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DELINEATION OF GROUNDWATER POTENTIAL ZONE USING REMOTE SENSING AND GIS TECHNIQUES WITHIN ZAMFARA REGION, NORTH WEST NIGERIA

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Abstract

Geographic information systems (GIS) and remote sensing (RS) techniques were utilized in this work to evaluate the groundwater potential of the geological terrain in Zamfara, Northwest Nigeria. In order to validate the groundwater potential model's outcome, a pumping test result from flowing boreholes was used. Geology, lineament density, rainfall, geomorphology, soil characteristics, slope, drainage density, land use, and aquifer thickness were among the ten thematic layers that were taken into consideration. The model assigned and normalized weight values to each tier using Saaty's analytic hierarchy technique. Four main zones were identified in the reclassification of the groundwater potential model. The groundwater potential zones of the underlying crystalline rock units are distributed spatially as follows: low (5,251.1 km²), medium (6,639 km²), high (7,334.71 km²), and extremely high (8,473 km²). In contrast, the sedimentary hydrogeological areas have a different distribution of 1,265 km² (15%) medium: 1,609.21 km² (21%), high: 2,327 km² (30%) and very high: 2,716 km² (34%) groundwater potential zones respectively. This suggests that the sedimentary environment (Gundumi Formation) is more viable for the development of groundwater resources. The result of model validation proved positive correlation to the yield from the aquifers of the area. This shows effectiveness of combined use of Multicriteria Decision Analysis (MCDA), RS and GIS in figuring out groundwater resources. Overall, it offers great advice for exploring & managing groundwater in the region.

1.0 INTRODUCTION

Due to the state's climate and predominant lithology, groundwater is a rare resource in Zamfara State, particularly during the dry season when surface water from rivers, streams, and impounding reservoirs dries up and open well and borehole yields decrease [1]. The majority of water utilized for home consumption comes from groundwater and impounding reservoirs, which are not abundant enough to provide enough water to meet demand. As a result, a lot of people turned to using hand-dug wells and streams that carried a significant danger of contaminated water [2]. Because of this dependence, groundwater resources have been widely and uncontrollably drained, and wells and boreholes have been strategically and badly positioned, increasing the risk that these water sources

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would fail. To lessen the possible negative repercussions of such indiscriminate exploitation, which could include declining water levels and poor groundwater quality, it is imperative to gain a comprehensive ux zbv xgffhn bgvm nderstanding of the hydrogeological conditions and groundwater potential in these basement terrains.

There are few research on groundwater resources of Zamfara State and out of the few available (such as research of [3] none have been able to bring into account the groundwater potential model or perhaps the amount of water use from both conjunctive surface/groundwater sources or whether the available is enough to meet the current water consumption, high level demand in an increasing population and urbanization regime except the research of [4], which is now over a decade. Although [5] research work which centered on the groundwater potential of fadama areas within Northern Nigeria equally dealt with some aspect of groundwater resources of the study area.

Remote sensing techniques allow for the rapid and easy exploration of groundwater resources [6]. Many factors influence the presence of groundwater in a given area. These include the earth's structure, topography, lithology, weathering extent, fissure distribution, and primary and secondary porosities. In addition, climate (rainfall), terrain, drainage patterns, slope, and land cover/use [7] all play important roles. To get a complete understanding of groundwater recharge processes, professionals perform on-site hydrogeological investigations and geophysical surveys to evaluate the results of combined remotely sensed data.

Lately, people have been leaning more towards remote sensing instead of traditional field studies or tests. Remote sensing shows a wide range of observations about space & time while saving both time & money [8, 9]. Other researchers noted that this technique can capture characteristics about the earth's surface, such as lineaments and geology, as well as aid in understanding groundwater recharge [10]. Integration of remote sensing (RS) with geographic information systems (GIS), offer effective way to get useful information on groundwater potential with maximum accuracy.

Exploring groundwater potential zones is made easier by the integration of data such as geology and geomorphology [11]. This combination of remote sensing and geographical information techniques aids in managing massive databases across wide regions, including difficult-to-reach locations [12], allowing for speedy and cost-effective assessments of the locations of groundwater potential zones.

