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HYDROGEOPHYSICAL VALIDATION OF GIS-BASED GROUNDWATER POTENTIAL MAPPING IN LAGOS ISLAND, NIGERIA

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Abstract

In rapidly urbanizing settings where public water supply systems are inadequate, stream or surface water has emerged as an important freshwater resource. The study combined the use of Geographic Information Systems (GIS), Remote Sensing (RS) and Vertical Electrical Sounding (VES) techniques to map and validate groundwater potential in Lagos Island, Nigeria. Six groundwater conditioning factors were prepared and integrated: geology, slope, rainfall, soil, drainage density, and lineament density, which were all done in a GIS environment using the Analytical Hierarchy Process (AHP) and weighted overlay analysis. To assess the subsurface aquifer conditions and to confirm the groundwater potential zones derived from GIS, Hydrogeophysical (Schlumberger electrode configuration) studies were done. The groundwater potential map produced revealed the study area to be under high, moderate and low groundwater potential with 78, 21 and 1 per cent of the area respectively. Overburden thickness, as interpreted from VES, ranged from 14 m to 46 m while the basement resistivity values were low, suggestive of fractured and water-bearing formations. A good agreement was found between the groundwater conditions obtained from the GIS-AHP results and VES results, which shows that the combination of the geospatial and the hydrogeophysical methods in groundwater exploration is reliable. The study emphasizes the benefits of hydrogeophysical validation to enhance the groundwater potential evaluation in a coastal urban setting. Recommendations for future groundwater exploration programmes include hydrogeophysical validation, groundwater monitoring systems and more field-based datasets to improve sustainable groundwater resource management in Lagos Island and other coastal urban settings.

Keywords: Hydrogeophysics, GIS, Ground water potential.

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1.0 Introduction

Since groundwater is the main source of drinkable water, it continues to be a crucial part of sustainable management of water resources [9]. Rising residential, agricultural, and industrial demands that put more strain on limited freshwater reserves increase its significance [18][17][24] . The need for water in urban areas to promote industries and population is rising due to a growing economy and population growth. There is a gap between water supply and demand in many urban areas, including Lagos, because water infrastructure construction has not kept up with rising water demand [15].

In many metropolitan areas, including Bengaluru [25], Lagos [16], and Nairobi [14], the availability of groundwater has frequently been essential in closing this gap and promoting socioeconomic and social health. Uncontrolled and unauthorized local groundwater extraction from manually dug wells and boreholes has been used to achieve this [8]. Due to excessive extraction and contamination of groundwater reserves from conventional drainage systems leaks, uncontrolled or unmanaged disposal of waste from industry and contaminants, or saltwater intrusions in coastal areas, many cities have seen a dramatic drop in their water table [26]. The rate at which aquifers are replenished in comparison to the rate at which groundwater is extracted determines how resilient groundwater is to various challenges. Therefore, in many developed places, developing sustainable water management strategies requires an in-depth knowledge of modifications to groundwater recharge and aquifer replenishment strategies [11].

Recent developments in geospatial technology offer consistent, quick access to data and are highly economical in terms of time and resources [21]. Based on a region's hydrodynamics, rainfall, geography, geology, soil texture, gradient, etc., groundwater availability varies spatiotemporally [10]. In recent times, groundwater studies have made extensive use of remote sensing (RS), geographic information systems (GIS), and multi-criteria decision analysis (MCDA) tools such the analytical hierarchy process (AHP) [6],[19],[13]. Researchers were able to gain a deeper understanding and analysis of the potential for groundwater by combining RS and GIS or Geospatial with MCDA [13]. Combining thematic data such as lithology, topography, and land cover has been shown to achieve more accurate results [13]. Hydrogeophysical technique is the use of geophysical tools to investigate groundwater that are based on physical property

measurements of the subsurface hydrogeology, for example, electrical resistivity; also used to deduce aquifer geometry and certain steady aquifer hydraulic parameters [22],[5],[1]. Vertical Electrical Sounding (VES) is one of these methods that is commonly used in groundwater exploration and aquifer evaluation.

