GIS-BASED INTEGRATED GROUNDWATER POTENTIAL ASSESSMENT OF OSUN DRAINAGE BASIN, SOUTHWESTERN NIGERIA

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ABSTRACT

A GIS-based integrated approach was adopted to assess the groundwater potential of Osun Drainage Basin underlain by the Basement Complex terrain of Southwestern Nigeria. Topographic parameters including surface curvatures, slope and elevation were derived from SPOT DEM and used to generate landform and relief maps for the study area. Spatial Analysis Module of ArcGIS 10.3 software was used to generate lineament proximity, hydrolineament density and drainage density maps for the study area. Vegetation Index module was employed to model the pattern of vegetation from Landsat imagery.Lithologic and soil layers were extracted from existing geological and soil maps. Five hundred Vertical Electrical Sounding datasets were quantitatively interpreted using partial curve matching technique and computer assisted 1-D forward modeling. Overburden thickness and aquifer thickness maps were generated from the VES interpretation results. Eleven raster-based thematic maps (lineament density, lineament proximity, drainage density, vegetation index, slope, elevation, landforms, overburden thickness, aquifer thickness, lithology, soil) were prepared from the generated maps and their individual influence on groundwater systematically determined. The thematic layers were subjected to Fuzzy Logic Overlay in ArcGIS environment in order to delineate the basin into various groundwater potential zones. The basin was delineated into five groundwater potential zones comprising very high, high, moderate, low and very low. Sixty one percent of the study area was rated very low to low, 16 percent was rated moderate and the remaining 23 percent was adjudged to have good groundwater potential. Seventy-six percent of the borehole yields correlated with the groundwater potential model with correlation coefficient of 0.872 at $\alpha = 0.01$. The study concluded that groundwater potential was generally low across Osun Drainage Basin. However, isolated zones with high groundwater potential were identified particularly in the upland area of the basin.

Keywords: Groundwater Potential, Remote Sensing, Lineaments, Hydrogeology, Topographic Parameters, Geo-electric Parameters

INTRODUCTION

One of the major problems facing the inhabitants of developing countries is inadequate potable water supply. Despite the economic prosperity and industrial development recorded in the 19th and 20th centuries, many of these countries cannot provide adequate potable water for their inhabitants (Akinwumiju, 2015). The Joint Monitoring Programme (2012) of the United Nations has observed that groundwater remains the only alternative source of potable water from which the inhabitants of the developing countries could be served. However, the occurrence, distribution and flow of groundwater is discontinuous and it is determined by the dynamic interactions of various environmental factors such as geotectonic structures, lithology, overburden thickness, weathering grade, geomorphology, fracture extent, drainage pattern, landuse/cover and climate (Surrette *et al.,* 2008; Yeh *et al.,* 2008). Consequently, groundwater is not uniformly distributed in terms of quantity and quality. Depending on the hydrogeological and climatic conditions, either the magnitude of natural groundwater resources or hydraulic parameters of rocks represent the limit of groundwater development (Krasny, 1997; Martin, 2012). Nevertheless, the influence of topography on borehole yield has been emphasized with a general result that wells located in valleys and flat areas show higher yield than wells located on slopes and hilltops (Krasny, 1997; Neves and Morales, 2007). Furthermore, in a basin where average annual rainfall is above 1000 mm, groundwater potential would be a function of secondary porosity (Sener *et al.,* 2005; Sander, 2007), vegetation (Akintola, 1874; Shaban *et al.,* 2006), overburden thickness (Ayoade, 1988; Olorunfemi, 1990), permeability of topsoil (Shaban *et al.,* 2006; Jha *et al.,* 2007; Yeh *et al.,* 2008), topographic characteristics (Olorunfemi, 1990; Wood, 1996; Solomon, 2003; Jha *et al.,* 2007;

Yeh *et al.,* 2008), surface drainage (Sener, *et al.,* 2005; *Jha et al.,* 2007; Sander, 2007), lithology (Jha *et al.,* 2007; Yeh *et al.,* 2008), landforms (Solomon, 2003; Teixeira *et al.,* 2008) and topographic characteristics (Wood, 1996; Florinsky, 2007; Teixeira *et al.,* 2008).

In recent years, several techniques for land and water management have evolved, and remote sensing and Geographic Information System (GIS) have gained acceptance (Jha *et al.,* 2007). One of the relevance of remote sensing technologies to groundwater studies is the provision of Imageries and images by the space-based- (satellite) and air-based- remote sensing systems, which acquire information within a wide range of digital values that must be processed (in some cases) before it can be utilized. The major contribution of remote sensing technology to groundwater exploration is the availability of free to affordable satellite imageries and digital elevation model, which serve as input data in various analyses. One of the important analyses is the lineament extraction from satellite imagery and digital elevation model. Lineaments, which depict the occurrence of fracture/faults (stress zones) within rocks, are indicators of groundwater occurrence within the crystalline rocks. Hence, lineaments are mapped to evaluate the groundwater potential of regions especially within the Basement Complex terrain. GIS is a powerful tool that can handle large volumes of data (both spatial and aspatial) with the capability to support various types of quantitative and qualitative spatial analyses and interpretation. Recently, the development and acceptance of object-based image analysis in Geographic Information Science has offered another opportunity to achieve better results in the field of digital image processing and interpretation. In the case of groundwater exploration especially lineament mapping and analyses, this development offers the opportunity to generate high precision data layers and adopt a knowledge-based image processing procedure. An important contribution of GIS to groundwater exploration is the possibility of integrating, analyzing and manipulating large volumes of multi-source spatial and non-spatial data as well as the availability of various output options for different end-users.

