring hydrological correctness of the DEM. This preprocessing step enhanced the accuracy of slope, flow direction, flow accumulation, and other terrain-related parameters required for groundwater potential analysis. The SRTM DEM was then used to derive slope and aspect using the Terrain Analysis tool in ArcGIS 10.8. Lineament density and drainage density were subsequently extracted using the Line Density and Drainage Density tools in ArcGIS, respectively.
- Rainfall Data: To determine the mean annual rainfall, rainfall data from the CHRS portal from 2000 to 2020 was processed. In order to do this, daily rainfall data had to be combined into annual totals, and the average over the course of 20 years had to be determined.
- Soil Geology Data: The FAO's Digital Soil Map of the World (DSMW) provided the soil geology map. Based on the types of soil found in the study area, the data was reclassified into groups that were pertinent to groundwater potential (e.g., low infiltration, high infiltration).

To ensure spatial consistency across all layers, we used the bilinear resampling technique in ArcGIS 10.8 to resample each spatial layer to a standard 30 m spatial resolution.

D. Data Accuracy and Temporal Consistency

Groundwater potential studies frequently integrate datasets with varying spatial resolutions and temporal origins. This study is no different, using data ranging from 1990 to 2023. While the Landsat 9 imagery (2023) provides a high-resolution snapshot of recent vegetation and land cover, older datasets like the SRTM DEM (2000) and soil geology data (1990) are still widely used in geospatial analyses due to their consistent global coverage and reliability [7, 8]. The rainfall data from the CHRS portal (2000-2020) provides a robust historical mean, which is more suitable for long-term groundwater recharge modeling than single-year data, as it smooths out annual anomalies.

The use of multi-temporal datasets is justified in this study because the parameters they represent exhibit temporal stability. Features such as topography, slope, and geology are not expected to undergo significant changes over a 20-30-year period. Therefore, the older data remains relevant and provides a reliable baseline for these relatively static parameters. To mitigate any potential temporal inconsistencies, all spatial layers were resampled to a common 30 m resolution, ensuring consistency across the model. This approach is supported by prior research that has successfully integrated multi-temporal data for groundwater assessments in similar contexts [8].

E. Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), a multi-criteria decision-making method, was used to assign weights to the nine thematic layers influencing groundwater potential. This technique, integrated with a GIS, is a well-established and validated method for groundwater potential mapping in a wide range of hydrogeological settings [7, 9]. The process involved parameter ranking and reclassification, followed by pairwise comparisons and weight derivation.

F. Parameter Ranking and Reclassification

Parameter Ranking and Pairwise Comparison Based on a comprehensive review of existing literature [12, 13, 14] and expert consultation, each of the nine parameters—Slope, LULC, DEM, Lineament Density, Drainage Density, Geology, Rainfall, NDVI, and NDWI—was assigned a ranking on a scale of 1 (least potential) to 9 (highest potential). For instance, built-up areas were ranked low due to impervious surfaces that limit groundwater recharge, while forested areas received a high rank for promoting infiltration. Similarly, a higher lineament density was correlated with greater groundwater potential due to extensive fractures, while low drainage density was favored for its role in reducing surface runoff and enhancing recharge.

To determine the relative influence of each factor, a pairwise comparison matrix was constructed using Saaty's 1-9 scale (Table II). The comparisons were informed by a consensus-based consultation with a panel of three hydrogeologists with over 15 years of experience in the hydrogeology of southwest Nigeria. This expert input, combined with a robust review of relevant academic literature, was used to populate the matrix (Table III), ensuring the final weights were not arbitrary but were scientifically justified. The higher weighting assigned to Lineament Density (0.190), for instance, reflects its critical role in facilitating groundwater percolation, particularly in the fractured basement and sedimentary aquifers of the study areas, as supported by previous studies [21, 22, 23, 24].

TABLE II. SAATY'S 1-9 SCALE FOR PAIRWISE COMPARISON

Intensity of Importance	Explanation
1	Two activities contribute equally to the objective
2	Experience and judgment slightly favor one activity over another
3	Experience and judgment moderately favor one activity over another
4	Experience and judgment strongly favor one activity over another
5	An activity is strongly favored and is essential
6	An activity is favored very strongly, and its dominance is demonstrated in practice
7	An activity is favored very, very strongly; its importance is almost absolute
8	An activity is of the highest order of importance and dominance
9	The evidence favoring one activity over another is of the highest possible order

TABLE III. PAIRWISE COMPARISON MATRIX

Factor	LULC	NDVI	NDWI	Rainfall	DEM	Slope	Lineament Density	Drainage Density	Soil Geology
LULC	1	1/2	1/2	1/3	1/2	1/3	1/4	1/3	1/2
NDVI	2	1	2	1	3	2	1	1	2
NDWI	2	1/2	1	1/2	2	1	1/2	1/2	1
Rainfall	3	1	2	1	4	2	1	2	3
DEM	2	1/3	1/2	1/4	1	1/2	1/3	1/2	1
Slope	3	1/2	1	1/2	2	1	1/2	1/2	2
Lineament Density	4	1	2	1	3	2	1	2	4
Drainage Density	3	1	2	1/2	2	2	1/2	1	2
Soil Geology	2	1/2	1	1/3	1	1/2	1/4	1/2	1

G. Weight Derivation And Consistency Analysis

The weights for each parameter were derived from the normalized pairwise matrix (Table IV) by computing the principal eigenvector. The consistency of the matrix was then evaluated using the Consistency Ratio (CR), calculated as the ratio of the Consistency Index (CI) to the Random Index (RI). The CR for our matrix was 0.019, which is well below the acceptable threshold of 0.1, indicating a high level of consistency in the expert judgments.

H. Weighted Overlay Analysis

All reclassified raster layers were integrated using the Weighted Overlay Tool in ArcGIS 10.8. The weights derived from the AHP process guided the final suitability score for each cell. The Groundwater Potential Index (GWPI) was determined using the following formula:

$$GWPI = \sum W_i \times R_i \qquad (3)$$

where Wi is the weight of the i-th parameter and Ri is its reclassified value (Table V). The generated GWPI values were subsequently categorized into zones of groundwater potential (e.g., high, moderate, low). The summary of the normalized weights and rank of groundwater influencing factors is also shown Table VI.

TABLE IV. NORMALIZED PAIRWISE COMPARISON MATRIX

Factor	LULC	NDVI	NDWI	Rainfall	DEM	Slope	Lineament Density	Drainage Density	Soil Geology
LULC	0.045	0.079	0.042	0.062	0.027	0.029	0.046	0.040	0.111
NDVI	0.091	0.158	0.167	0.185	0.162	0.176	0.185	0.120	0.111
NDWI	0.091	0.079	0.083	0.092	0.108	0.088	0.092	0.060	0.111
Rainfall	0.136	0.158	0.167	0.185	0.216	0.176	0.185	0.240	0.111
DEM	0.091	0.053	0.042	0.046	0.054	0.044	0.062	0.060	0.111
Slope	0.136	0.079	0.083	0.092	0.108	0.088	0.092	0.060	0.111
Lineament Density	0.182	0.158	0.167	0.185	0.162	0.176	0.185	0.240	0.111
Drainage Density	0.136	0.158	0.167	0.092	0.108	0.176	0.092	0.120	0.111
Soil Geology	0.091	0.079	0.083	0.062	0.054	0.044	0.062	0.060	0.111

TABLE V. RECLASSIFICATION AND RANKING OF GROUNDWATER INFLUENCING FACTORS

Factors / Parameters	Sub-classifications	Reclassify Value (Non-Coastal Zone)	Reclassify Value (Coastal Zone)	Normalized AHP Weight
Rainfall	2583 – 2708 mm	1	1	0.184
	2708.3 – 2853.3 mm	3	3	
	2853.4 – 2998.4 mm	5	5	
	2998.5 – 3143.5 mm	7	7	
	3143.6 mm above	9	9	
Lineament Density	0 – 0.27 km^{-1}	9	9	0.190
	0.28 – 0.53 km^{-1}	7	7	
	0.54 – 0.80 km^{-1}	5	5	
	0.81 – 1.10 km^{-1}	3	3	
	1.20 – 1.30 km^{-1}	1	1	
NDVI	-0.12 – 0.07	1	1	0.152
	0.08 – 0.18	3	3	
	0.19 – 0.26	5	5	
	0.27 – 0.33	7	7	
	0.34 – 0.47	9	9	
Drainage Density	0 – 0.23 km^{-1}	1	1	0.130
	0.24 – 0.68 km^{-1}	3	3	
	0.69 – 1.19 km^{-2}	5	5	
	1.20 – 1.78 km^{-2}	7	7	

	1.79 – 3.22 km^{-1}	9	9	
Slope	0 – 1.94°	9	9	0.096
	1.95° – 3.89°	1	1	
	3.90° – 6.93°	3	3	
	6.94° – 12.03°	5	5	
	12.04° – 30.99°	9	9	
NDWI	0.03 – 0.19	1	1	0.084
	0.20 – 0.21	3	1	
	0.22 – 0.23	5	3	
	0.24 – 0.27	7	5	
	0.28 – 0.64	9	9	
Soil Geology	Ferric Luvisols	7	7	0.064
	Eutric Nitosols	1	1	
	Dystric Regosols	3	3	
	Planosols	5	5	
DEM	0 – 160 m	1	1	0.057
	160.01 – 203 m	3	3	
	203.01 – 245 m	5	5	
	245.01 – 294 m	7	7	
	294.01 – 551 m	9	9	
Land Use/Land Cover	Thick forest areas	9	9	0.044
	Bare Surface	5	5	
	Wetland	7	7	
	Built-up Area	1	1	
	Waterbody	3	3	

TABLE VI. NORMALIZED WEIGHTS AND RANK OF GROUNDWATER INFLUENCING FACTORS

Index	Parameter	Normalized weight	Rank
1	Lineament Density	0.190	1
2	Rainfall	0.184	2
3	NDVI	0.152	3
4	Drainage Density	0.130	4
5	Slope	0.096	5
6	NDWI	0.084	6
7	Soil Geology	0.064	7
8	DEM	0.057	8
9	LULC	0.044	9

III. SENSITIVITY ANALYSIS

A sensitivity analysis was performed to evaluate the resilience of our groundwater potential model. The weights of the three most influential variables—Lineament Density, Rainfall, and Drainage Density—were systematically changed by ±10%, and we monitored the resulting changes in the spatial distribution of the groundwater potential zones. The analysis reaffirmed the dominant role of these factors, showing that the model was most sensitive to changes in the weight of Lineament Density, followed by Rainfall and Drainage Density. The detailed results of this analysis are presented in Table VII.