Despite advancements in geospatial modelling, ground-truth validation remains critical for model credibility. Ground-truth validation is still essential for model believability despite advances in geospatial modeling. Geophysical methods, particularly Vertical Electrical Sounding (VES), are extremely helpful in this situation [5],[23]. According to studies, integrating resistivity data to validate GIS-AHP outputs improves model credibility and aids in confirming aquifer boundaries found using thematic overlay [12],[20]. For example, [25] found that validation using resistivity data demonstrated good agreement with high potential zones indicated by AHP weighting and theme integration. This study aims to integrate RS, GIS, and VES techniques to delineate groundwater potential zones in Lagos Island, Nigeria, and to evaluate the effectiveness of such integration for sustainable groundwater management.

2.0 Study Area

The study area lies within the southwestern part of the Nigerian Precambrian basement complex and within the Latitude 7^0 21' 47" and 7^0 41' 43'N and Longitude 3^0 58' 42.71"E and 3^0 58' 49.14"E and it is accessible through Iyana Agbala Akoko. Lagos Island (*Ìsàlẹ̀ Èkó*) is the principal and central local government area (LGA) in Lagos, Lagos State. Lagos Island is generally at a low altitude with the highest part less than 15 meters above sea level and slopes towards the direction of the surrounding lagoons and creeks. The surface geology is made up of the Benin Formation (Miocene to recent), recent littoral alluvial. Just like Lagos, it has a tropical wet and dry climate with two distinct rainy seasons; the more intense season occurs between April and July, with a milder one from October to November. The temperature range in Lagos is fairly small, generally staying between a high of 91F (33C) and low of 70F (21C). The hottest month is March, when average daytime temperatures reach 91F (32C), while August is the coldest month with an average temperature of 77F (25C). However, the broader local area on the Island features a diverse coastal ecosystem characterized by mangrove swamps, freshwater swamp forests, lowland rainforests, and sparse shoreline beach vegetation.

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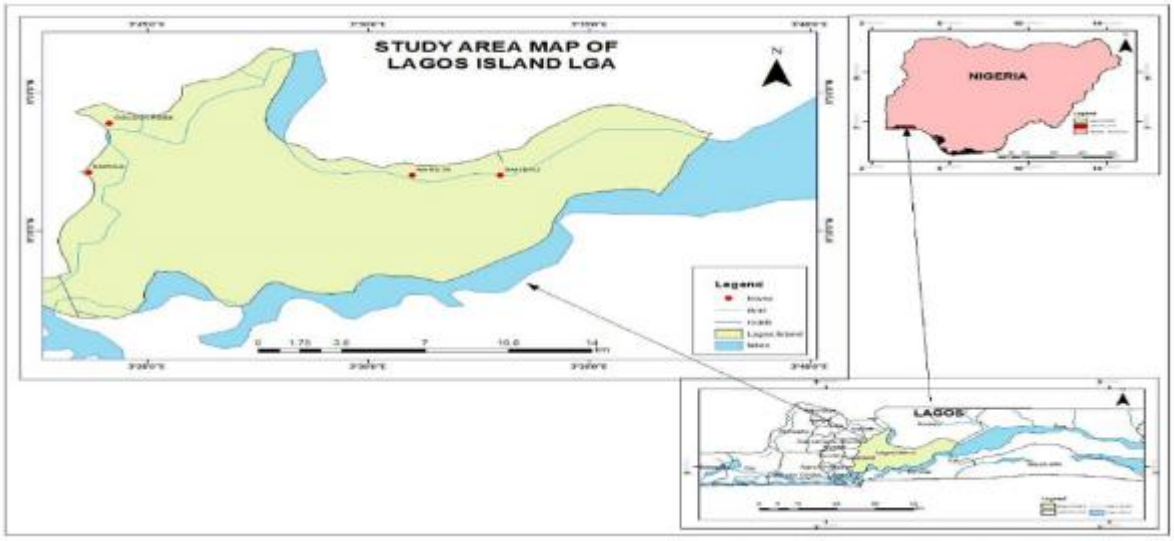


Figure 1: Study area map

3.0 Materials and Method

3.1 Data Sources

Geospatial and hydrogeophysical datasets obtained from secondary sources and field procedures were used to actualise the aim of this study. Table 1 presents data collection, sources, and the purpose for which they were collected for the study.