In Nigeria, groundwater studies are usually being undertaken on local scale within a small delimited geographic boundary particularly in the vicinity of water demand; or on the basis of political boundaries, which normally constitute parts of many watersheds that extend beyond the political boundaries. Consequently, this often leads to erroneous conclusion on the groundwater potentials of regions particularly within the Basement Complex terrain (Akinwumiju, 2015). Therefore, there is the need for a model that will allow for efficient groundwater resource assessment on the basis of naturally delimited boundary in Nigeria. The study area – Osun drainage basin – can be regarded as a megawatershed. Bisson *et al.* (1995) emphasized that megawatershed is a good model of study area that is most suitable for groundwater exploration particularly in the Basement Complex terrain. Megawatershed is a paradigm, which greatly extends the catchment, transmission and storage boundaries of traditional watersheds by recognizing the overriding influence of tectonically induced, large scale fracture permeability in defining the hydraulics and hydrology of a basin (Wright *et al.,* 1982; Alam, 1989; Bisson *et al.,* 1990; Bisson, 1994). In addition, groundwater studies on the basis of megawatershed provides an understanding of the interaction of surface water, shallow aquifers, and fractured bedrock aquifers and greatly improves the accuracy of sustainable groundwater resource evaluation. The premise of the megawatershed model is that aquifers contained in the fractured bedrock basins possess not only simple primary porosity but also pervasive fracture permeability (Bisson *et al.,* 1995). This concept of tectonically-induced, regional fracture permeability adds a new dimension of rainfall catchment, groundwater flow and storage, to currently recognized aquifers while at the same time defines new aquifers in previously discounted non-porous rocks. In this study, Osun Drainage Basin is conceived as megawatershed, which lies across the political boundaries of Ekiti and Osun States within Basement Complex terrain of Southwestern Nigeria.

Osun Drainage Basin is located within a region of extensive regional metamorphism (popularly known as Ilesa Schist Belt). Groundwater became the major source of potable water since the mid-1970s when the only water treatment plant (Ilesa Water Works) broke down and was completely shut down. However, an attempt to develop groundwater has not yielded the expected results due to very many failed projects that resulted from failed boreholes with extremely low yield. There is therefore the need to use geophysical, geological, hydrogeological, geomorphological and remote sensing attributes to accurately assess the groundwater resources of the study area. Thus, a GIS-based integrated approach was adopted to assess the groundwater potential of the Osun Drainage Basin with a view to delineating the study area into various groundwater potential zones.

The Study Area

Osun Drainage Basin lies within Latitudes 7°35'N and 8° 00'N and Longitudes 4°30'E and 5°10'E; in the forested undulating Yoruba Plain of Southwestern Nigeria (Figure 1). Osun Catchment (2,194.59 km^2) extends from the upland area of Ekiti State to the low lying area of Osun State, covering 21 Local Government Areas with projected population of 6.2 million as at December, 2014 (Akinwumiju, 2015). The study area is underlain by the Precambrian Basement Complex rocks that are characterized by both foliated and non-foliated rocks such as quartzite/quartzschist, amphibole schist, mica schist, migmatite, porphyritic granite, biotite granite, pegmatite, granite gneiss, banded gneiss and charnockite (De Swardt, 1953; Elueze, 1977; Akinwumiju, 2015) (Figure 2). Notable geological structures within the study area include Efon Ridge Mountains and the Zungeru-Ifewara Fault Zone that dissect the study area (De Swardt, 1953; Elueze, 1977; Boesse and Ocan, 1988; Oluyide, 1988; Odeyemi *et al.,* 1999; Awoyemi *et al.,* 2005).

METHODOLOGY

Required Data and Tools

This study involved the development and implementation of a GIS-based integrated approach to groundwater potential assessment in the study area by utilizing existing geo-spatial datasets as inputs (Table 1). Thereafter, field investigations were embarked upon in order to verify the reliability and limitation of the adopted approach. The methodology involved digital image processing for the extraction of linear features (including rivers and hydrolineaments), GIS processing (including rasterization of vector layers and line density analysis) and analyses for the extraction of input layers from remotely sensed and various ancillary data (geological map, topographical map, soil map) and the evaluation (in terms of number and the characteristics of extracted lineaments) of remotely sensed data (DEMs and Landsat Imagery) as well as field studies. The field studies comprised geophysical, geomorphological and structural investigations.