IV. RESULTS AND DISCUSSION

Nine different parameters—Slope, Land Use/Land Cover (LULC), Lineament Density, Drainage Density, Digital Elevation Model (DEM), Soil Geology, Rainfall, Normalized Difference Water Index (NDWI), and Normalized Difference Vegetation Index (NDVI)—were used to predict groundwater potential zones in the coastal (Ilaje) and non-coastal (Ile-Ife) regions. The spatial distribution of the nine thematic layers used in the GIS–AHP groundwater potential assessment is presented in Figures 2-4.

TABLE VII. SENSITIVITY ANALYSIS RESULTS DEMONSTRATING HOW VARIATIONS OF ±10% IN FACTOR WEIGHTS AFFECT THE AREAS OF GROUNDWATER POTENTIAL ZONES

	-10%	0%
DEM	0.063	0.07
Drainage Density	0.063	0.07
LULC	0.045	0.05
Lineament Density	0.225	0.25
NDVI	0.072	0.08
NDWI	0.027	0.03
Rainfall	0.153	0.17
Slope	0.153	0.17
Soil Geology	0.099	0.11

For clarity and consistency, the maps were grouped into three composites according to factor type and standardized to a uniform scale and resolution:

- Figure 2 shows the topographic and drainage-related factors (DEM, slope, drainage density, and lineament density).
- Figure 3 presents climatic and vegetation-related factors (rainfall, NDVI, NDWI, and LULC).
- Figure 4 illustrates the geological factors.

All thematic layers were processed in a GIS environment, reclassified, and subsequently analyzed using the AHP to assign weights to each parameter.

The topographic analysis revealed that both regions are relatively low-lying. In Ilaje, slope values range from 0.00° to 0.95°, while in Ile-Ife they range from 0.00° to 1.94°. These values are consistent with their respective elevations, –18 m to 26.01 m in Ilaje and 160 m to 245.01 m in Ile-Ife. Low slopes and depressions typically enhance infiltration and groundwater accumulation, which has similarly been reported in groundwater studies across basement terrains and sedimentary environments [25, 26]. Compared to studies in humid tropical settings, the gentle slopes in Ilaje and Ile-Ife reflect favorable recharge conditions, although the coastal flatness in Ilaje may increase vulnerability to salinity intrusion, a limitation noted in other coastal aquifers [27, 28].

Drainage density in both regions ranges between 0.10–0.68 km^{-1}, suggesting medium to high drainage concentration. This favors infiltration by reducing rapid runoff, consistent with earlier findings that medium drainage density is optimal for recharge in semi-humid African basins [28]. However, the role of drainage density can vary by lithology; for instance, [29] showed that high densities in impermeable basement terrains may enhance runoff instead. This highlights a limitation of using drainage density alone as a proxy for recharge potential without considering substrate permeability.

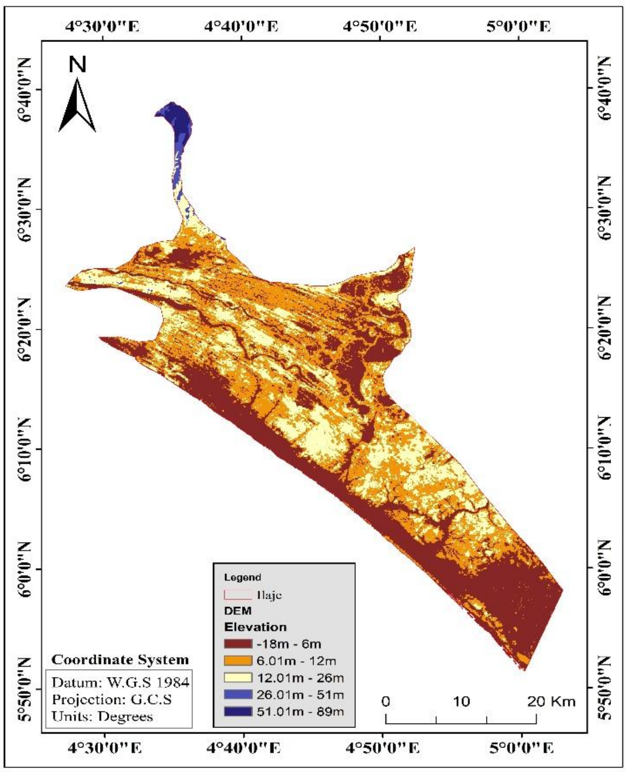
Soil geology further differentiates the two regions. Ilaje is dominated by Gleysols, known for their high porosity and groundwater storage capacity, while Ile-Ife is dominated by

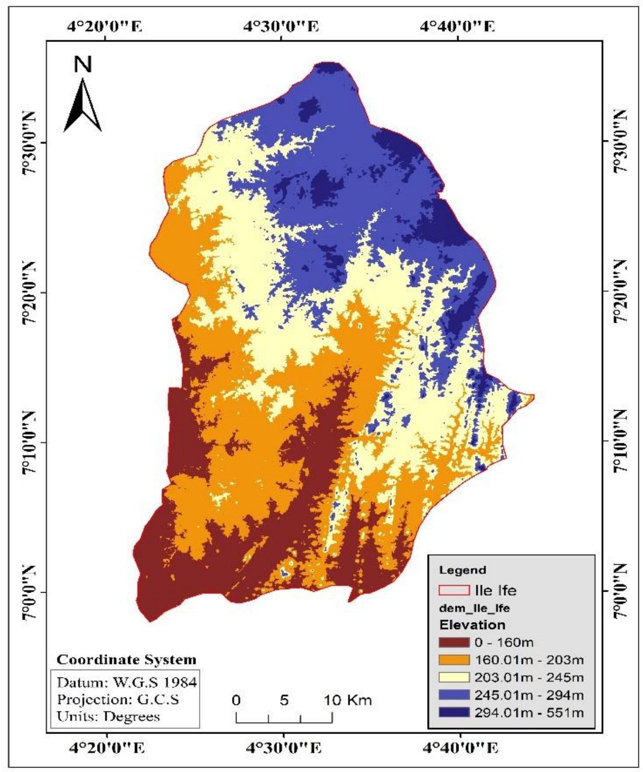
Ferric Luvisols, which are less favorable for groundwater storage, though localized aquifers may occur in areas with Lithosols and Eutric Nitosols. This pattern aligns with other Nigerian studies, where sedimentary soils were found to store more water than crystalline soils, but also demonstrated variability due to textural heterogeneity [23].

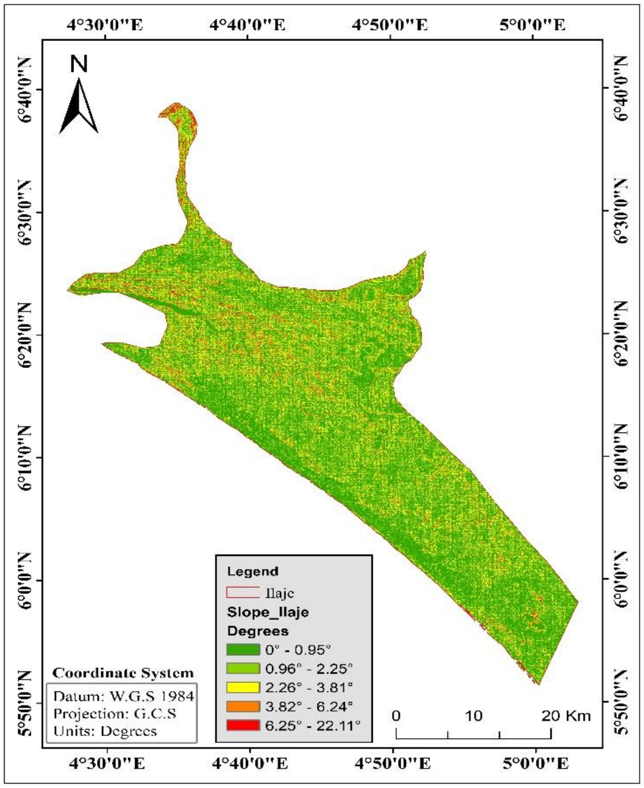
Remote sensing–derived indices provided additional insights. NDVI values range from –0.08 to 0.47 in Ilaje and –0.11 to 0.46 in Ile-Ife, reflecting substantial vegetation cover in both areas. Dense vegetation reduces surface runoff and supports infiltration, in agreement with studies applying vegetation indices to groundwater exploration [30]. Similarly, NDWI values highlighted surface water presence, which often correlates with recharge potential. However, as noted by [31, 32], NDVI and NDWI are seasonally sensitive, and the present study, based on a single period of imagery, may not capture interannual variability—representing a limitation of the remote sensing approach.