Table 1: Data Characteristics and Data Sources

Data	Source	Purpose
SRTM DEM	USGS	Slope and drainage extraction
Geological Map	Nigerian Geological Survey	Lithological characterization
Rainfall Data	Nigerian Meteorological Agency	Recharge assessment
Soil Map	FAO/National Soil Database	Infiltration assessment
Satellite Imagery	USGS Explorer	Lineament extraction
VES Data	Field Survey	Subsurface aquifer characterization

3.2 Preparation of Groundwater Conditioning Factors

The number of groundwater conditioning factors that were deemed important in the context of groundwater occurrence in the study area were selected as geology, slope, rainfall, soil, lineament density, and drainage density. A geological map of the study area was digitized and reclassified, using the lithological properties and the capacity to store groundwater. It was decided that formations with a greater permeability and porosity are more suitable, and thus obtained the highest suitability ranking. In addition, the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used in conjunction with spatial analysis tools in ArcGIS to derive the slope map. The reclassified slope map was then classified into groundwater suitability classes. This is because the infiltration and groundwater recharge processes were encouraged by low slope areas, and steep slopes, on the other hand, encouraged runoff and were given lower suitability values.

The spatial interpolation techniques were used to create a rainfall distribution map of the study area from the rainfall data. Higher groundwater suitability rankings were given to areas with relatively high rainfall due to the potential for higher recharge. The soil map was reconveyed to a new classification based on infiltration capacity and permeability features. The higher infiltration rates were given a higher groundwater suitability value for soils. Satellite imagery was used to isolate lineaments and then analysed to create a lineament density map. The areas with high lineament densities were thought to be favourable for groundwater occurrence because fractures and faults create secondary porosity and permeability. The drainage density was calculated from the DEM using drainage analysis tools. Low drainage density sites were given higher suitability values as low drainage density indicates high infiltration and good groundwater recharge potential.

3.3 Assignment of Weights Using Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) was used to determine the thematic elements' corresponding importance. The thematic weights were assigned based on hydrogeological significance and supported by previous groundwater potential studies in comparable terrains. The normalized weights were computed using Saaty's scale. The consistency ratio (CR) was calculated to ensure consistency in the paired comparisons. The weights acquired for the layers and subclasses were combined using the groundwater potential index (GWPI). The formula was implemented using the raster calculator tool in the ArcGIS environment. The groundwater potential distribution

map produced by the overlay approach was divided into three classes: high, moderate, and low groundwater potentials.

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

Where W_i is the normalised weight of the j thematic layer, X_j is the rank value of each class with respect to the j layer, m is the total number of thematic layers, and n is the total number of classes in a thematic layer. The resulting groundwater potential map was classified into High groundwater potential, moderate groundwater potential, and low groundwater potential.

3.4 Groundwater Potential Mapping (AHP)

The priority weights assigned to each theme were given in this section. The highest priority was given to geology, followed by Slope, Lineament density, Rainfall, Drainage density and Soil texture. Each theme was assigned a weight based on suitability, within each theme. Under Geology, for instance, sandstone (Abeokuta formation) was given the highest measure of weight of 28 while migmatite was given the weight of 13. The number of very low slopes was 20 and very high slopes was 4 under Slope. Very high density = 16 very low density = 1 under lineament density. These weights were based on the importance of each of these factors to groundwater potential.

