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Groundwater Potential Mapping of Oluku Community, Benin City Utilizing Analytical Hierarchy Process (AHP) and Geographic Information System (GIS)

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Abstract

Lack of groundwater potential mapping makes issues worse in areas where water scarcity is already a problem. Groundwater potential mapping provides valuable insights into the availability and sustainability of groundwater resources. Without this information, it becomes challenging to plan and develop water supply systems effectively. This research aims at presenting a method of determining the groundwater potential zones within Oluku community in Benin city using the multi-criteria decision analysis approach, particularly the Analytical Hierarchy Process (AHP) method and GIS. Eight groundwater conditioning factors were employed to comprehensively analyze groundwater potential within the study area. These factors encompassed soil, geology, land use/ land cover, drainage density, slope, flow direction, elevation and lineament density. These factors were ranked based on their potential contribution to groundwater occurrence and given factor weights according to the AHP technique, the combination of these groundwater conditioning factors with their corresponding weights in the ArcGIS software resulted in the groundwater potential map. Findings revealed that 7.62% (0.62 km^2), 70.59% (5.76 km^2), 21.16% (1.73 km^2) and 0.63% (0.05 km^2) of the entire study area had low, moderate, high and very high groundwater potential respectively. The research concluded that very few locations within the study area have very high likelihood of groundwater occurrence. The resulting groundwater potential map is essential in pinpointing locations that are ideal for groundwater extraction, reducing water scarcity and supplying water to expanding populations within the study area. Thus, groundwater potential mapping is a crucial and valuable tool for sustainable development, water security, and environmental protection.

1.0. Introduction

Water resources are essential for human survival. These resources which come from evaporation, precipitation and surface runoff comprises both of surface and subsurface water. Groundwater in a saturated zone fills the pore spaces between mineral grains as well as the fissures and fractures in a rock mass [1]. Nearly 20% of the water required by people is currently supplied by groundwater and this percentage is anticipated to rise over the following several decades [2]. According to [3], groundwater accounts for 30% of the world's fresh water resources.

Groundwater is the second-most significant freshwater reservoir after surface water and it is the ideal choice for both human and economic activity [4]. The hydrological environment and groundwater development in a region are governed by its geological and geomorphological structure [5]; flow, seepage, and percolation rates are regulated by physiographic parameters. Some studies consider factors like relief, slope, drainage, lithology, geological structures, soil, linear features, geomorphology, land use/land cover (LU/LC), amount of rainfall, proximity to the river, etc. Landscape, climate, and environmental factors often identify potential groundwater zones [6]. Natural streams and groundwater have a connection since river flow and environmental flow have an impact on groundwater formation [7]. Groundwater availability varies greatly throughout the year and river flows have a big impact on the recharge process [8]. When surface water from rainfall seeps into the earth and fills the pores of the soil and rock fragments, groundwater is created. In order to reach sources of discharge like wells, rivers, lakes, and seas, groundwater travels through the aquifer layer [9]. The socio-economic growth of a nation greatly depends on groundwater as a source of supply [10]. Stream flow has an impact on groundwater quality as well [11]. One-third of all freshwater consumption worldwide comes from groundwater, yet there is a lack of micro-spatial data on the potential groundwater source [12].

The analytical hierarchy process (AHP) is the MCDA technique that has gained the most traction. AHP is being used in many geology-related fields, but it is most prominently used in groundwater research where it has shown promise, especially in identifying groundwater potential zones [12-13]. Geographic Information System (GIS) is a tool that makes it possible to integrate, organize, and analyze huge amounts of data in order to pinpoint groundwater potential [12-13]. By using the weighted linear combination (WLC) technique to integrate these criteria (land use, soil, slope, rainfall, elevation, lithology, lineament density, drainage density, etc.) within the GIS to generate potential groundwater zones by ranking each category of these parameters [14], ground-water potential has been determined. The research is aimed at identifying and mapping out the groundwater potential zones within Oluku community, Benin city using multi-criteria decision analysis (a method- Analytical Hierarchy process) and a GIS environment.

2.0 Materials and Methods

2.1 The study Area

Benin City is the capital city of Edo State, the 22nd largest state by area in Nigeria. The study area Oluku community, Benin city covers specific places such as Oluku community market, Terminal Resort & Park, Seven up Bottling company, Iguosa Housing Estate, Oluku Bypass, Light guest House, Total Energies and others. The study area covers an area of 8.16 km^2 as shown in Figure 1. The coordinates of the study area are 6.4305ºN, 5.5932ºE. The study area contains socio-economic infrastructures which generates a lot of human activities around the area. The study area lies within the Ikpoba river basin and all the rainfall in the study area flows and ultimately discharges into Ikpoba River in Benin city. Annual precipitation in Benin city is around 190mm and has 274.89 rainy days (75.31% of the year). The yearly average temperature of Benin City is 29.75℃.

2.2 Groundwater Conditioning Factors and Their Method of Processing

Groundwater Potential mapping requires various input data which were collected from different sources and processed in ArcGIS. The original data, which were used to process groundwater conditioning factors, and their sources are reported in Table 1.