The usage of geographic information systems (GIS) and remote sensing (RS) has increased in hydrogeological research in recent years. Many studies have shown that GIS is useful at identifying groundwater potential zones, with noteworthy contributions from [13], [8], [14 – 16],
and [7], [17], used remote sensing techniques to reach similar results. Researchers such as [18], [8], [19 – 21] have successfully used remote sensing and GIS to investigate groundwater; outline suitable zones, and identify points of recharge.

Other researchers such as [22, 23], [20], [24 - 27] have also conducted research on groundwater modeling using GIS. GIS has also been utilized for multi-criteria analysis in resource appraisal, as shown by [25] and [28], which processed and interpreted groundwater quality data using GIS.

In order to solve these problems, the current study integrated hydrogeological, geomorphological, and climatic data for estimating groundwater resources in Zamfara's geological terrain using Analytic Hierarchy Process (AHP) coupled with GIS and RS methodologies. Finding the groundwater potential zones within the study area and developing a prospective reference map for groundwater exploration and exploitation are essential steps in ensuring the best and most sustainable uses of this crucial resource.

1.1.1 Study Area

Zamfara State, in northwestern Nigeria, has a total area of 39,762 km² and is located between 7°18′13.709″E and 10°49′4.152″N and between 5°1′27.638″E and 13°10′45.537″E (Figure 1).

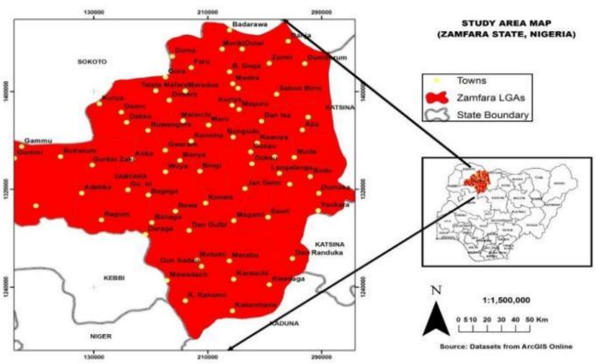

Figure 1: Map of Zamfara State

Extreme weather is common in the area; in January and December, the average daily minimum temperature is 19°C, and in April through June, the

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average daily maximum temperature is 40°C, with a minimum temperature of 30°C. In general, Zamfara State experiences low rainfall amount. Throughout the State, the yearly rainfall average varies from 500 to 1000 mm.

2.0 GEOLOGY OF THE RESEARCH AREA

Approximately 80% of Zamfara State is covered by different crystalline rocks of the northwest Nigerian basement complex, which are primarily made of gneiss, schist, migmatite, granite, and granodiorite [29]. They display structural characteristics such joints, faults, foliation, lineation, folds, and rock contacts. The earliest deposits from the Sokoto Basin, which [30, 31] have extensively detailed, make up the remaining portion of the State. Groundwater in the basement rock is accessed mainly through cracks and joints and through intergranular pores of fine to coarse sands and gravels in the depositional areas [30] (Figure 2).

It is thought that lacustrine and fluvial processes created the clay, sandstone, and pebbles that make up the Gundumi Formation. Its maximum thickness can reach up to 300 meters near the borders with Niger, and its base is defined by a well-preserved conglomerate layer exposed along the Tureta-Karlgo road [31].

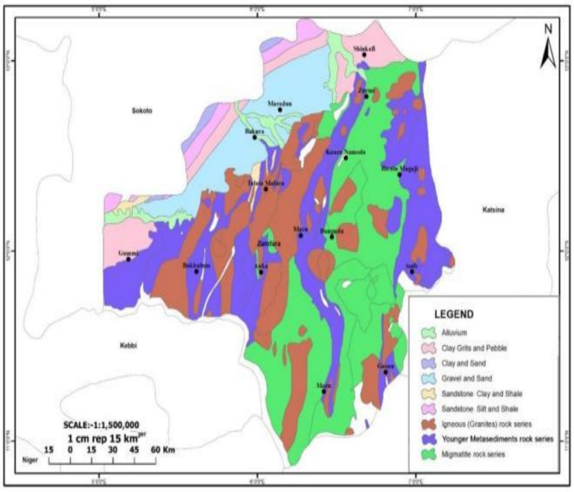

Figure 2: Geological Map of Zamfara

3.0 MATERIAL AND METHOD

This research framework included an integration of ten thematic maps such as conventional geology, lineament maps, rainfall data, aquifer thickness and remote sensing data such as landuse, drainage patterns, soil types, slope and topography. The integration was achieved using ArcGIS 10.4 software. All map layers were formatted in UTM projection zone 31 using WGS84 datum and 12.5-meter resolution. Two hundred and thirty (230) borehole data were obtained from Zamfara rural water and sanitation authority to validate the groundwater model output (Figure 3).