3.5 Vertical Electrical Sounding (VES)

The vertical electrical sounding techniques were carried out by the Schlumberger electrode array to examine the subsurface resistivity variations in the study area. The apparent resistivity data collected in the field were processed and interpreted for subsurface lithologic characteristics and aquifer conditions. The VES interpretation generated an overburden thickness map, a weathered layer resistivity map and a bedrock resistivity map. These parameters were used to evaluate aquifer potential and to validate the groundwater potential zones defined by the GIS.

3.6 Integration and Validation of Groundwater Potential Modelling

Groundwater potential modelling was integrated and validated by spatially comparing the groundwater potential zones derived from GIS with the hydrogeophysical data derived from VES analysis. The spatial relations between the zones derived from GIS and the aquifer characteristics derived from VES were evaluated in order to evaluate the reliability of the groundwater model.

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Finally, a weighted groundwater potential map was developed by integrating the GIS-based model with the VES-derived model.

4.0 Results and Discussion

4.1 Groundwater Conditioning Factors

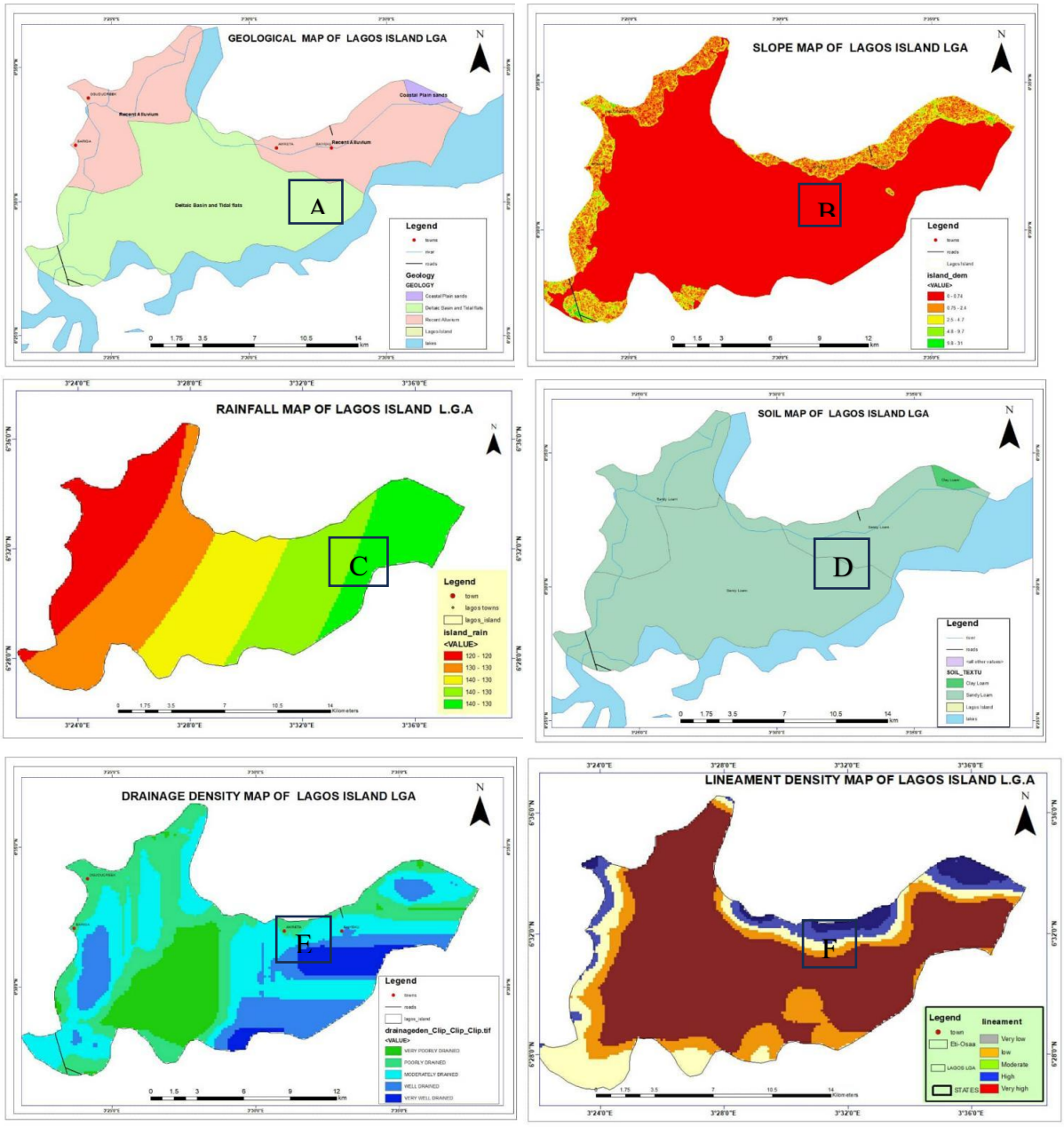


Figure 2: Groundwater conditioning factors: Geology (A), slope map (B), rainfall map (C), soil map (D), drainage density map (E), and lineament density (F)

Three main geological units were found in the study area. These include basement complex, recent alluvium, and metamorphic rocks (quartzites, quartz schist, and amphibolites). As shown in figure 2D, recent alluvium is present in Lagos Island LGA and has a limited spatial spread. The groundwater flows into two major collecting (converging) centers, according to the slope map. The primary groundwater flow directions exhibit geological structural patterns. Groundwater flows toward the low slope of the central, south-eastern, and southwestern portions of the project area and away from the high slope zones in the northwest and south-central portions.