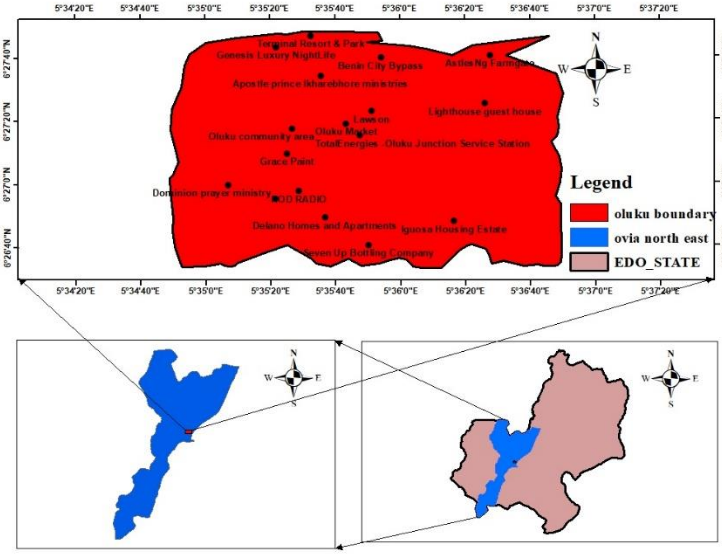

Figure 1: Map of the study area

Table 1: Source of original data

Data	**Format**	**Source**
DEM / SRTM	Raster file	Diva GIS Site
Landsat 8 imagery	Raster file	USGS Website
Soil data of the world	Vector	FAO soil website
Geological data	Vector	Diva GIS Site
Boundary data	Vector	Open street map

Eight groundwater conditioning factors were selected for the spatial modelling. These are: Slope (˚), River Drainage density(km/km^2), Elevation(m), Land Use/Land cover (km^2), Flow direction (°), Lineament Density (km/km^2), Geology (m) and Soil. All of the groundwater conditioning factors were processed in the ArcGIS software.

2.2.1 Elevation Map

Elevation is directly related to groundwater because the higher the elevation, the closer the water table is to the surface. When the elevation is higher, the groundwater is closer to the surface and more easily accessible. A Digital Elevation Model (DEM) was acquired from USGS website specifically from https://earthexplorer.usgs.gov, and imported into the ArcGIS environment. The existing shapefile of the study area was incorporated into the ArcGIS software, utilizing the "Clip Raster" function, the DEM was tailored to match the desired shape. Subsequently, the "Reclassify" function was employed to categorize the DEM based on elevation levels into five distinct groups, which were denoted as very high, high, moderate, low, and very low.

2.2.2 Slope Map

Steeper slopes result in faster groundwater flow, while slope inclination also impacts the capacity of an area to store groundwater. Regions with steep slopes generally exhibit lower groundwater storage compared to areas with gentler slopes. The slope map was generated from the DEM layer using the following path: ArcGIS System Toolboxes > Spatial Analyst Tools > Surface > Slope.

2.2.3 Soil Map

Soil characteristics, including type, texture, and structure, can impact the movement of water through the soil and its ability to reach the water table. To create the Soil Map, a scanned image of Nigeria's soil map was obtained from the FAO website. The study area layer was used to clip the vector layer (digitized soil map), the vector soil map was then converted into a raster format using the "Polygon to raster" feature in ArcGIS.

2.2.4 Drainage Density

Areas with higher drainage density typically exhibit lower potential for groundwater recharge. Conversely, regions with low drainage density, often characterized by more porous soils, tend to have a higher potential for groundwater recharge. The drainage density map was created using the “Line Density” tool in the ArcGIS software.

2.2.5 Land use/land cover Map

Land use and land cover can impact groundwater potential by influencing the infiltration of precipitation into the soil, the amount of water stored in the soil, and the rate of groundwater recharge. Satellite imagery, specifically Landsat 8 images for the year 2023, were acquired from the United States Geological Survey (USGS). The satellite images were imported into the ArcGIS 10.3 software. The land Use/Land Cover (LULC) Map was then created based on the acquired satellite imagery.

2.2.6 Geology Map

Geological characteristics can have an impact on the quantity and quality of available groundwater, as well as the nature of the aquifer. Geological formations can also influence soil permeability and the capacity of groundwater to flow through it. The geological map was obtained from USGS and clipped to the specific area of interest.

2.2.7 Lineament Density

Mapping lineaments aids in identifying areas with elevated groundwater potential, subsequently facilitating groundwater potential mapping. The lineament data was acquired from existing geological surveys, the lineament length was thereafter calculated and computed on the ArcGIS 10.3 software, which resulted in the lineament density map.

2.2.8 Flow Direction

Flow direction helps to determine the location of recharge areas, where groundwater is more likely to be found, and the location of discharge areas, where groundwater is more likely to be lost. The DEM dataset was analyzed to calculate the direction in which water flows from each cell based on the steepest downhill slope.