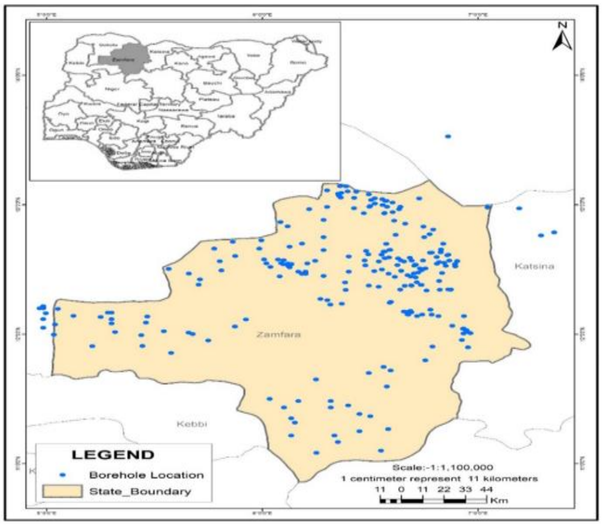

Figure 3: Location of Borehole Points within Zamfara State

The Nigerian Geological Survey Agency (NGSA) provided geological and lineament maps for the research area at a scale of 1:1,500,000. ArcGIS 10.4 software was used to georeferenced and digitized the maps [11, 32]. Landuse/land cover (LULC) map was derived from mosaicked Landsat ETM imagery of 25 October 2023 and classified with ENVI software. For this analysis, soil maps were extracted from the Food and Agricultural Organization (FAO) soil unit map of Nigeria. To construct thematic maps of topography and slope, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) with a resolution of 12.5 meters was utilized along with specific criteria. [11, 28, 33].

The Nigerian Meteorological Agency (NiMET) stations in the area gathered thirty years' worth of annual precipitation data that range between 1991 to 2021 from a variety of meteorological stations. In the ArcGIS environment, the spatial distribution of precipitation was analyzed using the Thiessen polygon technique [34 - 36].

A drainage density map was produced using the drainage maps that were downloaded from DIVAGIS (http://www.diva-gis.org). The research region was then divided into micro catchments using the drainage density map [37 - 40]. Based on their usefulness in evaluating groundwater potential using the Analytical Hierarchy Process (AHP) (Figure 4).

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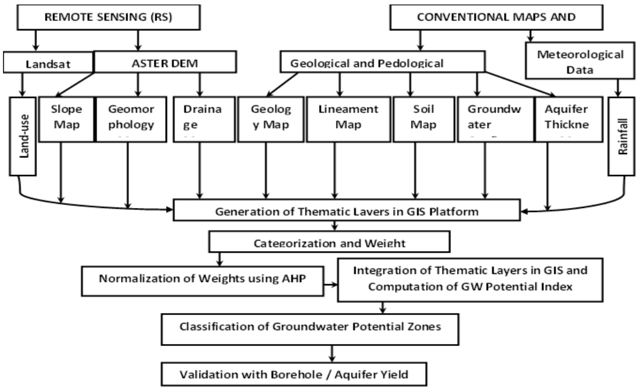

Figure 4: Groundwater Potential Model Flowchart

3.2 Thematic Map Integration in ArcGIS Environment

In order to assign weights to various issues and their accompanying qualities in the assessment of groundwater potential, this study used the Analytical Hierarchy Process (AHP), developed by [35], as a tool for decision-making. Based on how significant a role each theme feature had in determining the occurrence and flow of groundwater, the study's thematic attributes were given a weighted value between 1 and 4. According to earlier research [33], [28], [11]and [12], the weights given to each map subject represent their significance in terms of groundwater resources. Geology was the most significant feature associated with groundwater occurrence in the research region, with a normalized weight of 27, as shown in Table 1, whereas proximity to surface water bodies was deemed the least significant (normalized weight of 0.022).

The assigned and normalized weights for the qualities in the various thematic layers, together with the ranks that correspond to them, are compiled in Table 1.