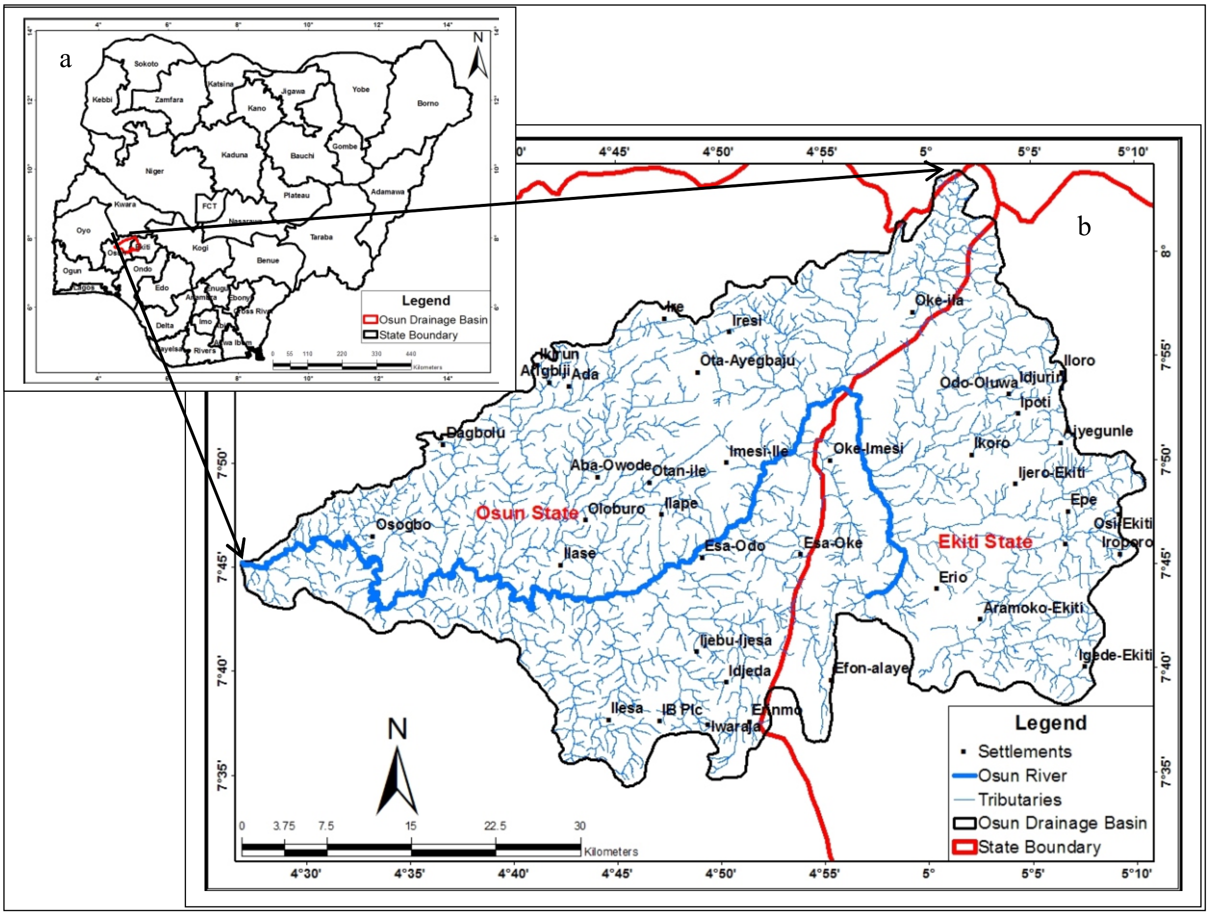

Figure 1: Map of the Study Area showing a): Nigeria's State Boundaries; b): Osun Drainage Basin

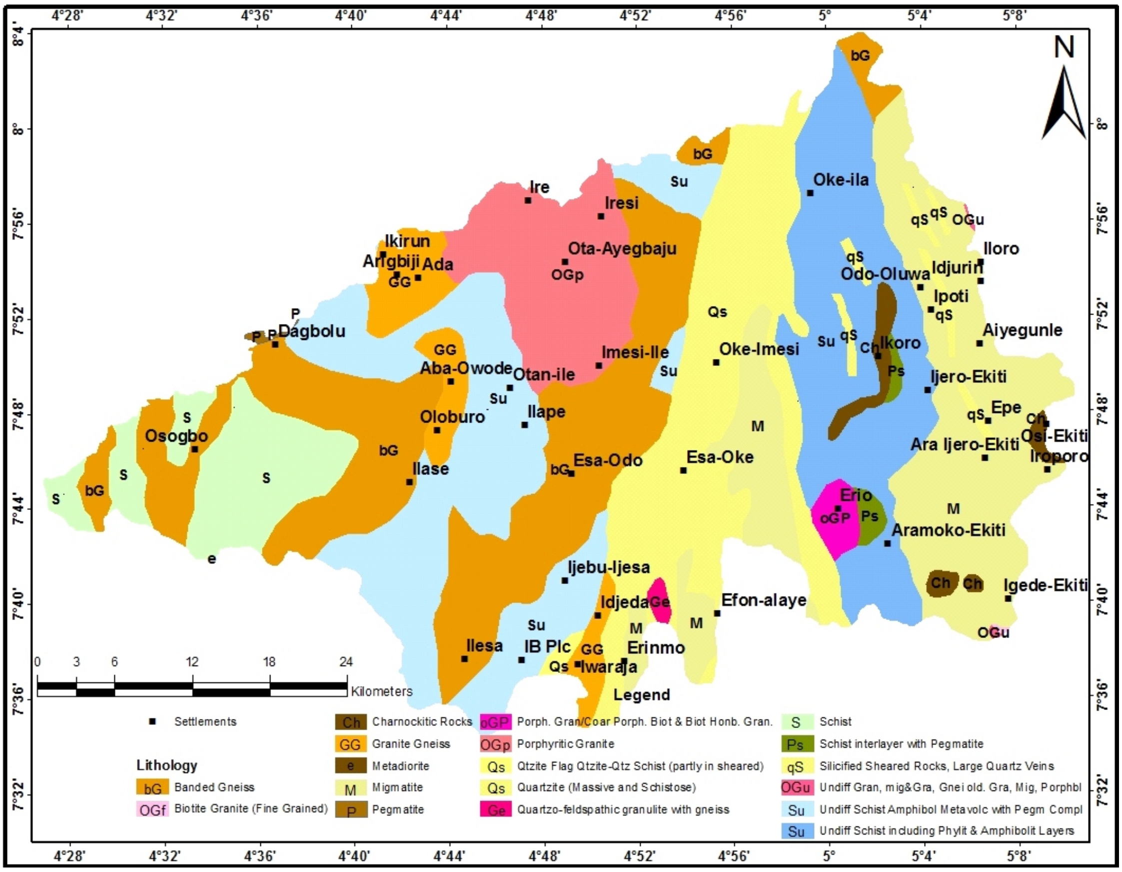

Figure 2: The Lithological Map of Osun Drainage Basin (Extracted from NGSA, 2006)

Table 1: Required Secondary Data and Expected Sources.

S/No.	DATA	DATE	SOURCES
1	ASTER Digital Elevation Model (DEM)	2009	Ministry of Economy, Trade, and Industry (METI) of Japan /United States National Aeronautics and Space Administration (NASA) Database.
2	Geological Map	2006	Nigeria Geological Survey Agency, Abuja
3	Topographical Map.	1966, 2010	Office of the Surveyor General of the Federation, Abuja, Nigeria.
4	Spot Digital Elevation Model (DEM)	2012	Office of the Surveyor General of the Federation, Abuja, Nigeria.
5	Landsat Imagery.	2014	Global Land Cover Facility.
6	Spot5 Imageries.	2009	Office of the Surveyor General of the Federation, Abuja, Nigeria.
7	Borehole Data.	2010-2014	RUWESA, Osun State; Bayowa (2013).

SPOT and ASTER DEMs, Landsat8 imagery, five hundred Vertical Electrical Sounding (VES) data, hydrogeological data from 72 boreholes and ancillary data were acquired. Lithological and soil maps were extracted from existing maps using ArcGIS 10.3 software. PCI LINE (PCI Geomatica, 2014) and Imagine Objective Line Extraction (Erdas Imagine, 2013) procedures were adopted to extract lineaments from enhanced images of the remotely sensed datasets. Details of the analytical procedure of lineament extraction are presented in Akinwumiju and Olorunfemi (2016).Line Proximity and Density modules were employed to generate hydrolineament proximity, hydrolineament density and drainage density maps using hydrolineaments and drainage network of the study area as inputs in ArcGIS 10.3 environment. The Line Density analysis is defined as:

$$\text{Density} = \frac{(L_1 \times V_1) + (L_2 \times V_2)}{\text{Area of Circle}} \quad \ldots\ldots\ldots \quad (1)$$

Where,

L_1 and L_2 represent the length of the portion of each line that falls within the circle; V_1 and V_2 are the corresponding populations' field values.