2.3 Multi-Criteria Decision Analysis: Analytical Hierarchy Process (AHP)

The AHP technique, a form of multi-criteria decision analysis, was employed to assign weights to the parameters. Central to this technique is the pairwise comparison process, which quantifies data to establish the weight of each parameter. The relative importance of the selected conditioning factors was assigned based on the empirical knowledge and recent studies, with values ranging from 8 (indicating utmost importance) to 1 (signifying minimal importance). To compute the weights for each criterion (groundwater conditioning factor), the AHP's pairwise comparison method was utilized. This involves deriving relative weights from the principal eigenvector of an 8 × 8 reciprocal matrix formed from pairwise comparisons between criteria. The pairwise comparison matrix is shown in the Table 3.

Table 3: Pair- comparison matrix wise

Factors	Distance to stream	Elevation	Flow direction	Slope	Drainage Density	LU/LC	Geology	Soil
Distance to stream	1	2	3	4	5	6	7	8
Elevation	0.5	1	2	3	4	5	6	7
Flow direction	0.33	0.5	1	2	3	4	5	6
Slope	0.25	0.33	0.5	1	2	3	4	5
Drainage Density	0.2	0.25	0.33	0.5	1	2	3	4
LU/LC	0.167	0.2	0.25	0.33	0.5	1	2	3
Geology	0.143	0.167	0.2	0.25	0.33	0.5	1	2
Soil	0.125	0.143	0.167	0.2	0.25	0.33	0.5	1

The normalized factor weights, and final weights (Wi) were calculated by the approximation method and is shown in the Table 4.

Table 4: The normalized factor weights, and final weights (Wi)

Factors	Distance to stream	Elevation	Flow Direction	Slope	Drainage Density	LU/LC	Geology	Soil	Weight (W1)
Distance to stream	0.368	0.436	0.403	0.355	0.311	0.275	0.246	0.222	0.327
Elevation	0.184	0.218	0.269	0.266	0.249	0.229	0.212	0.194	0.228
Flow direction	0.122	0.109	0.134	0.177	0.187	0.183	0.175	0.167	0.157
Slope	0.092	0.072	0.067	0.089	0.124	0.137	0.140	0.139	0.108
Drainage Density	0.074	0.054	0.044	0.044	0.062	0.092	0.105	0.111	0.073
LU/LC	0.062	0.044	0.034	0.029	0.031	0.046	0.070	0.083	0.050
Geology	0.053	0.036	0.027	0.022	0.021	0.023	0.035	0.056	0.034
Soil	0.046	0.031	0.022	0.018	0.016	0.015	0.018	0.028	0.024

Table 5: Saaty's 1-9 scale of relative importance

Scale	**Importance**
1	Equal importance
2	Weak
3	Moderate importance
4	Moderate plus
5	Strong plus
6	Strong importance
7	Very strong importance

8	Very very strong importance
9	Extreme importance

Source: [14]

After completing the AHP, the consistency ratio (CR) was calculated in order to examine the consistency of the developed ratings. The formula for calculating consistency ratio is shown in Equation 1.

$$CR = CI/RI \qquad (1)$$

Where RI is the random index which depends on the number of conditioning factors used and CI is the consistency index and is given by Equation 2:

$$CI = \lambda max - n \,/\, n - 1 \qquad (2)$$

Where n is the number of conditioning factors and λmax is the average value of the consistency vector. According to [14], the average value of the consistency vector should be less than 0.1 for the AHP to be consistent.

In this case, our value of λmax was calculated to be 8.293 and therefore, CI was calculated using Equation 2.

$$CI = \lambda max - n \,/\, n - 1 = 8.293 - 8 \,/\, 8 - 1 = 0.0419$$

From equation (1),

$$CR = CI/RI$$

The random index RI is shown Table 6:

Table 6: Various numbers of factors and their corresponding Random Index RI

N	1	2	3	4	5	6	7	8	9	10
R1	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

The value of random index (RI) for eight factors is 1.41, so then, CR was calculated using Equation 1

$$CR = 0.0419 \,/\, 1.41 = 0.0297$$

This value of CR is less than 0.1 so this confirms the consistency of the ratings.