A composite groundwater potential index (GWPI) was generated for the research region using the raster calculator features of the ArcGIS platform. This GWPI formed the basis for the overall groundwater potential map.

Table 1: Scaled Values Allocated to Various Parameters

S/No	Parameters	Range of Attributes	Rank	Priority	Weight (%)
1	Aquifer Depth	0-13.99	1	0.038	3.80%
		13.99-36.66	2		
		36.66-57.37	4		
		57.37-79.47	4		
2	Precipitation	150.78-162.71	1	0.18	18.10%
		162.71-176.50	2		
		176.50-196.31	3		
		196.31-209.20	4		
3	Slope	0-0.35	4	0.068	6.80%
		0.35-0.65	3		
		0.65-1.43	2		
		1.43-4.80	1		
4	Topography	241-354.7	4	0.113	11.30%
		375.7-434.2	4		
		434.2-526.1	2		
		526.1-754	1		
5	Drainage Density	0-4.57	5	0.067	6.70%
		4.57-11.44	4		
		11.44-18.93	2		
		18.93-38.92	1		
6	Soil	Loamy Sand	2	0.07	7%
		Sand	4		
		Sandy Clay	1		
		Sandy Loam	3		
7	Lithology	Older Metasediments	4	0.27	27%
		Younger Metasediments	3		
		Pan-African Granitoids	2		
8	Lineaments	0-5.48	1	0.132	13.20%
		6.49-13.62	2		
		14-23.02	3		
		21.02-41.40	4		
9	Landuse	Water bodies	4	0.027	27%
		Settlement	2		
		Bare land / Open space	3		
		Outcrop of rocks	1		
		Vegetation	4		

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4.0 RESULTS AND DISCUSSION

Lineaments in the studied region are the product of previous tectonic processes. Two major directional trends were identified: NE-SW and also N-S. The lineament density map provides a quantitative assessment of the length of linear features per unit area. The presence of these features typically implies groundwater permeable zones, which can indirectly suggest groundwater potential (Figure 5). Despite the extensive presence of lineaments in the research area, their distribution pattern indicates a strong geological influence. Those underlain by migmatite, gneiss, and granite have a lower lineament density than those dominated by metasediments.

Geomorphological assessment of the study area identified four main geomorphological units based on elevation data from remote sensing imagery (Figure 6). In this study, the lowlands and plains are mainly formed by sediments and heavily weathered parts of the basement.

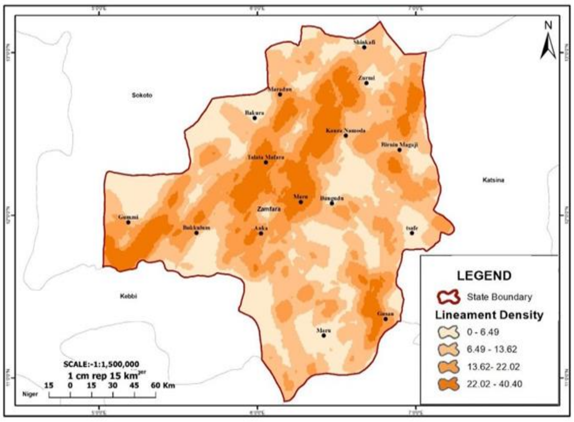

Figure 5: Lineament Intensity/Density of Zamfara State

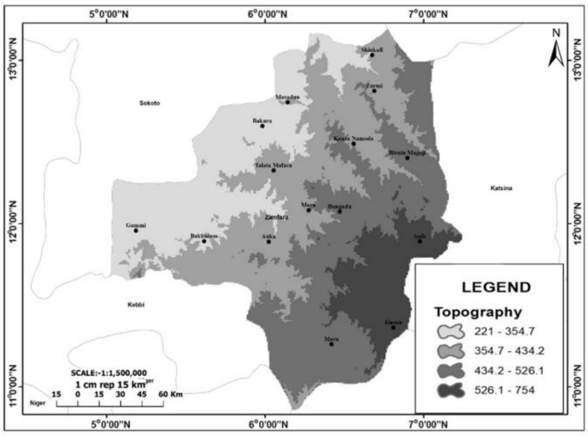

Figure 6: Topographic Map of Zamfara State

On the other hand, the study area contains ridges and inselbergs that form a series of hills and elevated ridges. These geomorphological features were assessed and classified according to their importance for groundwater resources as shown in Table 1.