One of the most critical differences lies in lineament density. Ilaje exhibits higher densities (up to 1.4 km⁻¹), enhancing porosity and permeability, while Ile-Ife's fractures are more dispersed, reflecting heterogeneity in basement aquifers. This supports the established view that fracture density and connectivity strongly influence well yields in basement terrains [33, 34]. Nevertheless, satellite-derived lineament mapping cannot fully account for subsurface fracture continuity, which remains a methodological limitation.

Rainfall distribution reinforces the hydrogeological contrast between the two regions. Ilaje records significantly higher rainfall (2586–4163 mm) compared to Ile-Ife (2383–3433 mm). While higher rainfall increases recharge potential, studies have shown that actual recharge depends strongly on soil infiltration capacity and geology [35, 36]. Thus, Ilaje's higher rainfall advantage may be offset in part by its salinity vulnerability, while Ile-Ife's moderate rainfall is constrained by basement aquifer storage.



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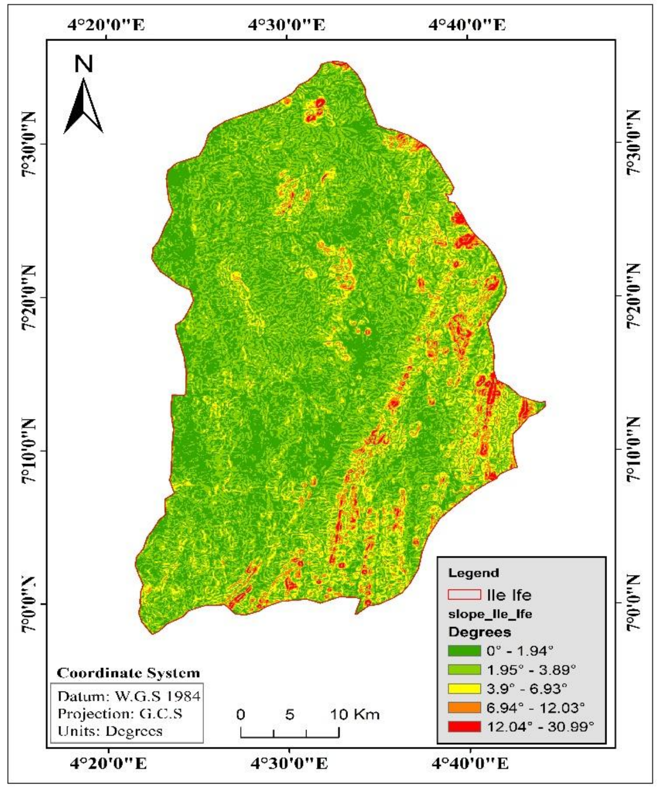
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0° - 1.94°
1.95° - 3.89°
3.9° - 6.93°
6.94° - 12.03°
12.04° - 30.99°
Coordinate System
Datum: W.G.S 1984
Projection: G.C.S
Units: Degrees
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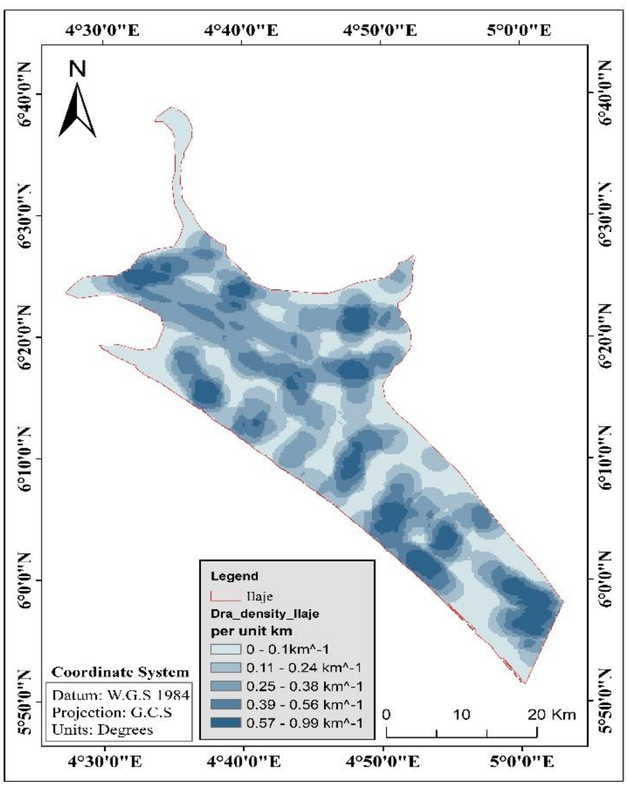
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per unit km
0 - 0.1km^-1
0.11 - 0.24 km^-1
0.25 - 0.38 km^-1
0.39 - 0.56 km^-1
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Projection: G.C.S
Units: Degrees
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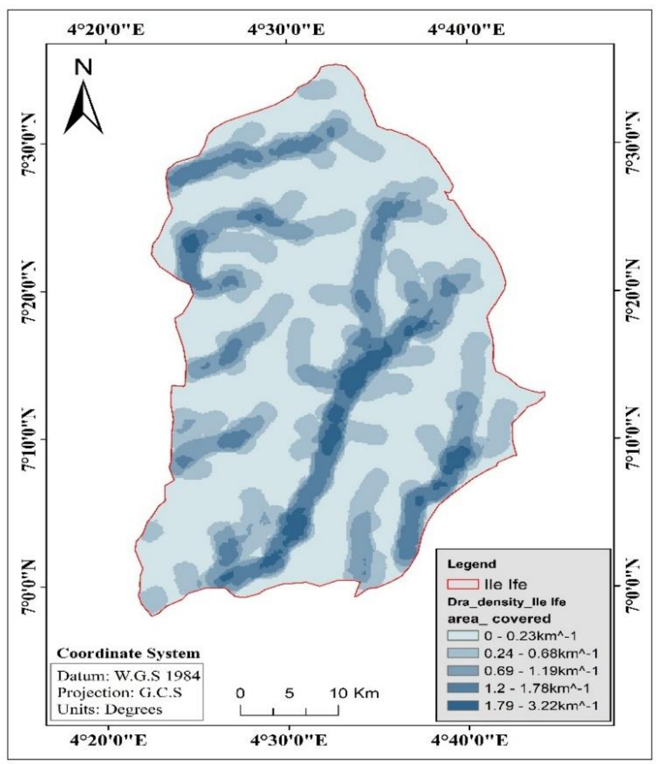
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Ile Ife
Dra_density_Ile Ife
area_ covered
0 - 0.23km^-1
0.24 - 0.68km^-1
0.69 - 1.19km^-1
1.2 - 1.78km^-1
1.79 - 3.22km^-1
Coordinate System
Datum: W.G.S 1984
Projection: G.C.S
Units: Degrees
0 5 10 Km