3.0 Result and Discussion

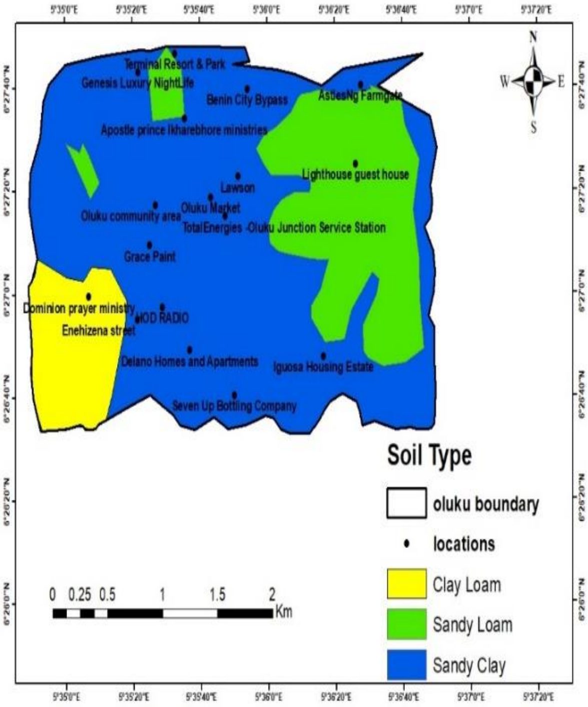

Figure 2a: Soil map

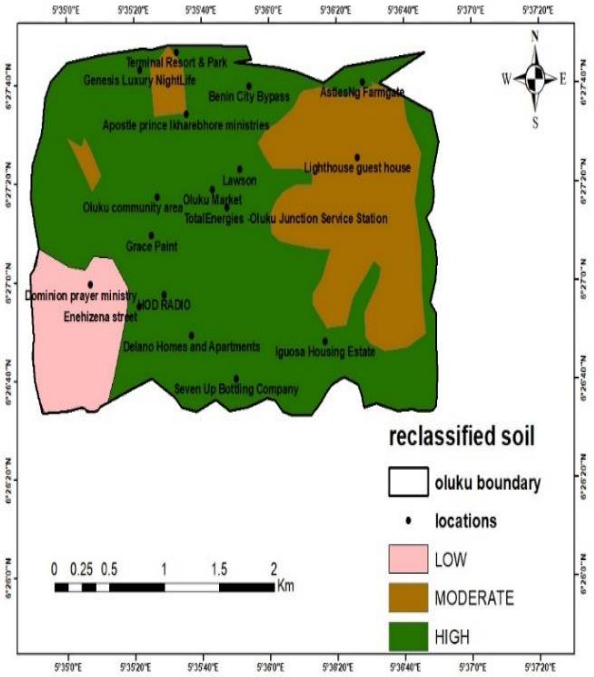

Figure 2b: Reclassified soil map

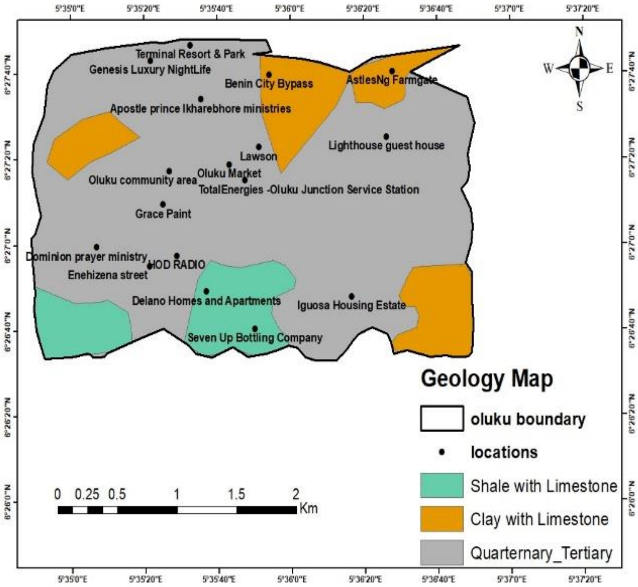

Figure 3a: Geology map

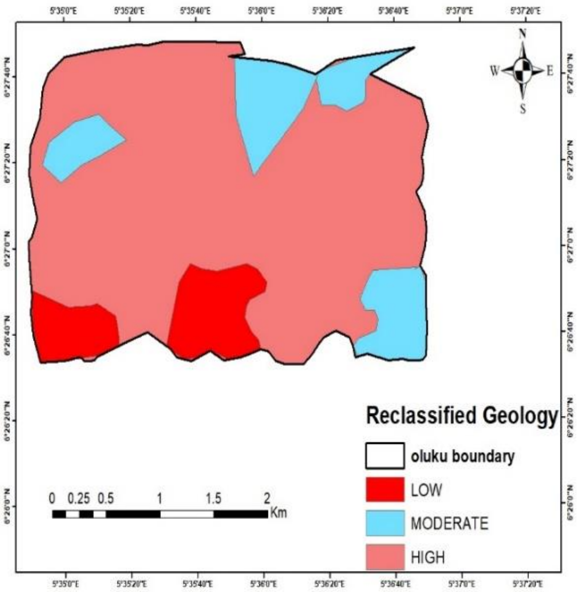

Figure 3b: Reclassified Geology map

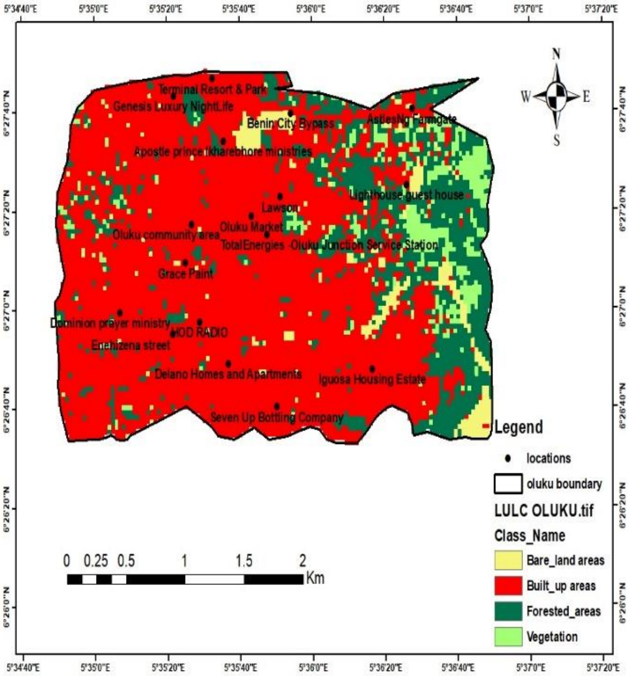

Figure 4a: Land use/ land cover map

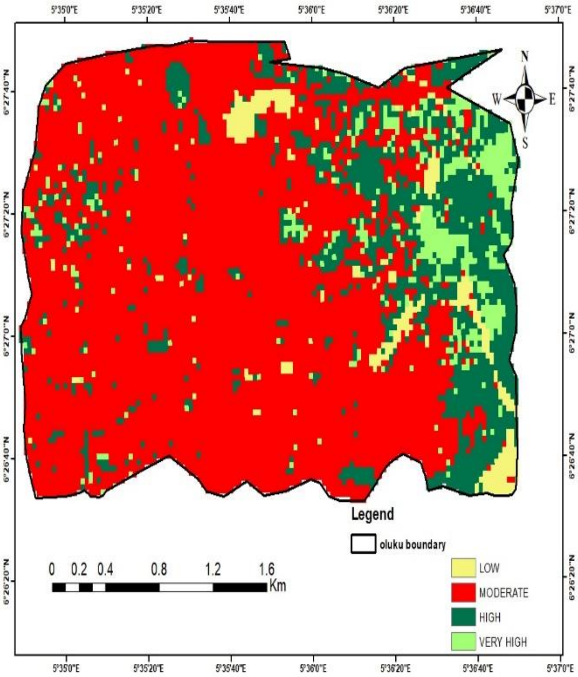

Figure 4b: Reclassified land use/ land cover map

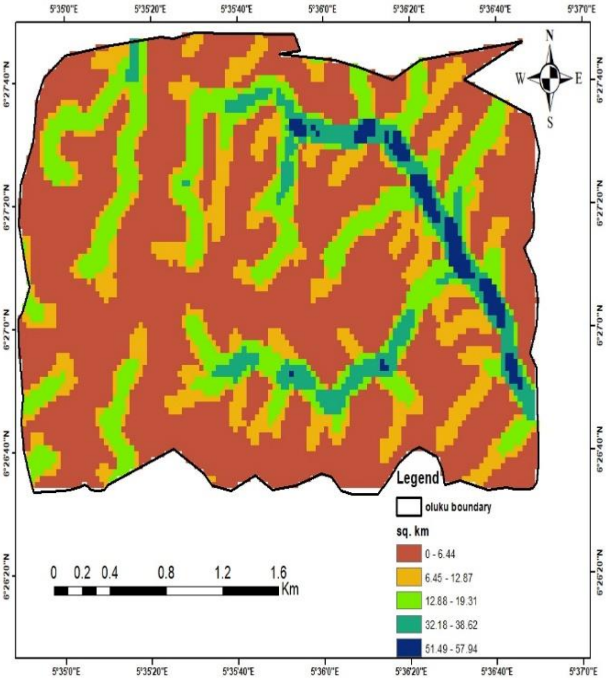