The output lineaments were sub-mapped into hydrolineaments and lineament cross points. Topographic parameters including surface curvatures and slope were derived from DEMs (using ENVI 5.0 software) and used to generate 2D landform model of the study area. Also, drainage network of the study area was extracted from SPOT DEM using ArcGIS 10.3 software.Normalized Difference Vegetation Index (NDVI) was employed to model the pattern of vegetation from Landsat imagery using the equation:

$$NDVI = \frac{IR - R}{IR + R} \quad \ldots\ldots\ldots\ldots \quad (2)$$

Where, IR = Infrared band, R = Red Band

The VES data were quantitatively interpreted using partial curve matching technique and computer assisted 1D forward modelling. Overburden thicknesses and aquifer thicknesses were generated from VES interpretation results. Eleven thematic maps (lineament density, lineament proximity, drainage density, vegetation index, slope, elevation, landforms, overburden thickness, aquifer thickness, lithology and soil) were prepared and their individual influence on groundwater systematically determined. The thematic layers were subjected to Fuzzy Logic Overlay in ArcGIS 10.3 environment in order to delineate the basin into various groundwater potential zones. All input layers were integrated in a GIS environment and analyzed to assess the groundwater controlling features. Finally groundwater potential map was generated based on the GIS analyses. The reliability of the groundwater potential map was tested by correlating the overall potential score of borehole location with the yield of the borehole in Statistical Package for Social Scientists (SPSS) environment.

GIS Modelling

A multi-criteria analysis was performed on 11 raster layers (lineament density, lineament proximity, drainage density, vegetation index, slope, elevation, landforms, overburden thickness, aquifer thickness, lithology and soil) in order to generate index evaluation of groundwater potential of the study area. To delineate the study area into zones of groundwater potential, a geo-database was created from the raster datasets in

ArcGIS 10.3 environment and organized in different data layers, which include an evaluation that focused mainly on geology (lithology, structure, overburden thickness and aquifer thickness), geography (vegetation index, drainage, soils) and geomorphology (landforms, topography, relief). This approach demands that different layers be integrated considering different weight factors. Each input map with its specific weight and inner scores was used to determine the groundwater potential of every location within the study area by using the spatial analysis function of ArcGIS 10.3 software. The grid raster data structure was adopted, and each raster cell value is a result of the score sum from the explanation factors (the eleven raster layers) listed above. The Fuzzy Logic Method (FLM) was adopted to conceptualize the input layers. FLM requires that all input data must be in grid (raster) format with cell values ranging from 0 to 1 depending on their association with the model.Thus the Fuzzy Membership Tool and Fuzzy Logic Combinational Operators were employed to standardize and integrate the members respectively. In this case, the highest rated groundwater potential areas would be the locations where all explanation factors have the higher score.

Groundwater Potential Factor Establishment

This study analyzed the geologic, geophysical, geomorphological and geographic attributes of Osun Drainage Basin and identified 11 major factors influencing groundwater potential, as listed above. Each factor was carefully examined and assigned appropriate weight. The potential factors would influence groundwater occurrence to varying degrees and these factors are interdependent. The conceptual model that illustrates the interrelationships among the groundwater potential factors is presented in Figure 4. A major interrelationship between two factors was assigned a weight of 1.0 while a minor interrelationship between two factors wasassigned a weight of 0.5. Thereafter, the total weight of each factor was the representing weight of its potential. For instance, lineament is significantly related to lithology, landforms, drainage, aquifer thickness, overburden thickness, slope, elevation and minor influence on vegetation. Thus, its evaluated weight is 7.5. This high weight value means that lineament significantly influences the groundwater potential within the study area. The procedure for determining the relative rate of each factor is presented in Table 2a. The extent of the influence of every factor on groundwater potential was assessed from the interrelationships (major and minor) among the factors. Analytical results demonstrated that the factors influencing the groundwater potential ofOsun Drainage Basin, in descending order, are lineament, lithology, landforms, drainage, overburden thickness, slope, elevation, vegetation, topsoil and aquifer thickness.This procedure revealed that lineament, lithology, landforms, drainage and vegetation are the major influencing factors of groundwater potential across the study area. The score of a given potential factor was determined by calculating its percentage weight of the total weight of all the potential factors. This procedure is presented in Table 2b. The scores of the groundwater potential factors wereused to determine their internal weights. In this case, the upper threshold of the score of each groundwater potential factor was set to its highest possible internal weight. Internal rating for lithology was based on rocks' susceptibility and resistance to chemical and physical weathering as well as the end product of weathering. Soil internal rating was based on clay and stone content as well as the occurrence of concretionary layer. Landform units were rated based on their ability to enhance infiltration and groundwater accumulation.