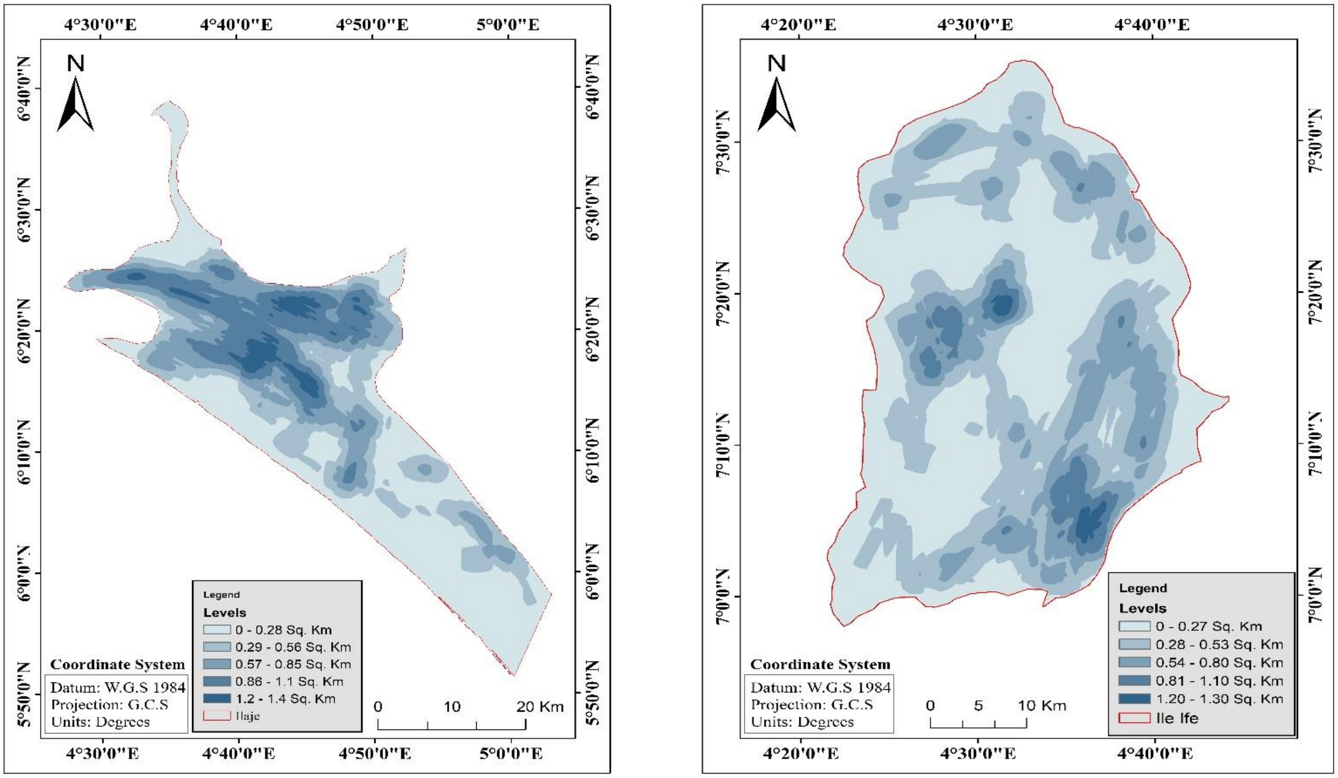
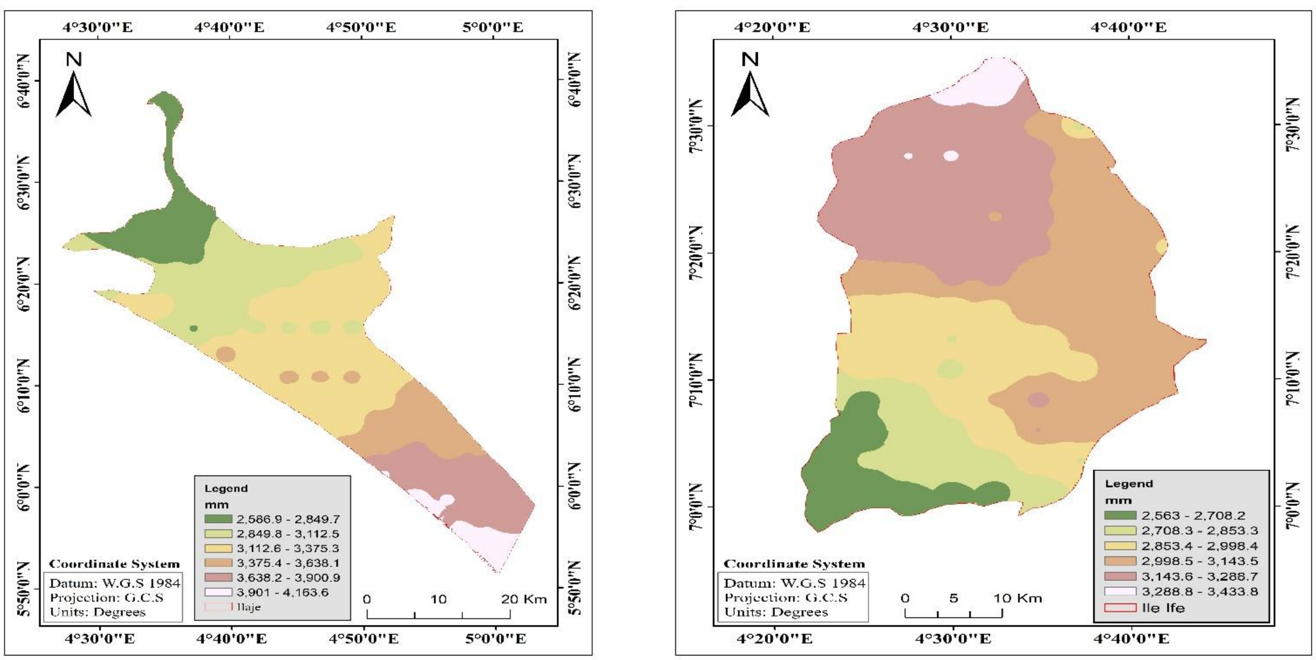
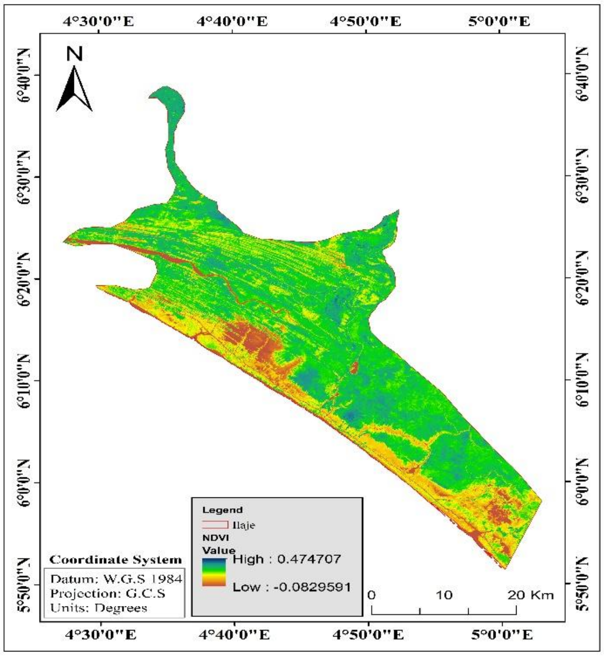


Fig. 2. Topographic and Drainage Factors: Composite maps of DEM, slope, drainage density, and lineament density for groundwater potential assessment in Ilaje (coastal) and Ile-Ife (non-coastal).




4°30'0"E
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4°50'0"E
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N
6°40'0"N
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6°20'0"N
6°10'0"N
6°0'0"N
5°50'0"N
Legend
Ilaje
NDVI
Value
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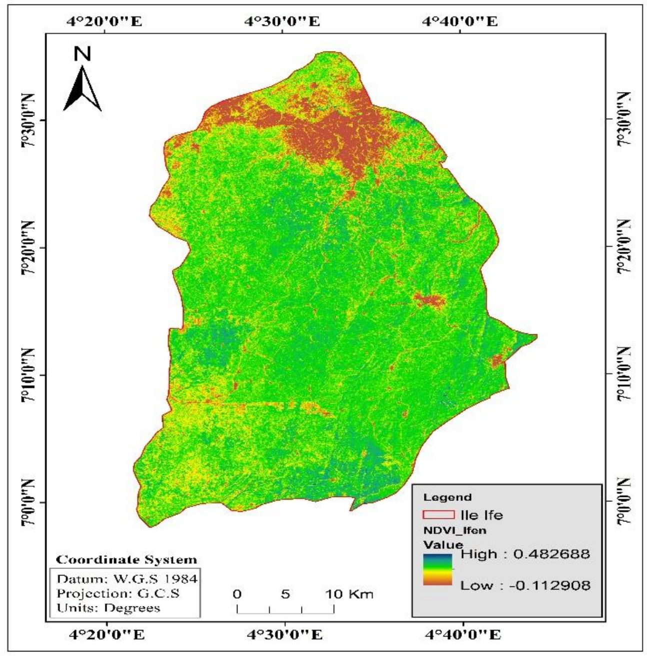
Low : -0.0829591
Coordinate System
Datum: W.G.S 1984
Projection: G.C.S
Units: Degrees
0 10 20 Km


4°20'0"E
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Legend
Ile Ife
NDVI_Ifen
Value
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Projection: G.C.S
Units: Degrees
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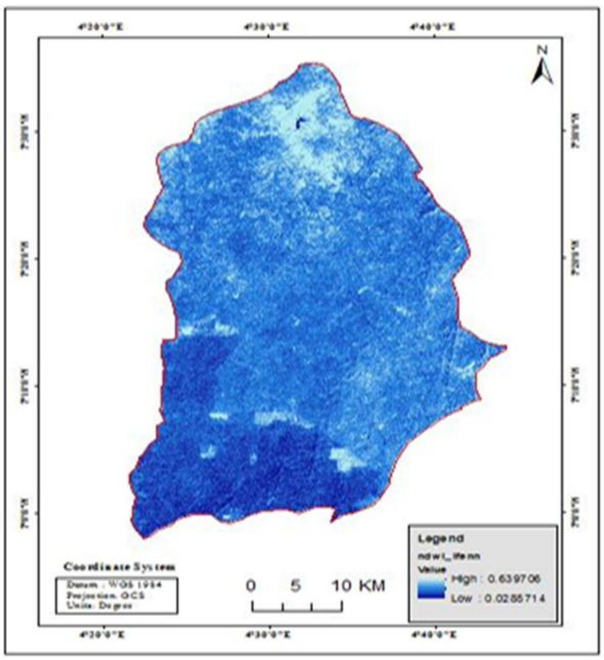
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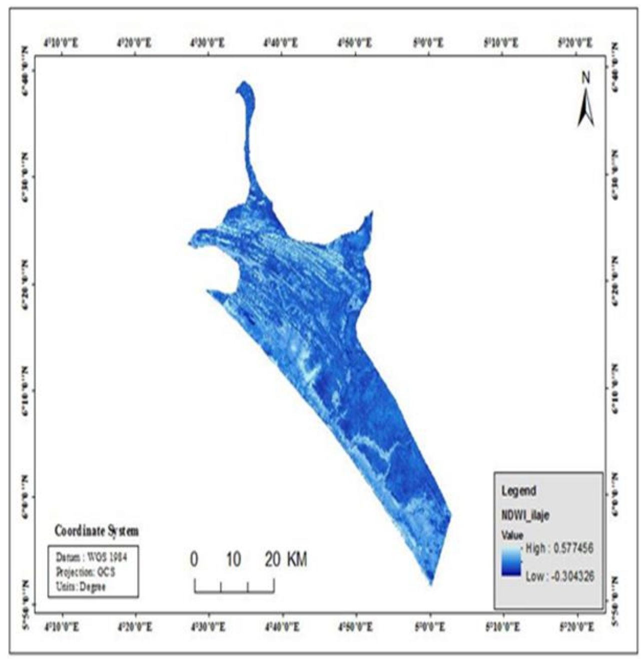
Coordinate System
0 5 10 KM