Figure 5a: Drainage Density map

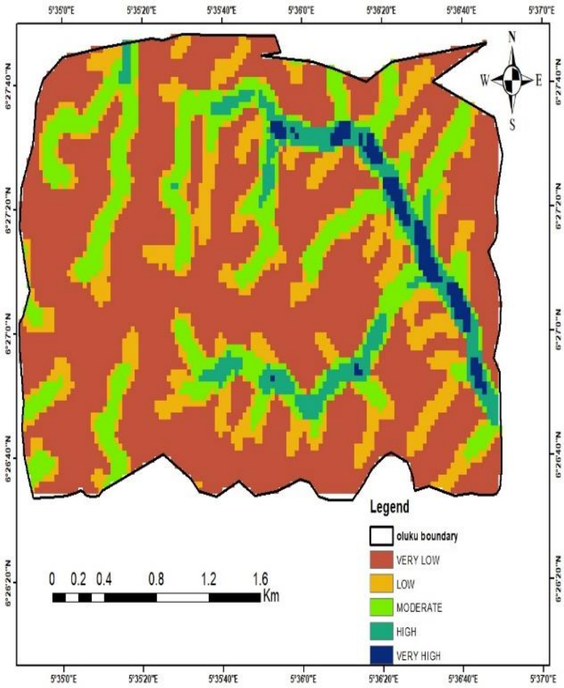

Figure 5b: Reclassified drainage density map

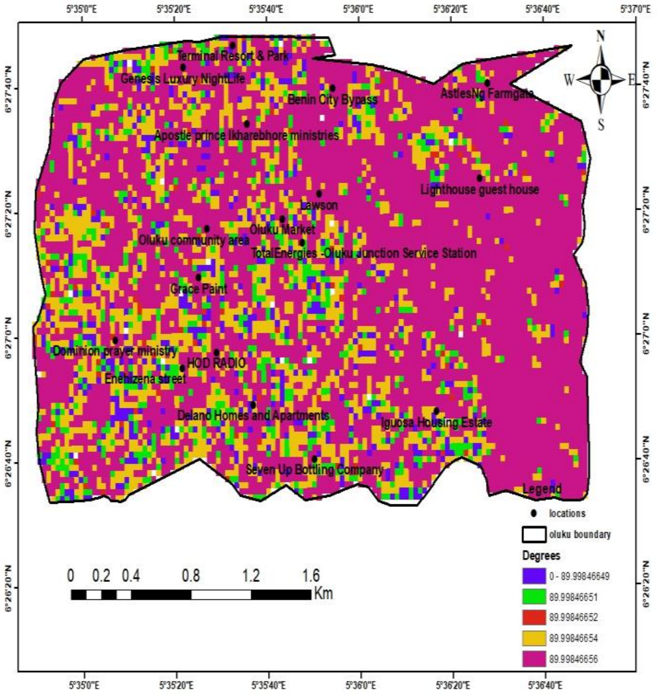

Figure 6a: Slope map

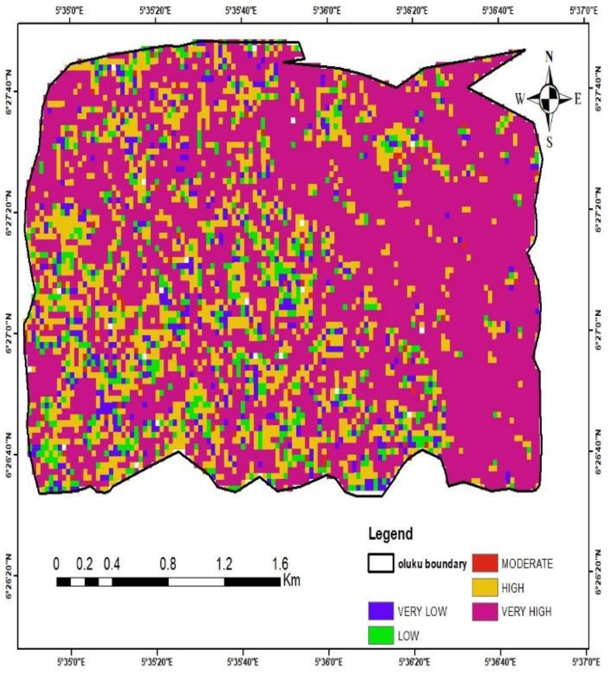

Figure 6b: Reclassified Slope map

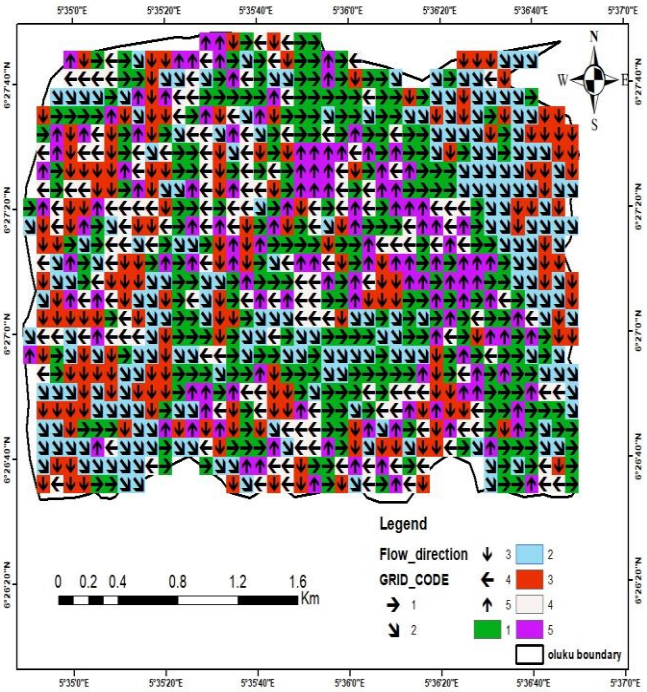

Figure 7a: Flow Direction map

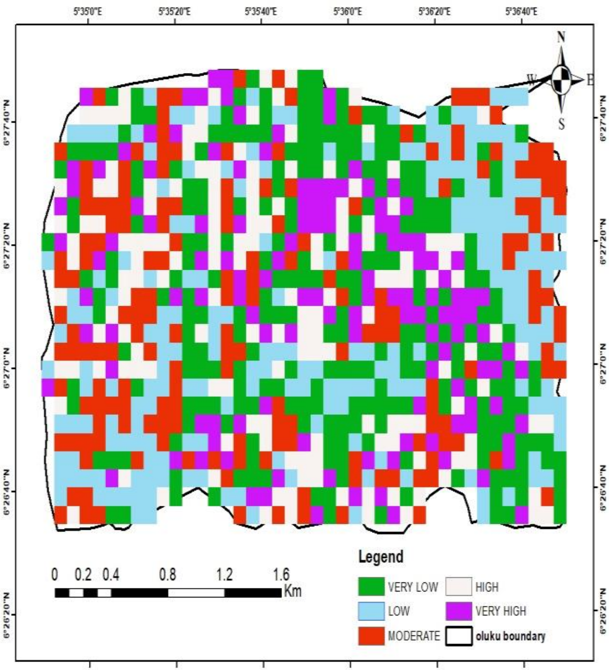

Figure 7b: Reclassified flow direction map

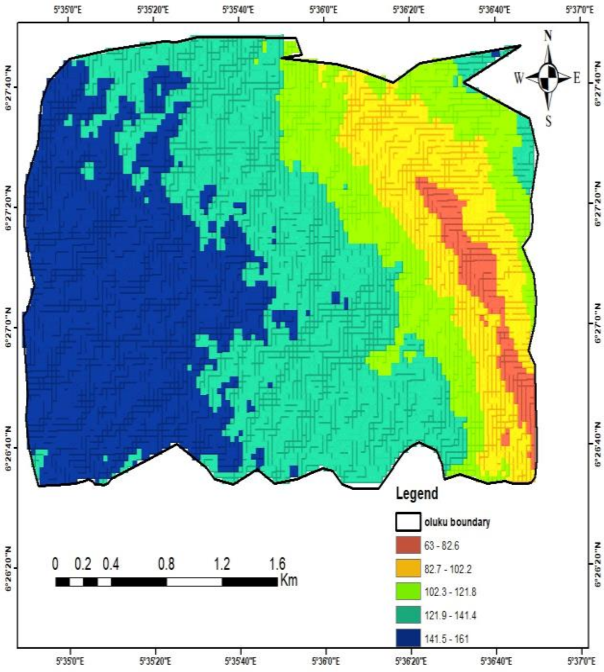

Figure 8a: Elevation map