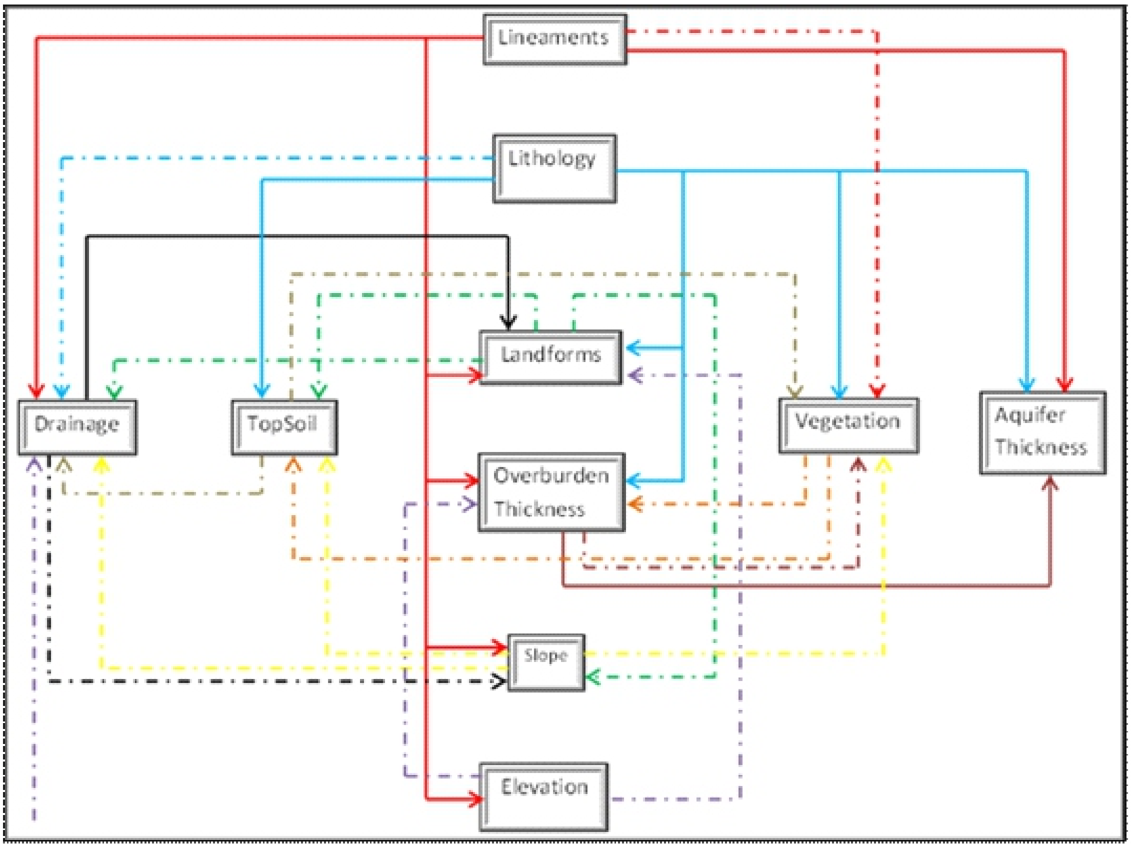

Figure 4: The Interactive Influence of Factors of Groundwater Potential (Modified from Shaban*et al.,* 2006) (*The solid arrows represent major influence while the broken arrows represent minor influence)*

For example, the highest internal weight of lineament is 32 while that of landforms is 7. The resultant internal weights of all the groundwater potential factors considered in this study are presented in Table 3.

Table 2a: Relative Rate of Each Groundwater Potential Factor

S/No	Factor	Calculating Procedure	Relative Rate
1	Lineament	(7 × 1.0) + (1 × 0.5)	7.5
2	Lithology	(5 × 1.0) + (1 × 0.5)	5.5
3	Landforms	(3 × 0.5)	1.5
4	Drainage	(1 × 1.0) + (1 × 0.5)	1.5
5	Slope	(3 × 0.5)	1.5
6	Elevation	(3 × 0.5)	1.5
7	Vegetation	(2 × 0.5)	1
8	Topsoil	(2 × 0.5)	1
9	Overburden Thickness	(1 × 1.0) + (1 × 0.5)	1.5
10	Aquifer Thickness	(0.5)	0.5
			23

Table 2b: Score of Each Groundwater Potential Factor

S/No	Factor	Calculation Procedure	Score
1	Lineament	(7.5 ÷ 23) × 100	32
2	Lithology	(5.5 ÷ 23) × 100	23
3	Landforms	(1.5 ÷ 23) × 100	7
4	Drainage	(1.5 ÷ 23) × 100	7
5	Slope	(1.5 ÷ 23) × 100	7
6	Elevation	(1.5 ÷ 23) × 100	7
7	Vegetation	(1 ÷ 23) × 100	4
8	Topsoil	(1 ÷ 23) × 100	4
9	Overburden Thickness	(1.5 ÷ 23) × 100	7
10	Aquifer Thickness	(0.5 ÷ 23) × 100	2
			100

Groundwater Potential Model Validation

The yields of boreholes were used to validate the groundwater potential index map that was generated for the study area. Ordinary Least Square (OLS) statistics was employed to assess the correlation and possible relationship between boreholes yields and the groundwater potential.

Table 3: Determination of Internal Weight for the Factors of Groundwater Potential

Lineament Density

S/No	Domain of Influence	Internal Weight
1	0 – 0.47	4
2	0.47 – 0.72	8
3	0.72 – 0.97	12
4	0.97 – 1.27	16
5	1.27 – 1.67	20
6	1.67 – 2.21	24
7	2.21 – 3.10	28

Drainage Density

S/No	Domain of Influence	Internal Weight
1	0 – 0.18	1
2	0.18 – 0.53	2
3	0.53 – 0.83	3
4	0.83 – 1.10	4
5	1.10 – 1.30	5
6	1.30 – 1.54	6
7	1.54 – 2.15	7

NDVI

S/No	Domain of Influence	Internal Weight
1	-0 – -0.03	1
2	-0.03 – 0.15	2
3	0.15 – 0.28	3
4	0.28 – 0.60	4

Topsoil

S/No	Domain of Influence	Internal Weight
1	IW, ON, EG	1
2	IT, JA	2
3	MA	3
4	OK	4

Lineament Proximity

S/No	Domain of Influence	Internal Weight
1	250 m Buffer	4
2	500 m Buffer	3
3	1000 m Buffer	1
4	2000 m Buffer	0.5

Lithology

S/No	Domain of Influence	Internal Weight
1	S, e, Ch, OGf	3
2	OG, bG, Su(Phylite &Amphibolite)	7
3	Su (Amphibolite & Pegmatite Complex), oGP	11
5	M, Ge, OGu, qS	15
6	Ps	19
7	Qs, OGp, P	23

Elevation

S/No	Domain of Influence	Internal Weight
1	270 – 352	7
2	352 – 395	6
3	395 – 442	5
4	442 – 492	4
5	492 540	3
6	540 – 591	2
7	591 – 720	1

Aquifer Thickness

S/No	Domain of Influence	Internal Weight
1	0 – 0.18	1
2	0.18 – 0.53	2
3	0.53 – 0.83	3
4	0.83 – 1.10	4
5	1.10 – 1.30	5
6	1.30 – 1.54	6

Overburden Thickness

S/No	Domain of Influence	Internal Weight
1	0 – 0.18	1
2	0.18 – 0.53	2
3	0.53 – 0.83	3
4	0.83 – 1.10	4
5	1.10 – 1.30	5
6	1.30 – 1.54	6
7	1.54 – 2.15	7