N
Legend
NDWI_ilaje
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0 10 20 KM

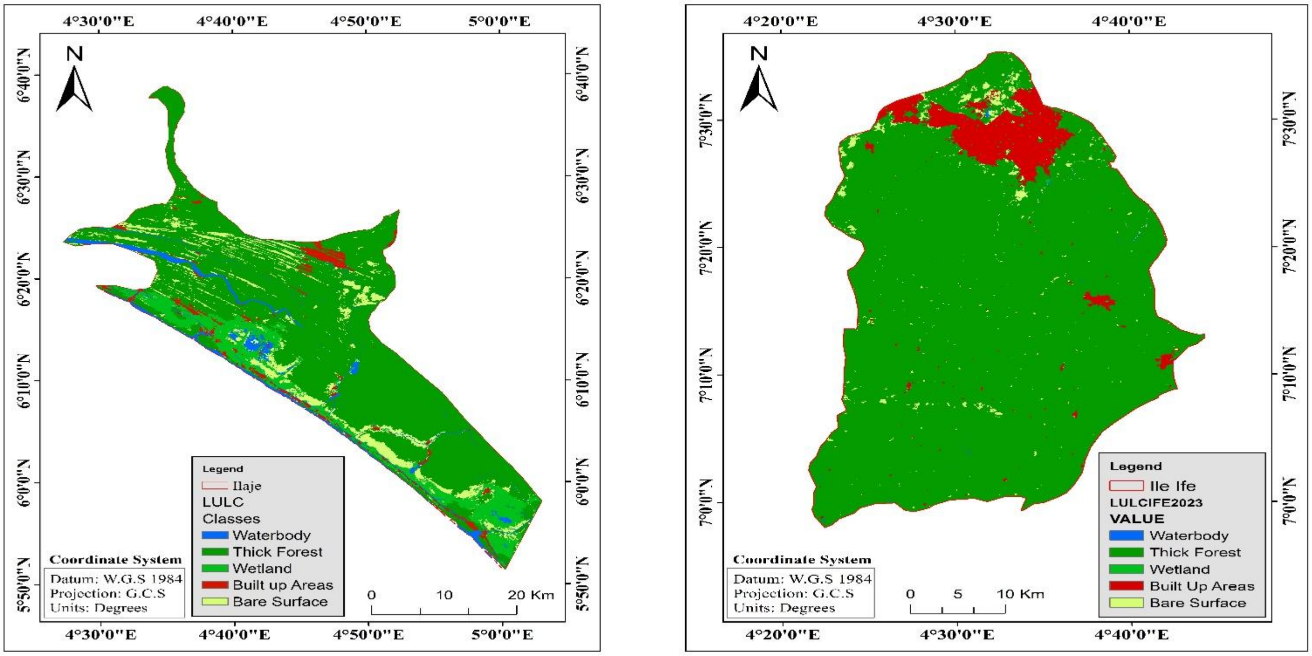

Fig. 3. Climatic and Vegetation Factors: Composite maps of rainfall, NDVI, NDWI, and LULC for Ilaje (coastal) and Ile-Ife (non-coastal).

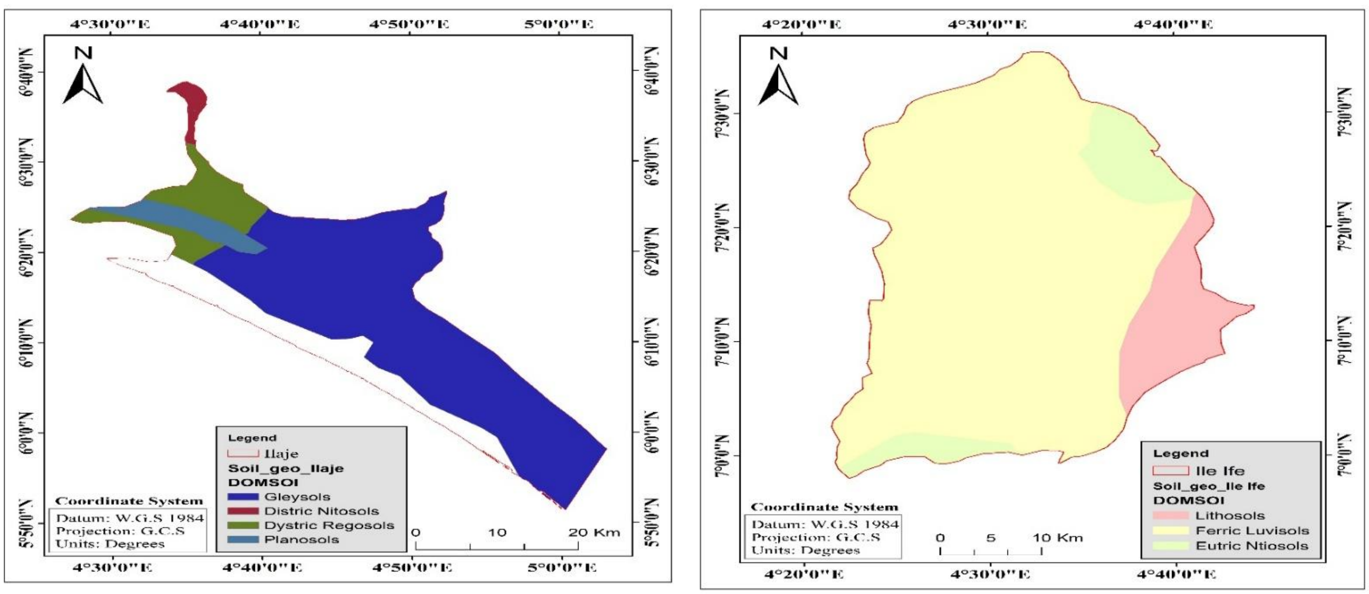

Fig. 4. Geological Factor: Composite maps of geology for Ilaje (coastal) and Ile-Ife (non-coastal).

A. Groundwater Potential Zones and Comparative Analysis

The GIS-based AHP model effectively captured the multifaceted effects of these parameters on groundwater dynamics, producing a spatially detailed understanding essential for regional assessment. The model's stability was further confirmed by the sensitivity analysis (Table V), which identified lineament density, slope, and rainfall as the primary parameters to which groundwater potential delineation responds most strongly.

The weighted overlay analysis produced a Groundwater Potential Zone (GPZ) map with five distinct classes for both Ilaje and Ile-Ife (Figures 5 and 6). The spatial distribution and area coverage of these zones, as summarized in Table VIII, reveal a significant contrast in groundwater availability, a finding rooted in their distinct hydrogeological settings (Table IX).

TABLE VIII. CLASSIFICATION OF GROUNDWATER POTENTIAL ZONES AND CORRESPONDING AREA COVERAGE (IN KM² AND PERCENTAGE) FOR ILAJE AND ILE-IFE.

Groundwater Potential Classes	Coastal Region (Ilaje)		Non-Coastal Region (Ile-Ife)	
	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)
Highly available	89.34	6.15	72.86	4.00
Available	220.55	25.29	253.29	13.91
Moderately Available	371.12	24.07	699.62	38.43
Fairly Available	422.31	33.35	589.61	32.39
Not Available	350.50	24.11	205.02	11.26

TABLE IX. SUMMARY OF GEOLOGICAL AND HYDROLOGICAL FACTORS INFLUENCING GROUNDWATER POTENTIAL IN ILAJE AND ILE-IFE.

Factor	Ilaje (Coastal)	Ile-Ife (Non-Coastal)	Implications for Groundwater
Slope	0 - 0.950	0 - 1.940	Ilaje: Flatter terrain
Elevation	-18m to 26.01m	160m to 245.01m	Ile-Ife: Higher elevation range
Drainage Density	0.10 - 0.68 km-1	0.10 - 0.68 km-1	Both suitable, ranges differ
Geology	Predominantly Gleysols	More Ferric Luvisols, Lithosols, Eutric Nitosols	Ilaje: Gleysols facilitate drilling, Ile-Ife: Mixed suitability
NDVI	Differs	Differs	Varying vegetation water stress
Lineament Density	0 - 1.4 km-1	0 - 1.30 km-1	Ilaje: Higher, more N-ward conc.
Rainfall	2586 - 4163mm	2383 - 3433mm	Ilaje: Higher rainfall
NDWI	Differs	Differs	Varying surface water
Salinity	Higher	Lower	Ilaje: Risk of saltwater int.
Water Table	Shallower	Deeper	Influence on extraction costs

1) Groundwater Potential Zones and Comparative Insights

Ilaje, the coastal region, exhibits a higher proportion of *Highly Available* groundwater zones (6.15%) compared to Ile-Ife (4.00%). This pattern reflects Ilaje's unique hydrogeology, including its flat topography, significantly higher annual rainfall, and high primary porosity from sedimentary geology. Similar findings have been reported in other sedimentary basins, where flat terrain and unconsolidated sediments enhance recharge and storage capacity [37]. However, this apparent abundance comes with a critical caveat: the presence of elevated salinity, which raises the risk of saltwater intrusion in low-lying zones near the Atlantic Ocean. Comparable challenges have been highlighted in studies of coastal aquifers in India, Egypt, and other deltaic environments, where seawater intrusion offsets otherwise high groundwater availability [38, 39]. This emphasizes that groundwater potential in coastal settings must be evaluated not only in terms of quantity but also in terms of quality and long-term sustainability.