Additionally, rainfall declines from the north to the south of the Lagos Island LGA and ranges from 1,469.6 mm to 1304.2 mm annually throughout the study region. Additionally, the results of the soil map showed that there are two types of soil in the study region: Rainforest soil, which covers the majority of the study area in the north, and wetland soil, which covers some areas in the southeast. These kinds of soils have different water circulation and infiltration patterns. The variability on the lineament density map ranges from 0 to 154 units. Relatively high lineament density closures are found in the southeast and north central/northeast regions. The northwestern and southwestern flanks, as well as the central area that includes the city core, have modest lineament sensitivity. It was shown that when one gets farther away from the lineaments, the extent of groundwater potential decreases. The slope highs of the basement rock outcrop are correlated with the zones of high lineament density, whereas the low (relatively) flat plains are correlated with areas of low lineament frequency, according to a correlation between the lineament density and the slope map. The main rivers and their tributaries contribute to replenishing the groundwater supply, according to the drainage density chart.

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4.2 GIS-Based Groundwater Potential Mapping (AHP Weight Assignment and Thematic Influence)

Table 2: AHP Weight Assignment and Thematic Influence

Theme	Priority %	Class	Assigned weight
Geology	28	Migmatite	13
		Sand stone(Abeokuta formation)	28
Slope	20	Very low	20
		Low	17
		Moderate	12
		High	9
		Very high	4
Soil Texture	10	Sandy Loam	10
		Sandy clay	7
		Clay loam	3
Rainfall	13	Very low	1
		Low	3
		Moderate	6
		High	9
		Very high	13
Lineament density	16	Very low	1
		Low	4
		Moderate	9
		High	13
		Very high	16
Drainage Density	13	Very low	1
		Low	4
		Moderate	7
		High	10
		Very high	13

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4.3 Spatial Distribution of Groundwater Potential Zones