A slope theme map with maximum values of 1.44% and 4.90%, with slopes ranging from 0% to 1%, is shown in Figure 7. The large variety and distribution of slopes in the study area suggests variable groundwater potential features in the crystalline basement setting, which in turn indicates variable runoff and recharge.

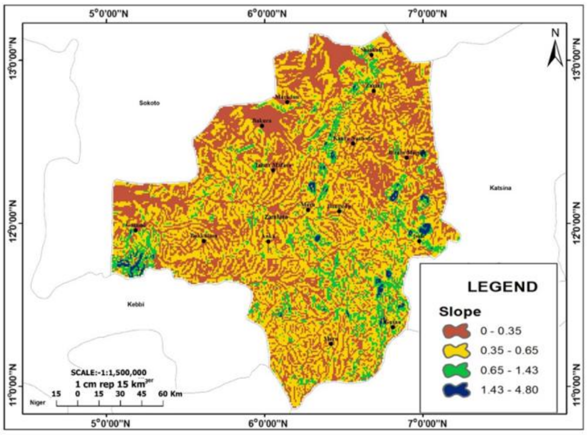

Figure 7: Slope of the Research Area

The structural characteristics and drainage system in the research region demonstrate how structural controls affect the drainage patterns, which are in line with the directions of lineaments. The region has parallel and dendritic drainage patterns, which suggests the existence of structures that serve as subsurface water storage or route systems (Figure 8). Locations with very high drainage densities tend to have more compacted drainage channel arrangements, while areas with lower drainage densities show more space between these channels. This finding led to the allocation of weighted values. Hence, lower drainage density indicates potential groundwater zones by corresponding with reduced runoff and a higher potential for groundwater recharge (Figure 8).

Figure 9 illustrates the precipitation patterns in the study area, revealing that the entire region receives an annual rainfall of less than 1,000 mm, typical of a Sudano-Sahelian tropical climate. Areas with higher rainfall amounts were given greater weightage factors, while regions with moderates to low rainfall received lower weightage values (Table 1).

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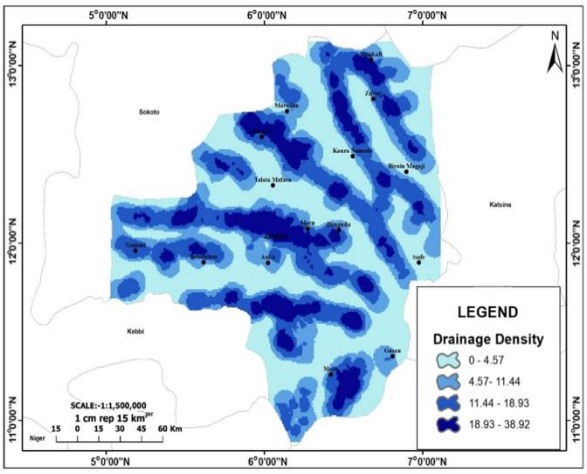

Figure 8: Drainage Density of Zamfara State

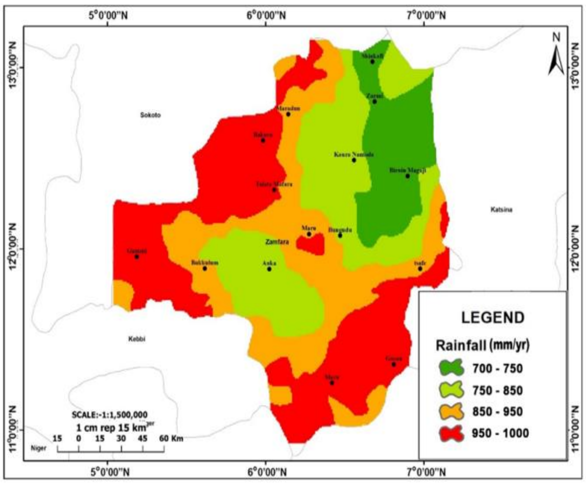

Figure 9: Rainfall Distribution across Zamfara State

The land use and cover (LULC) of an area has a major impact on groundwater recharge rate. Barren land/open regions, hills (rock outcrops), settlements, flora, and water bodies were the five groups into which LULC was separated in the research region (Figure 10). As indicated in Table 1 a weighting value was assigned to each category based on how important it was for groundwater potential.