In sharp contrast, Ile-Ife is dominated by *Moderately Available* zones (38.43%), with a much smaller proportion of highly available zones. This distribution is consistent with the basement complex geology, where groundwater occurs primarily in weathered overburden and fractured bedrock aquifers with limited storage capacity. Comparable results were observed in basement terrains of Ondo and Ekiti, Nigeria, where aquifers are controlled more by secondary porosities than by lithological storage [20, 40]. The higher elevation and deeper water table in Ile-Ife further constrain recharge compared to Ilaje, aligning with well-established hydrogeological principles for upland terrains [12, 41, 42].

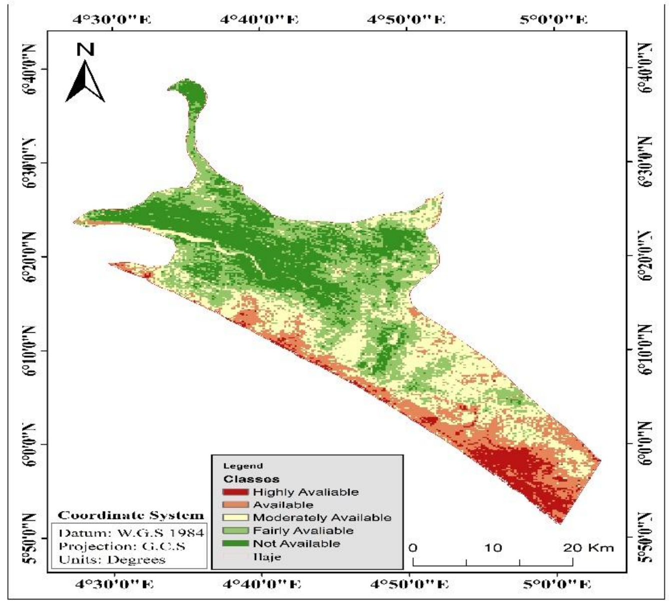

Fig. 5. Groundwater Potential Zone map for Coastal Region (Ilaje)

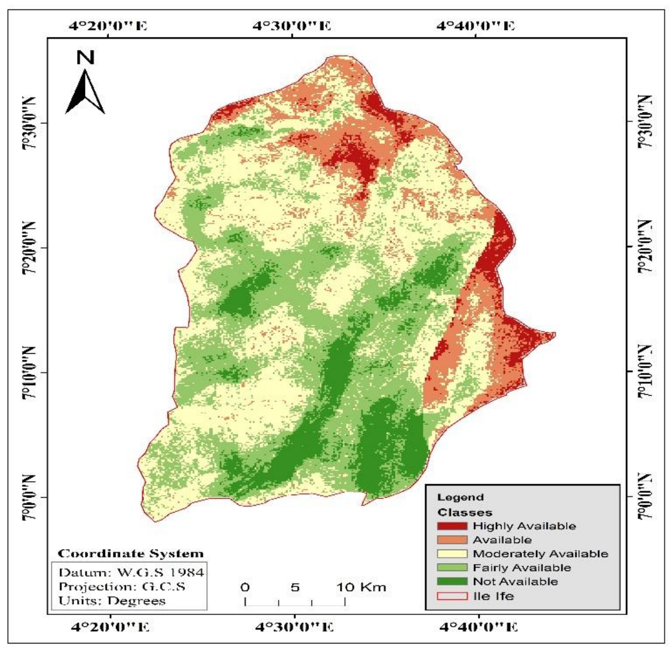

Fig. 6. Groundwater Potential Zone map for Non-Coastal Region (Ile-Ife, Osun state).

These contrasting outcomes reinforce both the predictive capacity of the GIS–AHP model and long-established hydrogeological theories regarding sedimentary versus crystalline aquifer systems. They demonstrate that even under similar climatic drivers, geomorphological and geological contexts fundamentally shape groundwater dynamics, a finding consistent with comparative studies in India, and southern Nigeria [38, 40]. The strength of this study lies in its integrative approach—using multiple thematic datasets and AHP to simultaneously capture topographic, hydrological, climatic, geological, and remote sensing–based indicators. However, some limitations remain: the model is sensitive to input data quality, and factors such as salinity, fracture connectivity, and seasonal recharge dynamics cannot be fully captured by the available datasets.

2) Wider Implications for Water Resource Management

The comparative analysis of Ilaje and Ile-Ife has important implications for groundwater policy and management. In Ilaje, the identification of high-potential zones highlights opportunities for groundwater development, but the salinity factor necessitates cautious abstraction, continuous water quality monitoring, and potentially the application of Managed Aquifer Recharge (MAR) strategies. Similar adaptive management approaches have been suggested for other vulnerable coastal aquifers [43].

In Ile-Ife, where groundwater availability is generally moderate to low, resource management should focus on optimizing existing boreholes, promoting efficient water use, and exploring artificial recharge through small-scale surface impoundments. Such recommendations align with strategies adopted in basement complex regions of Africa and India to maximize limited groundwater reserves [38].

The clear visual and quantitative contrasts in groundwater potential between the two regions (Figures 7–10) highlight the risks of adopting a "one-size-fits-all" groundwater policy. Instead, water resource planning must be context-specific, integrating both hydrogeological conditions and socio-environmental pressures. This study therefore contributes empirical evidence to support Nigeria's efforts to strengthen climate-resilient water governance and advances the global pursuit of Sustainable Development Goal 6 (Clean Water and Sanitation).

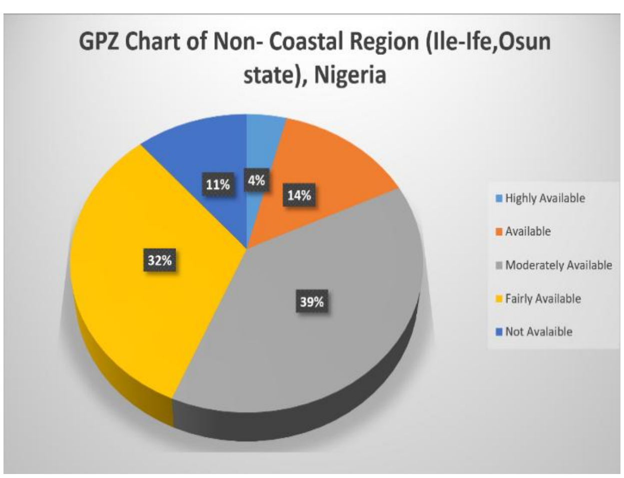

Fig. 7. Pie Chart representation of Ile-Ife

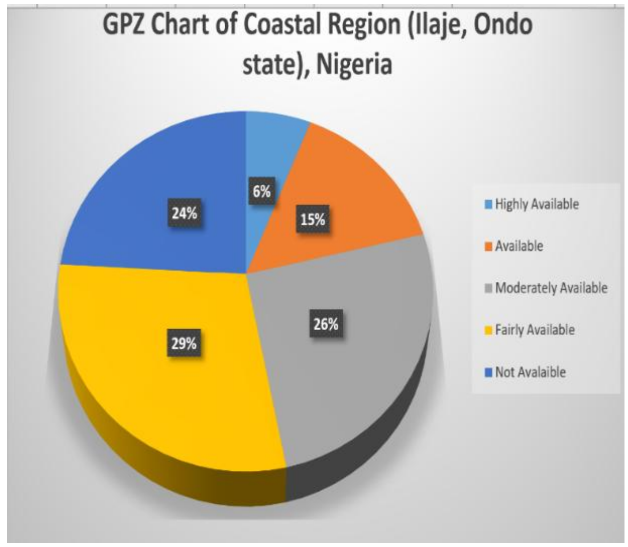

Fig. 8. Pie Chart representation of Ilaje

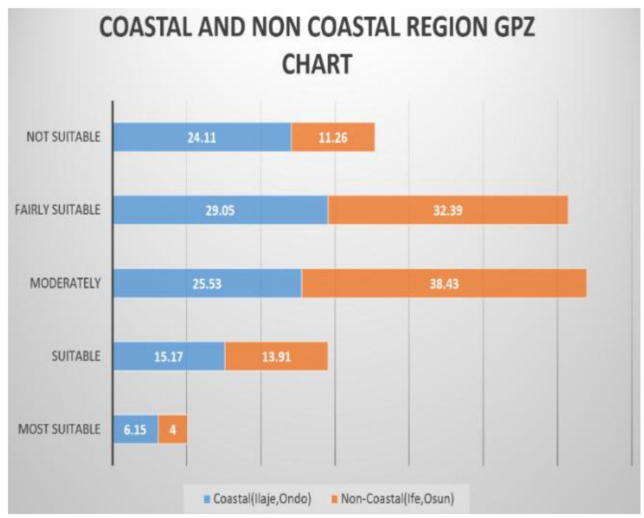

Fig. 9. Bar chart comparing groundwater potential classification between Coastal and Non-Coastal Regions

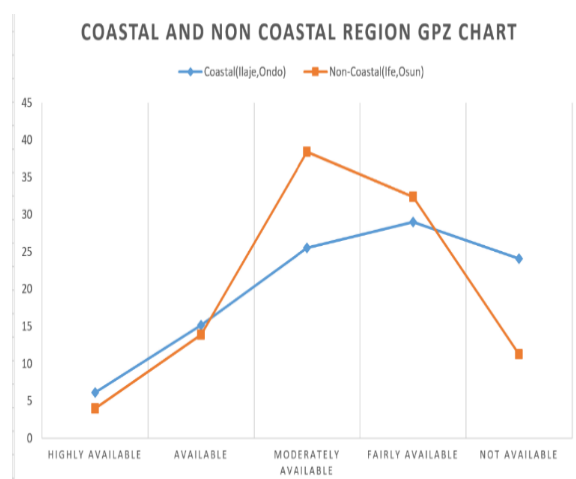

Fig. 10. Line chart showing groundwater potential trends between Coastal and Non-Coastal Regions

V. Study Limitations

While the use of AHP-GIS techniques in this study offered a methodical and data-driven way to map groundwater potential, there are a number of inherent limitations that should be critically examined. The input datasets' temporal consistency and spatial resolution are two major limitations. For example, although widely used and dependable for general hydrological assessments, the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) from 2000, with a 30-meter resolution, may not fully resolve the micro-topographic features and subtle fracture systems that are frequently essential for capturing intricate groundwater flow paths, particularly within the complex, heterogeneous basement terrains characteristic of Ile-Ife.