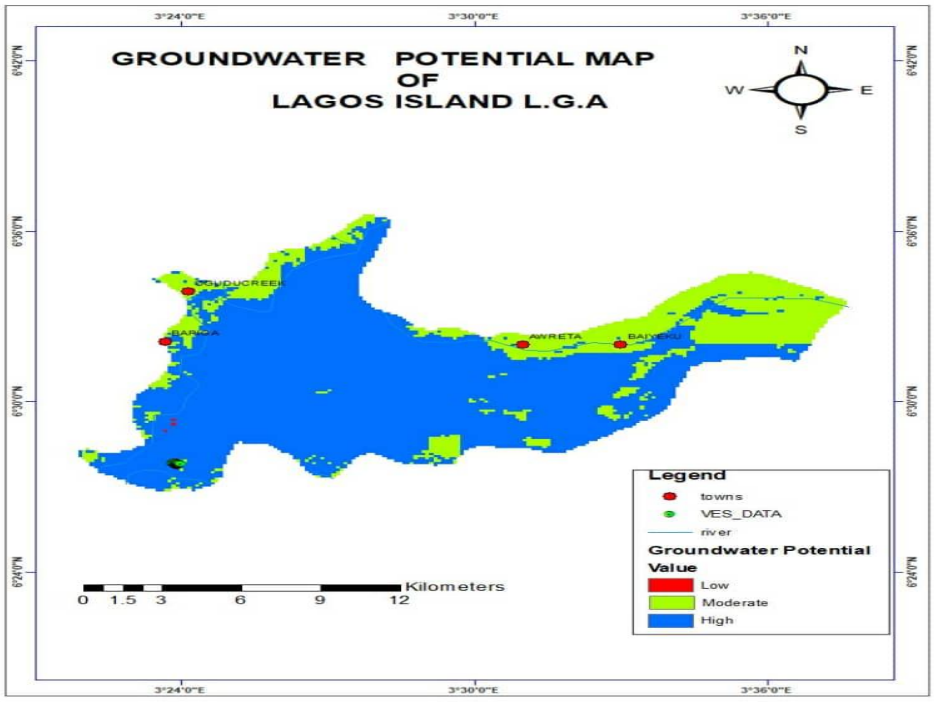


Figure 3: Groundwater potential zone map of the study area

The result of the groundwater potential zone indicated that Lagos Island LGA is viable for groundwater development. The maps produced show three classes of groundwater potential zones. Out of the LGA total land mass, 1% of the area translates to a low groundwater potential zone, 21% of the area are medium rated groundwater potential zone and 78% of the area was classified as high groundwater potential zone. The predominance of high groundwater potential zones across the study area reflects the combined influence of favorable geological formations, low slope conditions, significant structural controls, and thick overburden development. These conditions collectively enhance infiltration, groundwater storage, and subsurface transmissivity.

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4.4 Hydrogeophysical Analysis