Landforms

S/No	Domain of Influence	Internal Weight
1	IS, RW	0
2	H	0.5
3	RG, UL	1
4	LH	2
5	RT	3
6	FS	4
7	UP	5
8	GUP, VF	6
9	DP, CH	7

Slope

S/No	Domain of Influence	Internal Weight
1	1 – 4	7
2	4 – 8	6
3	8 – 13	5
4	13 – 19	4
5	19 – 26	3
6	26 – 36	2
7	36 – 89	1

Landform Codes and Interpretation:*IS= Inselberg; RW = Ruware; H = Hills; RG = Ridge; UL = Uplands; LH = Low Hills; RT = Rolling Topography; FS = Footslope; UP = Undulating Plain; GUP = Gently Undulating Plain; VF = Valleyfill; DP = Depression; CH = Channels.*

Soil Codes and Interpretation: *IW = Iwo Series; ON = Ondo Series; EG = EgbedaSeries;IT = Itagunmodi Series; JA = Jago Series; MA = Mamu Series; OK = Okemesi Series*

See Figure 2 for the interpretation of Lithology Codes

RESULTS AND DISCUSSION

Lineament Analysis

The hydrolineament density and hydrolineament proximity maps (Figures 5 and 6) were generated for the study. Hydrolineament density values ranged from 0 km/km^2 to 3.1 km/km^{2}while the hydrolineament proximity (buffer) ranged between 250 m to 6000 m (see Table 3). The groundwater potentialis expected to increase with increasing hydrolineament density values. Thus, areas that are characterized by high hydrolineament density values are expected to have high groundwater potential. Lineaments have been identified as the most influencing factor of groundwater potential in the Basement Complex terrain (Olorunfemi, 1989; Olorunfemi and Fasuyi, 1993; Solomon, 2003; Afolayan *et al.,* 2004; Akinluyi, 2013; Bayowa, 2013; Akinwumiju, 2015). This is because; lineaments act as conduits for groundwater flow and reservoir for groundwater storage in the crystalline rocks.