A localized misclassification of high-potential zones or an underestimation of recharge pathways where such fine-scale features predominate could result from the spatial uncertainty this introduces.

Furthermore, the incorporation of thematic layers from various eras invariably introduces inconsistencies. While geologically stable parameters like slope (derived from the 2000 DEM) and bedrock geology (1990) are thought to be relatively constant over short to medium spans, rapidly changing urbanization, climate variability, and land management practices can cause significant spatiotemporal changes in other dynamic parameters like rainfall (2000-2020 mean) and, in particular, land use/land cover (2023 Landsat imagery). Since urban sprawl is common in rapidly developing non-coastal areas like Ile-Ife, the accuracy of recharge estimations may be impacted by the older datasets' potential failure to fully reflect the current hydrogeological realities, despite their wide range of applications.

Moreover, the Analytical Hierarchy Process (AHP) has inherent subjectivity even though it is strong and successful at incorporating expert knowledge. Cognitive biases may affect the model results due to the pairwise comparison process, which depends on expert judgment for weight assignment. Even though the study carefully made sure that the Consistency Ratio ($CR < 0.1$) was acceptable and included a sensitivity analysis (Table V) to measure the impact of changes in parameter weighting on spatial results, this only lessens, not completely removes, the subjective component. A more thorough examination would recognize that even though the derived weights are statistically consistent, they still represent the opinions of the experts who were consulted and the particular literature that was examined, which might not fully account for all potential hydrogeological subtleties.

The findings' context-specificity and the model's underlying spatial uniformity assumption present further restrictions. The model's assumption that each factor's influence (and consequently its derived weight) stays constant throughout the entire study area (i.e., applies equally to both regions within the single AHP matrix) may not be entirely accurate given the stark differences between the geological formations of Ilaje (sedimentary) and Ile-Ife (crystalline basement). This simplification, which is typical in AHP applications at the regional level, may result in situations where the groundwater potential in specific localized zones is misclassified because their particular circumstances may require a different optimal weighting. Finally, this GWPZ model's calibration is especially suited to the hydrogeological and environmental features of Ile-Ife and Ilaje. Therefore, the derived GWPZ maps may not be directly transferable or applicable to other regions with significantly different hydrogeological settings without further thorough field investigation and model refinement, unless they are adequately revalidated and recalibrated using local primary data and possibly incorporate dynamic hydrogeological parameters (such as observed water levels or well yields).

The study did not include groundwater salinity indicators, such as electrical conductivity or total dissolved solids, which are critical for assessing water quality in coastal aquifers. As such, while Ilaje exhibits high recharge potential, the quality of that groundwater remains uncertain without further hydrochemical analysis.

VI. Conclusion

This study successfully mapped groundwater potential zones (GWPZs) in Nigeria's contrasting coastal Ilaje and non-coastal Ile-Ife regions using a robust GIS-based multi-criteria decision analysis (MCDA) with the Analytical Hierarchy Process (AHP). The research provides a significant scientific contribution by demonstrating that a direct comparative analysis across hydrogeologically disparate regions yields unique insights into the context-dependent behavior of groundwater influencing factors. The results validate that while sedimentary basins typically possess a higher intrinsic groundwater potential, their sustainability is critically threatened by factors like saltwater intrusion, a vulnerability absent in the less permeable basement complexes.

The findings have profound implications for water resource management in Nigeria. They validate that a "one-size-fits-all" strategy is unsustainable and emphasize the need for spatially differentiated management policies. The study goes beyond traditional GWPZ mapping by offering a critical understanding of the specific vulnerabilities and management needs of coastal sedimentary versus inland crystalline aquifers. The AHP-GIS methodology, enhanced by a thorough sensitivity analysis, proved to be a flexible and transparent approach for preliminary assessments.

Based on our findings, we offer the following context-specific recommendations:

- Ilaje (Coastal Region): To mitigate the risk of saltwater intrusion and enhance groundwater sustainability, Managed Aquifer Recharge (MAR) strategies such as infiltration ponds and controlled recharge basins should be implemented. These systems can improve freshwater retention and buffer against salinity encroachment.
- Ile-Ife (Non-Coastal Region): Given the moderate to variable recharge rates, decentralized rainwater harvesting systems and shallow recharge trenches should be promoted. These can help increase infiltration during peak rainfall events and support domestic and agricultural water supply during dry spells.

By promoting these context-specific interventions, Nigeria can work towards more resilient and sustainable water resource management that is tailored to its diverse hydrogeological landscape.

REFERENCES

[1] Das, B., Pal, S., Malik, S., & Chakrabortty, R. (2018). Modeling groundwater potential zones of Puruliya district, West Bengal, India using remote sensing and GIS techniques. *Geology, Ecology, and Landscapes*, *3*, 223–237.

[2] Kordestani, M. D., Naghibi, S. A., Hashemi, H., Ahmadi, K., Kalantar, B., & Pradhan, B. (2019). Groundwater potential mapping using a novel data-mining ensemble model. *Hydrogeology Journal*, *27*(1), 211–224.

[3] Upadhyay, R. K., Tripathi, G., Đurin, B., Šamanovic, S., Cetl, V., Kishore, N., Sharma, M., Singh, S. K., Kanga, S., & Wasim, M. (2023). Groundwater Potential Zone Mapping in the Ghaggar River Basin, North-West India, Using Integrated Remote Sensing and GIS Techniques. *Water*, *15*, 961. https://doi.org/10.3390/w15050961

[4] Gnanachandrasamy, G., Zhou, Y., Bagyaraj, M., Venkatramanan, S., Ramkumar, T., & Wang, S. (2018). Remote sensing and GIS based groundwater potential zones mapping in Ariyalur district, Tamil Nadu. *Journal of the Geological Society of India*, *92*(4), 484–490.

[5] Jhariya, D. C., Khan, R. A., Mondal, K. C., Kumar, T., Lekha, I., & Singh, V. P. (2021). Assessment of groundwater potential zone using GIS-based multi-influencing factor (MIF), multi-criteria decision analysis (MCDA) and electrical resistivity survey techniques in Raipur city, Chhattisgarh, India. *Journal of Water Supply: Research and Technology-Aqua*, *70*(1), 129–148.

[6] Doke, A. B., Zolekar, R. B., Patel, H., & Das, S. (2021). Geospatial mapping of groundwater potential zones using multi-criteria decision-making AHP approach in a hardrock basaltic terrain in India. *Ecological Indicators*, *127*, 107685.

[7] Saidu, A. A., Aldrees, A., Dan'azumi, S., & Abba, S. I. (2024). Groundwater potential mapping in a semi-arid region of Northern Nigeria by integrating the analytic hierarchy process and GIS.

[8] Ifediegwu, S. I., Nnebedum, D. O., & Nwatarali, A. N. (2021). Assessment of groundwater potential zones using GIS and AHP techniques: a case study of the Lafia district, Nasarawa State, Nigeria. *Applied Water Science*, *12*(1), 1–21.

[9] Kassa, S. B., Zimale, F. A., Mulu, A., Worku, T. A., Wossene, M. L., Meshesha, T. M., ... & Mekonnen, H. A. (2025). Groundwater Potential Assessment Using Integrated Geospatial and Analytic Hierarchy Process Techniques (AHP) in Chemoga Watershed, Upper Blue Nile Basin, Ethiopia. *Air, Soil and Water Research*, *18*(1), 14-19.

[10] Ahmed, S., Ifeakor, A. R., Zayyan, A. S., & Dadan-Garba, A. (2022). Groundwater potential zone (GWPZ) mapping using analytical hierarchy process (AHP), remote sensing and GIS for Enugu metropolis, Nigeria. *Academy Journal of Science and Engineering*, *16*(1), 10-21.

[11] Ejepu, J. S., Jimoh, M. O., Abdullahi, S., & Mba, M. A. (2022). Groundwater exploration using multi-criteria decision analysis and analytic hierarchy process in Federal Capital Territory, Abuja, Central Nigeria. *International Journal of Geosciences*, *13*(1), 33–53.