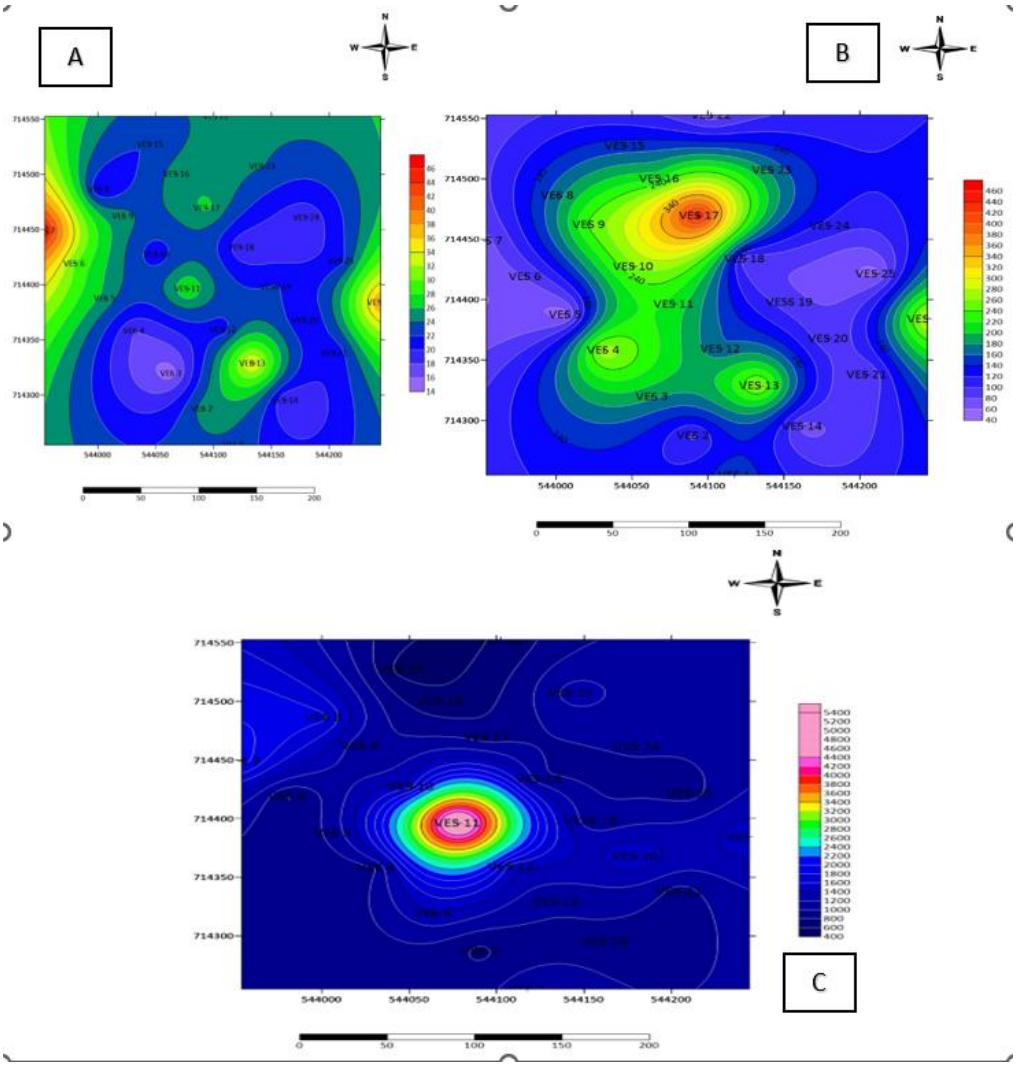


Figure 4: overburden thickness map (A), bedrock resistivity map (B), and weathered layer resistivity map of the study area

The generation of an overburden thickness map revealed the aquifer geometry of subsurface. The overburden encapsulates the Top wet Clay/Sand, Sand/Clay, and Fractured rock/zone/gravel. The overburden thickness ranged from 14 to 46m. The overburden is very thick at the eastern and southeast zones of the study area, and hence has a probable high groundwater potential. Although all other VES points have an overburden greater than 15m, which was associated with high groundwater potential, except for VES 3 that is encapsulated with thin overburden, which could result to low groundwater potential. All the VEs were fractured as depicted from the low basement resistivity (< 750 Ω m). It can be inferred that some amount of water is contained within the

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fractures which further support the groundwater potential of these points however VES 6 was the best among them since it had the least value of resistivity. VESs 1 and 5 had aquifer resistivity range from 21 to 100Ωm, which suggests sandy clay/slit aquifer of medium—to—good groundwater potential.