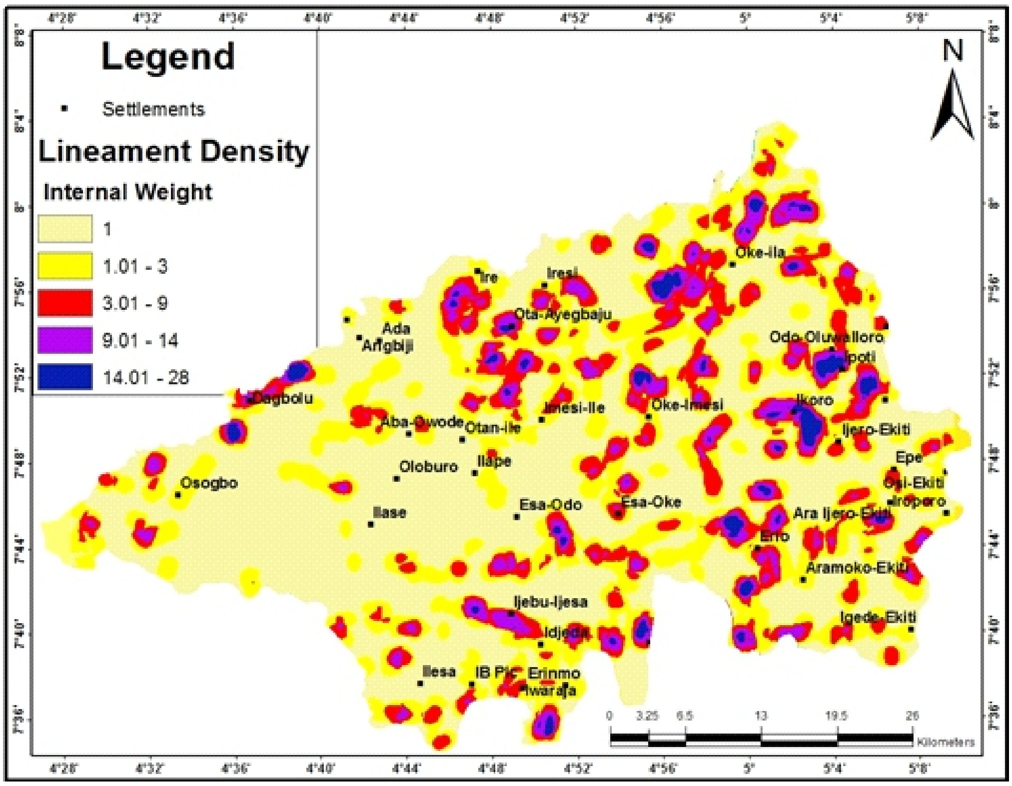

Figure 5: Weighted Hydrolineament Density Map

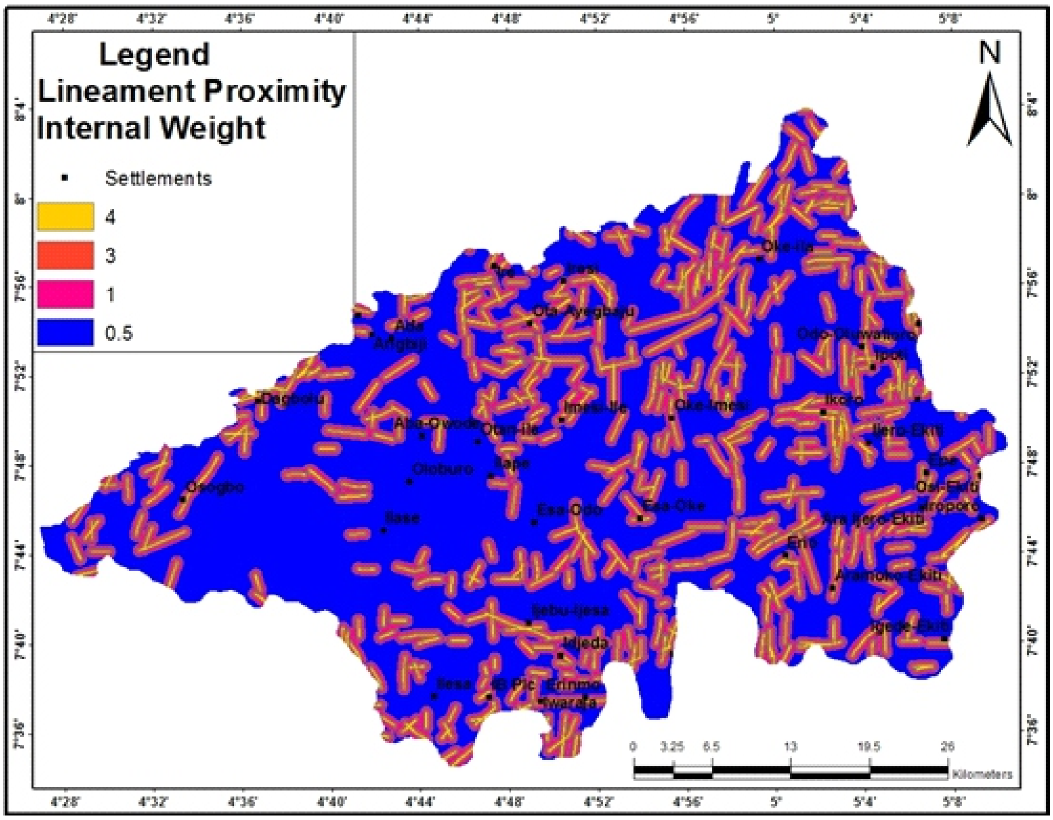

Figure 6: Weighted Hydrolineament Proximity Map

It has also been observed that groundwater yield exhibits significant inverse relationship with distance from the nearest hydrolineaments (Solomon, 2003; Akinwumiju, 2015). However, direct influence of hydrolineament on borehole yield has been observed to be of less importance beyond the distance of 2 km (Sander *et al.,* 1999; Mogowe and Carr, 1999; Henriksen, 2006). It is pertinent to note that the groundwater potential of a given basin does not solely depend on the density of lineaments but the hydrogeological significance of the lineaments as well as the occurrence, the extent (horizontal and vertical) and the storativity of aquifers within a basin.

Vegetation Index

The weighted Normalized Difference Vegetation Index (NDVI) Map of the study area is presented in Figure 7. The study area is characterized by light to slightly heavy forest, which has been anthropogenically disturbed, in many places. The evident all year round green tree vegetation is an indicator of availability of adequate soil moisture that provide underground water to the trees and other vegetation types in the dry season. On the other hand, the observed vegetation pattern signifies enhanced groundwater infiltration potential across the study area with the exception of rock outcrops and heavily populated urban areas. Akintola (1974) and Shaban *et al.* (2006) have earlier observed that infiltration potential decreases with decreasing plant density and vigour. The vegetation index values calculated for the study area ranged from -0.49 to 0.54., indicating various land cover types such as water body, bare ground, rock outcrops, light vegetation and slightly heavy forest with varying degrees of influence on groundwater potential.

Landforms

The internally weighted landform map of the study area is presented in Figure 8. The eastern axis of the study area constitutes residual landforms, which include the rolling topography, undulating terrain and heavily dissected topography particularly around the Effon Ridge. Uplands predominate the northern axis of the basin around Iresi-Oke-Ila area. At the western axis of the drainage basin, a large expanse of gently undulating terrain is evident and this constitutes the Obokun, part of Ilesa, Ibala and Osogbo areas (see Figure 1). The southern axis constitutes gently undulating terrain that is characterized by landform units such as low hills, ruware and hills. It has earlier been observed that landforms exert its influence on groundwater potential of a given basin. For example, while landform units such as channels, valley fills, plains and terraces have been associated with high groundwater potential, landform units such as peak and ridge have been associated with poor groundwater potential (Solomon, 2003; Teixeira *et al.,* 2008).