[12] Bekri, S., & Hoskan, N. (2023). Investigation of Groundwater Potential within the Coastal and the Orontes Basins in Syria by Using Remote Sensing, Analytical Hierarchy Processes (AHP) and Geographic Information Systems (GIS). *Research Square*. https://doi.org/10.21203/rs.3.rs-2650753/v1

[13] Albhadili, S., Almallah, I., & Almulla, S. (2023). Mapping groundwater potential recharge zones of Wadi Al-Batin alluvial fan, using remote sensing and GIS techniques, Southwestern Iraq. *Iraqi Journal of Science*, *19*(1), 99–115.

[14] Ali, D., Szucs, P., & Mohammed, S. H. (2021). Integrated remote sensing and GIS techniques to delineate groundwater potential area of Chamchamal basin, Sulaymaniyah, NE Iraq. *Kuwait Journal of Science*, *48*(3), 2-10. https://doi.org/10.48129/kjs.v48i3.9699

[15] Ankana, H., & Dhanaraj, G. (2021). Study of selected influential criteria on groundwater potential storage using geospatial technology and multi-criteria decision analysis (MCDA) approach: A case study. *The Egyptian Journal of Remote Sensing and Space Sciences*, *24*(1), 22-25.

[16] Ndhlovu, G. Z., & Woyessa, Y. E. (2021). Integrated Assessment of Groundwater Potential Using Geospatial Techniques in Southern Africa: A Case Study in the Zambezi River Basin. *Water*, *13*, 2610. https://doi.org/10.3390/w13192610

[17] Selvam, S., Majesh, N., Sabarathinam, C., Ramamanickam, M., & Sashikkumar, M. (2015). A GIS-based identification of groundwater recharge potential zones using RS and IF technique: A case study in Ottapidaram taluk, Tuticorin district, Tamil Nadu. *Environmental Earth Sciences*, *73*(7), 3785–3799.

[18] Bourjila, A., Dimane, F., Hossain, E., Ouarghi, N., Nouayti, N., Morad Taher, ... & Bensiali, A. (2021). Groundwater potential mapping by applying GIS, remote sensing and multi-criteria decision analysis in the Ghiss basin, Northern Morocco. *Groundwater for Sustainable Development*, *10*, 100293. https://doi.org/10.1016/j.gsd.2021.100293

[19] Mallick, S., Standish, J. J., & Bizimis, M. (2016). Constraints on the mantle mineralogy of slow and ultra-slow spreading ridges: Hafnium isotopes in abyssal peridotites and basalts from the 9–15 S Southwest Indian Ridge. *Earth and Planetary Science Letters*, *440*, 42–53.

[20] Roy, B. P., Rramkumar, M., & NnagAran, R. (2018). Cenozoic Chemostratigraphy: Understanding the Most Recent Era of the Earth's History. In G. A. N. & F. M. (Eds.), *Geophysical Monograph Series* (Vol. 240, pp. 261–277): *Chemostratigraphy across Major Chronological Boundaries*. https://doi.org/10.1002/9781119382508.ch13

[21] Fatah, K. K., Mustafa, Y. T. & Hassan, I. O (2022. Flood susceptibility mapping using an analytic hierarchy process model based on remote sensing and GIS approaches in Akre District, Kurdistan Region, Iraq. The Iraqi Geological Journal, 123-151

[22] Fatah, K. K., Mustafa, Y. T., & Hassan, I. O. (2024). Geoinformatics-based frequency ratio, analytic hierarchy process and hybrid models for landslide susceptibility zonation in Kurdistan Region, Northern Iraq. Environment, Development and Sustainability, 26(3), 6977-7014.

[23] Oyelowo, G. B., Martins, O. O., Francis, O. A., & Ademilua, O. L. (2014). Integration of hydrogeophysical and remote sensing data in the assessment of groundwater potential of the basement complex terrain of Ekiti State, Southwestern Nigeria. *Ife Journal of Science*, *16*(3), 353–363. https://doi.org/10.4314/IJS.V16I3

[24] Idris, M. A., Garba, M. L., Kasim, S. A., Madabo, I. M., & Dandago, K. A. (2018). The role of geological structures on groundwater occurrence and flow in crystalline basement aquifers: a status review. *Bayero Journal of Pure and Applied Sciences*, *11*(1), 155–164. https://doi.org/10.4314/BAJOPAS.V11I1.27

[25] Akinwumiju, A. S. (2016). GIS-based integrated groundwater potential assessment of Osun drainage basin, southwestern Nigeria. *Ife Journal of Science*, *18*(1), 147–168. https://doi.org/10.4314/IJS.V18I1

[26] Oni, A. G., Adediran, T. A., Olorunfemi, M. O., Eniola, P. J., & Adewale, E. A. (2020). Evaluation of the groundwater potential of Modomo Community in Ile-Ife, Southwest Nigeria, using integrated geophysical techniques. *Sustainable Water Resources Management*, *6*(6), 1–18. https://doi.org/10.1007/S40899-020-00467-8

[27] Grinevskii, S. O. (2014). The Effect of Topography on the Formation of Groundwater Recharge. *Moscow University Geology Bulletin*, *69*(1), 47–52. https://doi.org/10.3103/S0145875214010025

[28] Michael, H. A., Scott, K. C., Koneshloo, M., Yu, X., Khan, M. R., & Li, K. (2016). Geologic influence on groundwater salinity drives large seawater circulation through the continental shelf. *Geophysical Research Letters*, *43*(20). https://doi.org/10.1002/2016GL070863

[29] Scherler, D., & Lodes, E. (2023). *Exploring lithological controls on drainage density in Santa Gracia, Central Chile*. https://doi.org/10.5194/egusphere-egu23-11578

[30] Ige-Olumide, O. (2013). *Spatial analysis of soil fertility estimates and NDVI in south-western Nigeria: A new paradigm for routine soil fertility mapping*.

[31] Chu, D., Lu, L., & Zhang, T. (2007). Sensitivity of Normalized Difference Vegetation Index (NDVI) to Seasonal and Interannual Climate Conditions in the Lhasa Area, Tibetan Plateau, China. *Arctic, Antarctic, and Alpine Research*, *39*(4), 635–641. https://doi.org/10.1657/1523-0430(07-501)[CHU]2.0.CO;2

[32] Prajesh, P. J., Kannan, B., Pazhanivelan, S., Kumaraperumal, R., & Ragunath, K. P. (2019). Analysis of seasonal vegetation dynamics using

MODIS derived NDVI and NDWI data: a case study of Tamil Nadu. *Madras Agricultural Journal*, *106*, 362–368. https://doi.org/10.29321/MAJ.2019.000275

[33] Fang, W., Qin, X., Liu, C., Wang, R., Pu, J., Jiang, H., & He, W. (2022). Quantitative Evaluation of Well Performance Affected by Fracture Density and Fracture Connectivity in Fractured Tight Reservoirs. *Geofluids*, *2022*, 1–14. https://doi.org/10.1155/2022/2805348

[34] Petrik, A., Vahle, C., Gianotten, I. P., Trøan, L. I., Rojo, L., & Galbraith, K. (2024). *Fracture Connectivity and Effective Permeability based on High-Resolution Borehole Images*. https://doi.org/10.3997/2214-4609.202410437

[35] Jeon, B. C., Lee, S. G., Kim, S. S., Kim, K. S., & Kim, N. (2019). *A Study on the Rainfall Infiltration Capacity of Soil (A Study on the Mid-Mountain Area of Jeju Island)*. *29*(2), 99–112. https://doi.org/10.9720/KSEG.2019.2.099

[36] Nimmo, J. R., & Shillito, R. (2023). Infiltration of Water Into Soil. *Oxford Research Encyclopedia of Environmental Science*. https://doi.org/10.1093/acrefore/9780199389414.013.768

[37] Dijksma, R., Brooks, E. S., & Boll, J. (2011). Groundwater recharge in Pleistocene sediments overlying basalt aquifers in the Palouse Basin, USA: modeling of distributed recharge potential and identification of water pathways. *Hydrogeology Journal*, *19*(2), 489–500. https://doi.org/10.1007/S10040-010-0695-9

[38] Naik, P. C. (2017). *Seawater Intrusion in the Coastal Alluvial Aquifers of the Mahanadi Delta*. https://www.amazon.com/Seawater-Intrusion-Alluvial-SpringerBriefs-Technology/dp/3319665103

[39] Abd-Elhamid, H. F., Abd-Elaty, I., & Negm, A. M. (2018). *Control of Saltwater Intrusion in Coastal Aquifers* (pp. 355–384). Springer, Cham. https://doi.org/10.1007/698_2017_138

[40] Ijila, P., Kolebaje, O., Ojo, A., & Akinyemi, P. (2018). Geophysical Characterization of the Basement Rocks and Groundwater Potential Zones Using Electrical Resistivity Sounding Technique. *Journal of Environment and Earth Science*, *8*(7), 21–33. https://www.iiste.org/Journals/index.php/JEES/article/download/43352/44680

[41] Zwick, P. C. (2007). *Smart land-use analysis: The LUCIS model*. Esri.

[42] Paquette, J., & Lowry, J. (2012). Flood hazard modelling and risk assessment in the Nadi River Basin, Fiji, using GIS and MCDA. *South Pacific Journal of Natural and Applied Sciences*, *30*, 33. https://doi.org/10.1071/SP12003

[43] Hiscock, K. M., Balashova, N., Cooper, R. J., Bradford, P., Patrick, J., & Hullis, M. (2023). Developing managed aquifer recharge (MAR) to augment irrigation water resources in the sand and gravel (Crag) aquifer of coastal Suffolk, UK. *Journal of Environmental Management*, *351*, 119639. https://doi.org/10.1016/j.jenvman.2023.119639