4.5 Groundwater Potential Map from VES Data

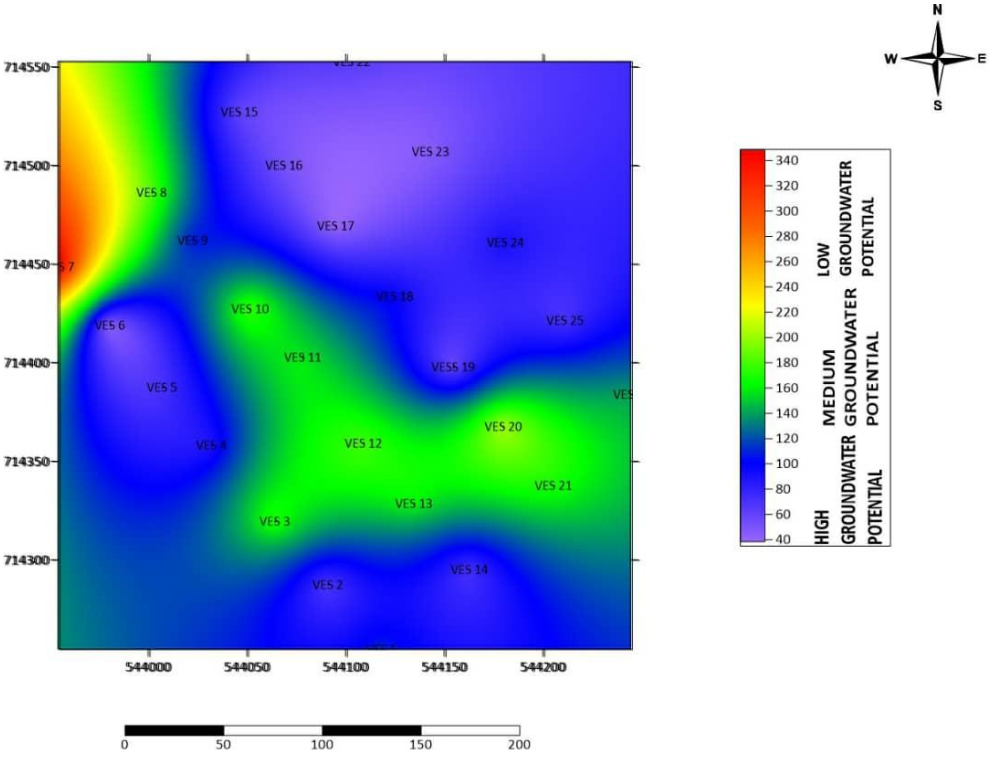


Figure 5: Groundwater potential map from VES Data

The three categories of groundwater potential zones in the study area namely: high (78%), medium (21%) and low (1%) were identified and delineated. This result correlates with the result from the groundwater potential delineation using GIS-AHP as earlier reported. The integration of remote sensing, GIS and Hydrogeophysics data produced several maps and profiles which have been used to define the groundwater potential of Lagos Island. This finding aligns with other existing studies [2]; [1]; [7], whose studies revealed that structurally controlled terrains often exhibit enhanced groundwater productivity.

5.0 Conclusion

The study revealed the efficacy of using GIS, Remote Sensing (RS) and hydrogeophysical survey in mapping and validating groundwater potential in Lagos Island in Nigeria. The groundwater potential map was prepared after integrating all the groundwater conditioning factors by adopting Analytical Hierarchy Process (AHP), weighted overlay analysis, and showed good results. The outcome of the results showed that a large part of the island of Lagos has favourable conditions for groundwater, about 78% of the study area was grouped in high, 21% in moderate and 1% in low groundwater potential. Favorable geological formations, low slope conditions, high lineament density, and suitable recharge characteristics were the most important factors affecting the predominance of high groundwater potential zones. The groundwater potential zones determined in the GIS were further supported by hydrogeophysical investigations. The VES data showed thick development of overburden and low resistivity of basement rocks, which is a sign of fractured and water bearing rocks suitable to groundwater accumulation. The observed consistency of the GIS-AHP model and the hydrogeophysical results verifies the consistency of using both surface and subsurface data to estimate groundwater. The study, therefore, concludes that the incorporation of GIS-AHP modelling in validation by VES is an effective and reliable approach for groundwater exploration and sustainable groundwater resource management in coastal urban areas. Recommendations for future groundwater exploration programmes include hydrogeophysical validation, groundwater monitoring systems and more field-based datasets to improve sustainable groundwater resource management in the Lagos Island and other coastal urban settings. The recommended that future groundwater exploration programmes should include hydrogeophysical validation, groundwater monitoring systems, and more field-based datasets to improve sustainable groundwater resource management in the Lagos Island and other coastal urban settings.

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