The quality of topsoil greatly affects how well surface water seeps into the ground. Because fine-grained soils have limited permeability, they frequently restrict infiltration, whereas coarse-grained soils have higher permeability, which facilitates greater water movement. Figure 11 displays the four primary soil zones used in this study. Given the correlation between sand concentration and permeability, soils with higher permeability were given more weight in the analysis, as shown in Table 1.

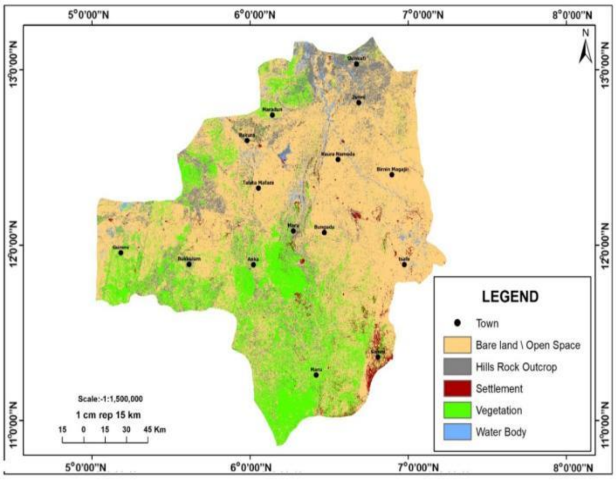

Figure 10: Land use (LULC) of Zamfara State

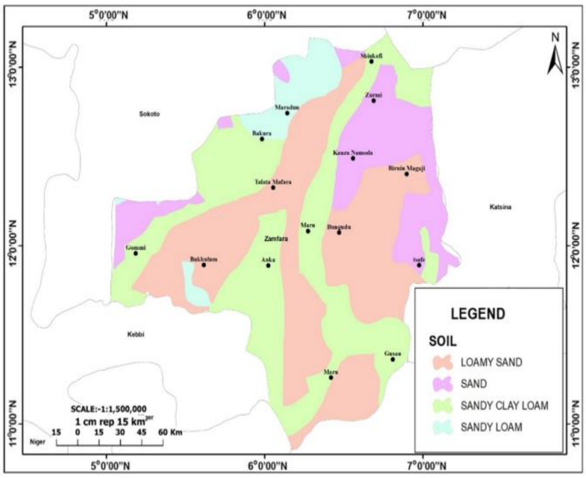

Figure 11: Soil Map of Zamfara State

Groundwater Potential Zone Characterization:

As seen in Figure 12, the combination of nine thematic maps led to a reclassification that produced four types of possible groundwater zones. These zones' overall spatial distribution is a reflection of the regional variations in terrain, rainfall, groundwater depth, lineaments, drainage, and lithology. Four distinct categories were used to categorize the possible groundwater zones: low/poor, medium/moderate, high, and very high. The corresponding areas of these categories were 6,378.90 km² (18%), 8,201.44 km² (24%), 9,235.39 km² (28%), and 10,724.96 km² (30%). After a separate analysis of each formation, complicated bedrock made up around 80% of the

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region, with Gundumi Formations making up the remaining 20%.
The spatial distribution of groundwater potential zones in the subsurface rock units is as follows: low: 5,251.1 km² (18%), medium: 6,639 km² (25%), high: 7,334.71 km² (27%) and very high: 8,473 km² (30%). In contrast, the sedimentary hydrogeological areas have a different distribution: low - 1,265 km² (15%), medium and 1,609.21 km² (21%), highland 2,327 km² (30%) and very highland - 2,716 km² (34%).