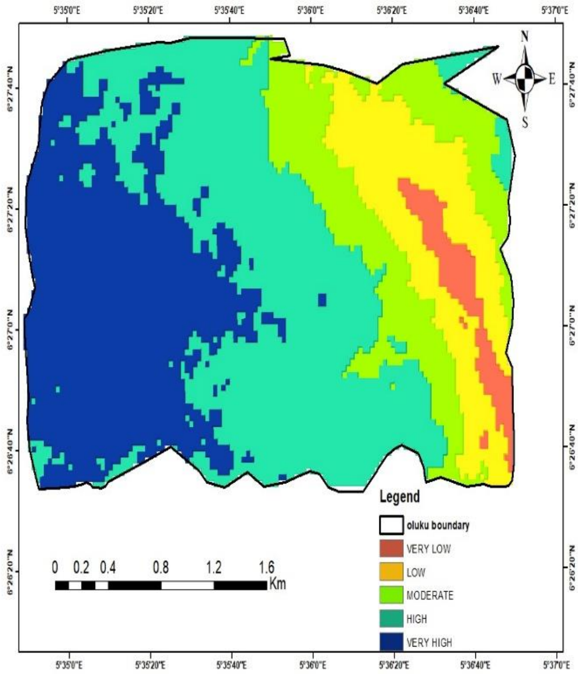

Figure 8b: Reclassified elevation map

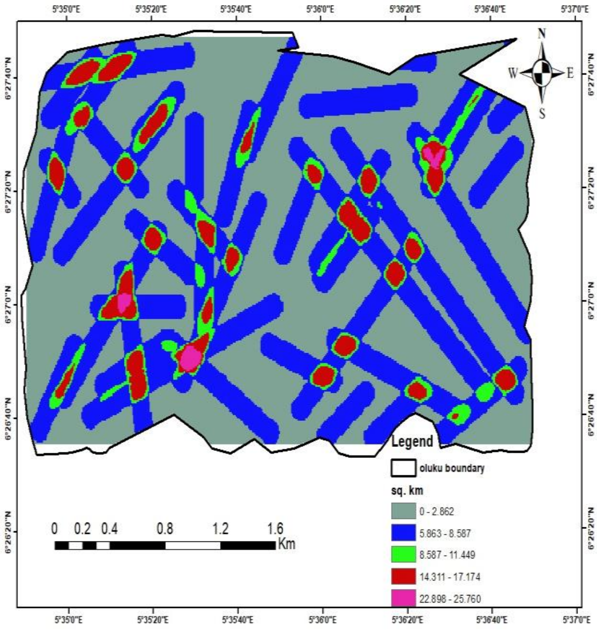

Figure 9a: Lineament Density map

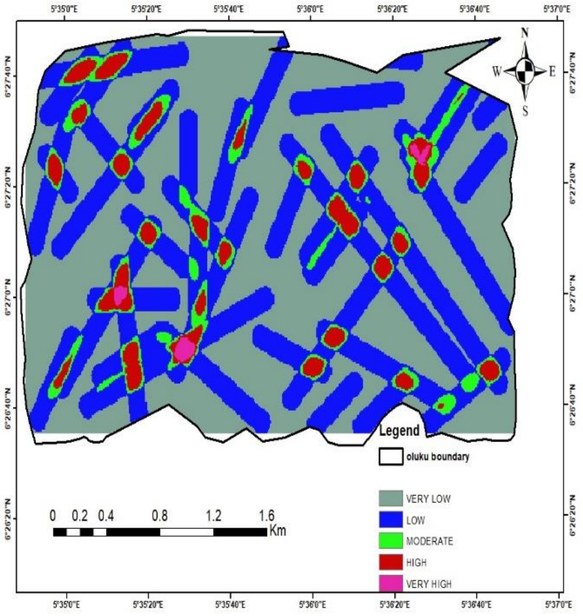

Figure 9b: Reclassified lineament density map

3.1 Analysis of Groundwater Potential Map

After applying the weighting sum of all conditioning factors, the final groundwater potential map was obtained as shown in Figure 10. Table 6 presents the area coverage of groundwater potential within Oluku community. The analysis showed that the areas that have low and moderate groundwater potential were 0.62 km^2 (7.62%) and 5.76 km^2 (70.59%) of the entire area respectively. The high groundwater potential areas covered a spatial extent of 1.73 km^2 (21.16 %), while the very high groundwater potential areas covered 0.05 km^2 (0.63%). This imply that areas with high and very high groundwater potential covered 21.79% of the entire study area, which means that very few locations within the study area have high likelihood of groundwater occurrence.