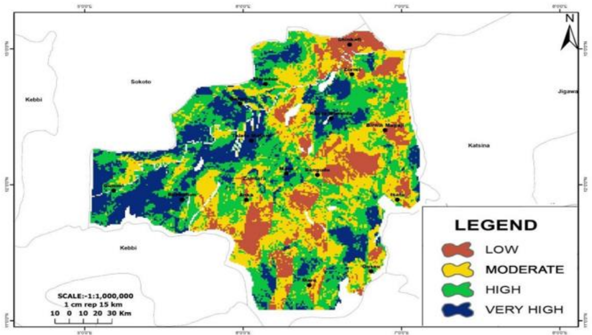

Figure 12: Groundwater Potential Model of Zamfara State

The research area's groundwater resources are quickly evaluated using a groundwater potential map, which reveals that the regions beneath the bedrock units that run from northeast to south often have low to moderate potential. At select places, nevertheless, sites with good slopes and a high density of weathering and fracture can have a high or extremely high potential.
While places with steep slopes and at the interface with the bedrock units indicate low to moderate potential, the whole sedimentary landscape of the Gundumi Formation has high to very high potential for groundwater. Rainfall, groundwater density, groundwater piezometric level, soil characteristics, aquifer thickness, and geological factors all have a significant impact on the distribution of possible groundwater zones. The areas beneath the shallow rock units have very high groundwater potential due to the presence of lineaments and intense weathering. Conversely, high slopes, inselbergs and rocky outcrops contribute to low groundwater potential in certain areas, especially along the mountain ranges with very steep slopes, dense lithology and long distances from lineaments.
Furthermore, surface drainage, high precipitation, low slopes and primary porosity of the sedimentary rock units (Gundumi Formation) promote water infiltration into the groundwater system, resulting in the generally high groundwater potential observed in these areas (Figure 12).

4.1 Groundwater Potential Model Validation (Using Aquifer Yield and Static Water Level)

Measurements and observations made in the field were used to validate the Groundwater Potential Model (GPM). Initially, a groundwater configuration map was created using ArcGIS's spatial analyzer extension and water level data from production wells located throughout the research region (Figure 13). It shows that although groundwater recharge occurs in certain limited areas, it primarily flows toward the northwest portion of the research area. This localized recharge is a significant component in the research area's high groundwater development potential. In addition, tests were conducted on a number of producing wells in the research region to determine their discharge rate. The average yield from these production wells, as shown in Figure 14, suggests that the Gundumi formation has a greater aquifer capacity than the aquifers in the basement environment.

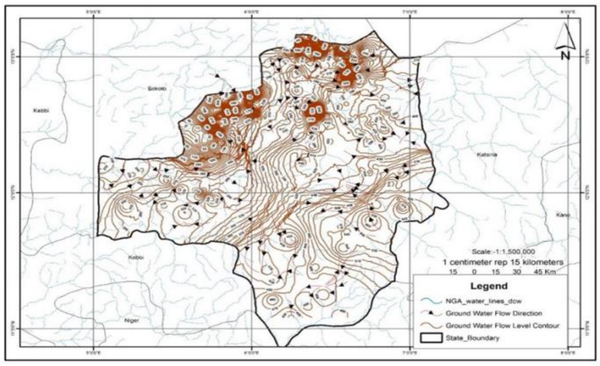

Figure 13: Groundwater Configuration Map

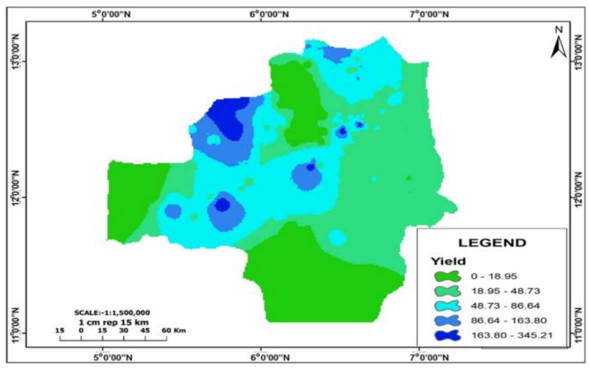

Figure 14: Spatial Distribution of Groundwater Yield in Zamfara State

5.0 CONCLUSIONS

This project's main objective is to use GIS and remote sensing technologies to locate, evaluate, and analyze the groundwater potential zones' geographic distribution throughout the study area. Groundwater potential map (GPM) was created utilizing ten thematic maps generated from satellite images, existing databases, and field observations. This GPM was then checked and validated against runoff data from several producing wells in the research region. The results indicated a good association with the runoff data, indicating that higher yielding wells are primarily found near locations with high groundwater potential.

The study showed significant regional variance in groundwater potential, with the most promising areas associated with sedimentary rock formations. These areas are influenced by secondary structures and are identified by interconnected pore spaces, moderate slopes, and low drainage density. Furthermore, these formations benefit from strong base flow rates from bedrock plateaus. The significance of lineaments, geomorphological features, and geological variables in identifying groundwater zones is emphasized by the groundwater potential model.

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