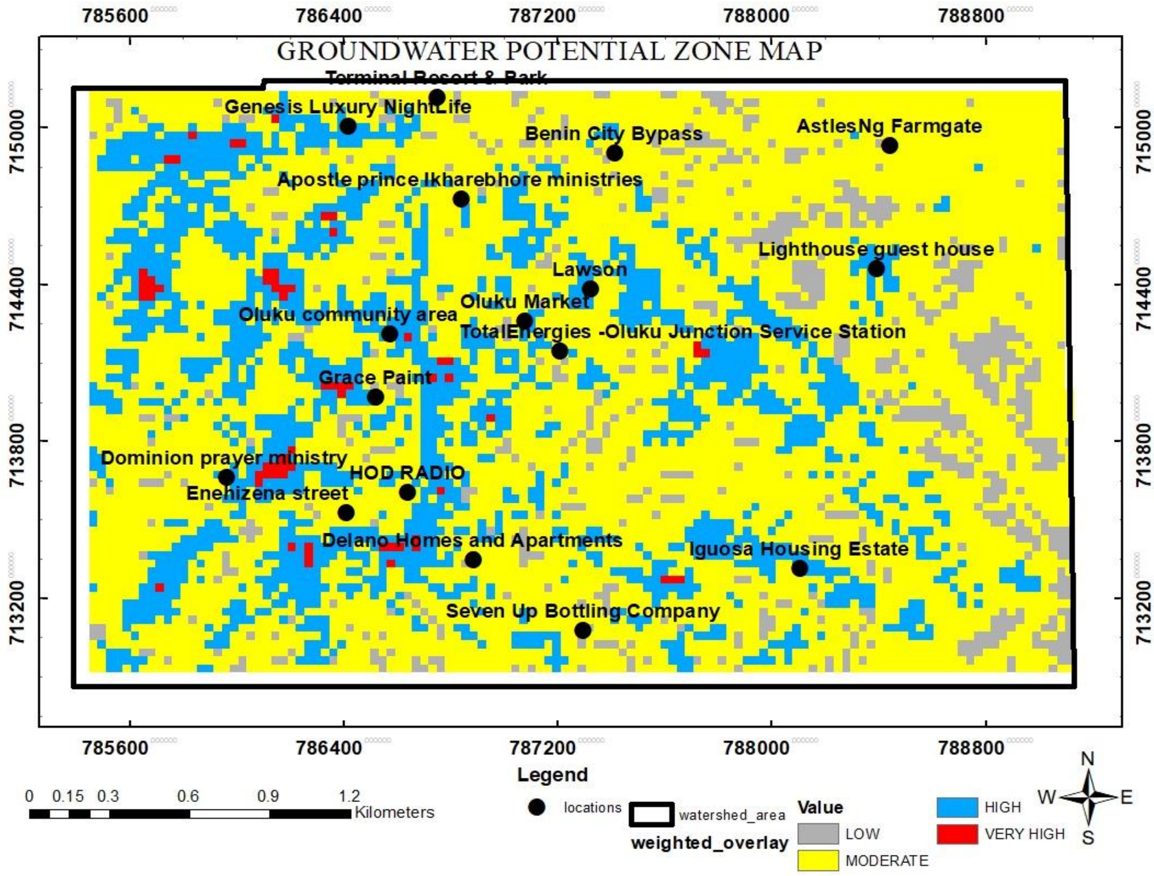

Figure 10: Groundwater Potential Map

Table 7: Area coverage of groundwater potential.

Groundwater potential level	**Spatial extent (km^2)**	**Percentage (%)**
LOW	0.62	7.62
MODERATE	5.76	70.59
HIGH	1.73	21.16
VERY HIGH	0.05	0.63
TOTAL	8.16	100

4.0 Conclusion

The aim of the research has been achieved by producing a groundwater potential map of Oluku community. From this research, we have been able to identify the groundwater potential zones within our study area, and with this knowledge, suitable sites for constructing wells and drilling boreholes to provide safe drinking water to communities can be located by necessary authority. With this information, water conservation strategies can be developed, sustainable water management techniques can be put into effect to protect the environment and human needs. It is essential to continually monitor and re-evaluate these groundwater potential zones, especially considering factors like climate fluctuations and land use alterations. Establishing a robust monitoring and maintenance system for groundwater infrastructure is strongly recommended to ensure the sustainable utilization of these resources over time. These recommendations are aimed at responsible and sustainable management of groundwater potential zones, benefiting both current and future generations while maintaining environmental integrity.

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