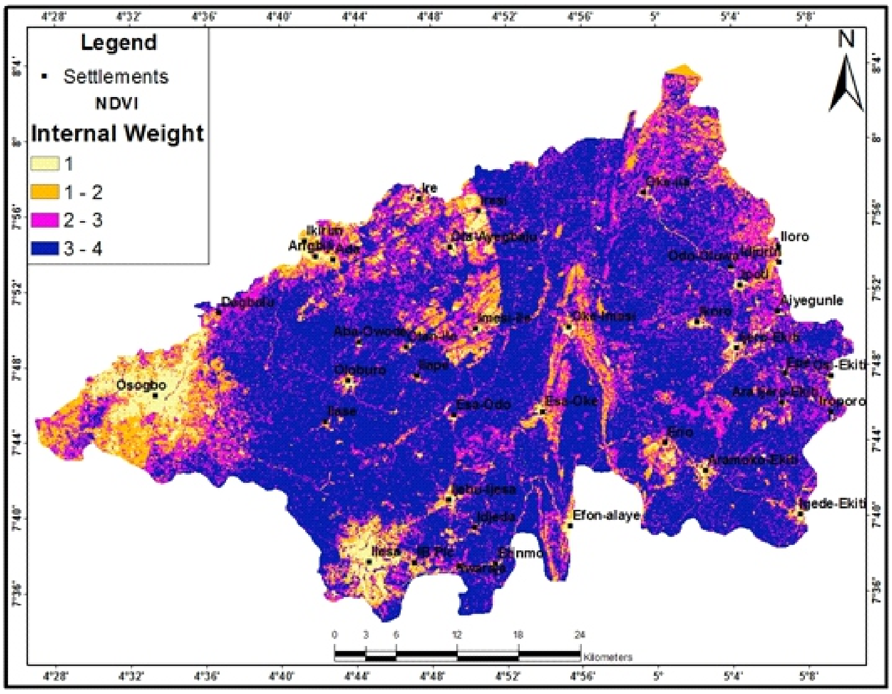

Figure 7: Weighted Vegetation Index Map

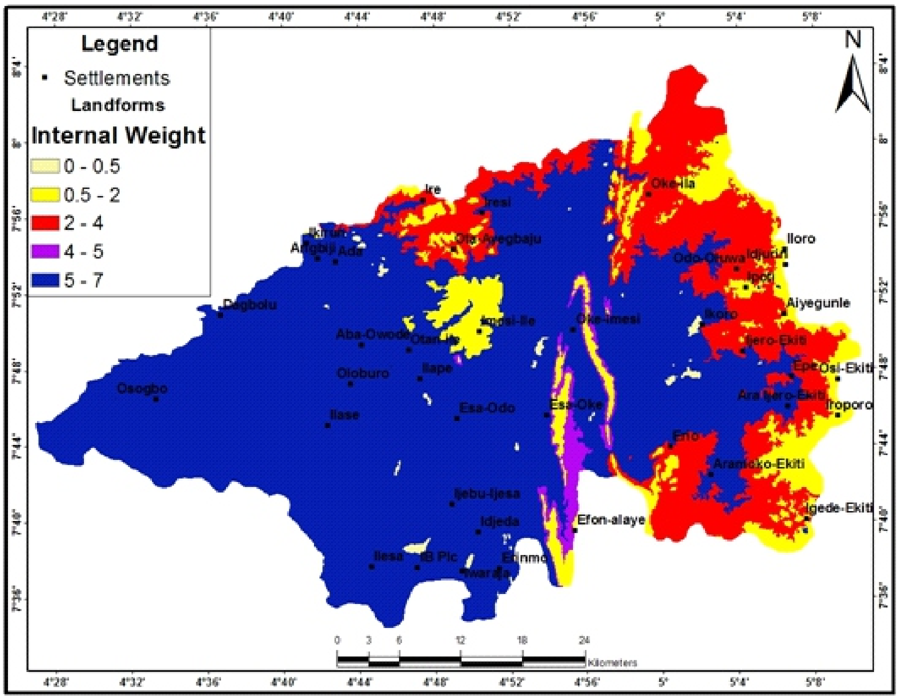

Figure 8: Weighted Landform Map

Slope

The internally weighted slope map of the study area is presented in Figure9. The slope of the study area generally ranged between 0 and 89 degrees, indicating that the terrain of the study area is characterized by extreme high and low topography. The slope map shows that favourable areas of high infiltration potential occur within various landform units in the study area. However, very low slope values were recorded for gently undulating terrain, which is an indicator of enhanced infiltration potential. Slope exerts its influence on groundwater potential by determining (to some extent) the rate of infiltration at any given location within a drainage basin (Wood, 1996; Florinsky, 2007; Teixeira *et al.,* 2008). In this case, the flatter the topography of a land surface, the greater the time lag for runoff water to infiltrate and consequently, the greater the chances of groundwater accumulation.

Relief

The internally weighted relief map of the study area is presented in Figure 10. The elevation of the study area ranged from 270 m to 720 m above sea level(see Table 3). Most of the high relief areas are located within the eastern axis of the basin. It has been earlier observed that groundwater yield exhibits significant relationship with elevation (Solomon, 2003; Jha *et al.,* 2007; Yeh *et al.,* 2008). In this case, high groundwater yield has been ascribed to low elevation as it has been scientifically proved that water will always flow from region of higher elevation to region of lower elevation in isotropic medium (Toth, 1963).

Drainage Density

The internally weighted drainage density map is presented in Figure 11. Drainage density values ranged from 0 km/km^2 to 2.2 km/km^2 (see Table 3). As earlier observed, high drainage density signifies low infiltration potential (Sener *et al.,* 2005; Jha *et al.,* 2007; Sander, 2007). Thus, the observed relatively high drainage density within the western axis of the basin can be attributed to low infiltration potential of the topsoil. On the other hand, high drainage density has also been observed as an important influencing factor of groundwater potential in the Basement Complex terrain (Lee, 2008; Akinwumiju, 2015). This is because shallow (mostly unconfined) aquifers are being recharged by river inflows particularly during the dry season. In groundwater studies, drainage density map could be analyzed, either as an indicator of groundwater potential or as an inverse index of infiltration potential.

Soils

The internally weighted soil map is presented in Figure 12.Seven types of tropical soils were identified in the study area (Smyth and Montgomery, 1962; Adejuwon and Jeje, 1975). These include the Jago series (poorly drained sandy soils), Okemesi series (well drained sandy soils), Iwo/Ondo series (stony concretionary clayey soils), Mamu series (very stony clayey soils), Egbeda series (concretionary clayey soils with few stones) and the Itagunmodi series (concretion-free clayey soils with few stones) (Table 3).Soils of the study area generally have low infiltration due to the prevalence of clay minerals and the occurrence of concretionary lateritic layer in many places, which collectively hamper the percolation of surface water into the subsurface. The permeability of the topsoil is very crucial to infiltration potential vis-à-vis groundwater accumulation (Shaban *et al.,* 2006; Jha *et al.,* 2007; Yeh *et al.,* 2008).Thus, clayey and concretionary lateritic soils would cause low infiltration, high runoff and consequently low *in situ* groundwater accumulation.

Lithology

The internally weighted lithologic map of the study area is presented in Figure 13. The study area is underlain by Slightly Migmatized to Non-migmatized Meta-sedimentary and Meta-igneous Rocks which belong to the Schist Belt. In their fresh states, the groundwater potential of these rocks is generally low as a result of their low porosity. The rocks generally weather into clayey materials characterized by high storativity and low permeability with generally low to moderate level (at best) groundwater potential rating. Past studies have emphasized that groundwater potential of a given basin depends largely on its lithology, particularly in the Basement Complex terrain (Olorunfemi, 1980, 1990; Olorunfemi and Fasuyi, 1993; Solomon, 2003; Akinluyi, 2013; Bayowa, 2013; Ojo *et al.,* 2015; Akinwumiju, 2015). Thus, lithological analysis constitutes a crucial part of groundwater potential assessment in the crystalline rock environment.

Overburden Thickness

The internally weighted overburden thickness map of the study area is presented in Figure 14. The overburden thickness ranged between 0.43 and 133.5 m (see Table 3). The areas that are characterized by thick overburden are underlain by mica schist, which is known for its extremely low groundwater potential. The groundwater potential of the Basement Complex terrain has been found to be highly dependent on overburden thickness particularly where rocks have not been significantly fractured (Ayoade, 1988; Olorunfemi, 1990). However, the groundwater potential of weathered layer largely depends on the physicochemical properties of the parent rocks.

Aquifer Occurrence

The internally weighted aquifer thickness map is presented in Figure 15. Two types of aquifer were delineated within the study area. These include the weathered layer and fractured aquifer.

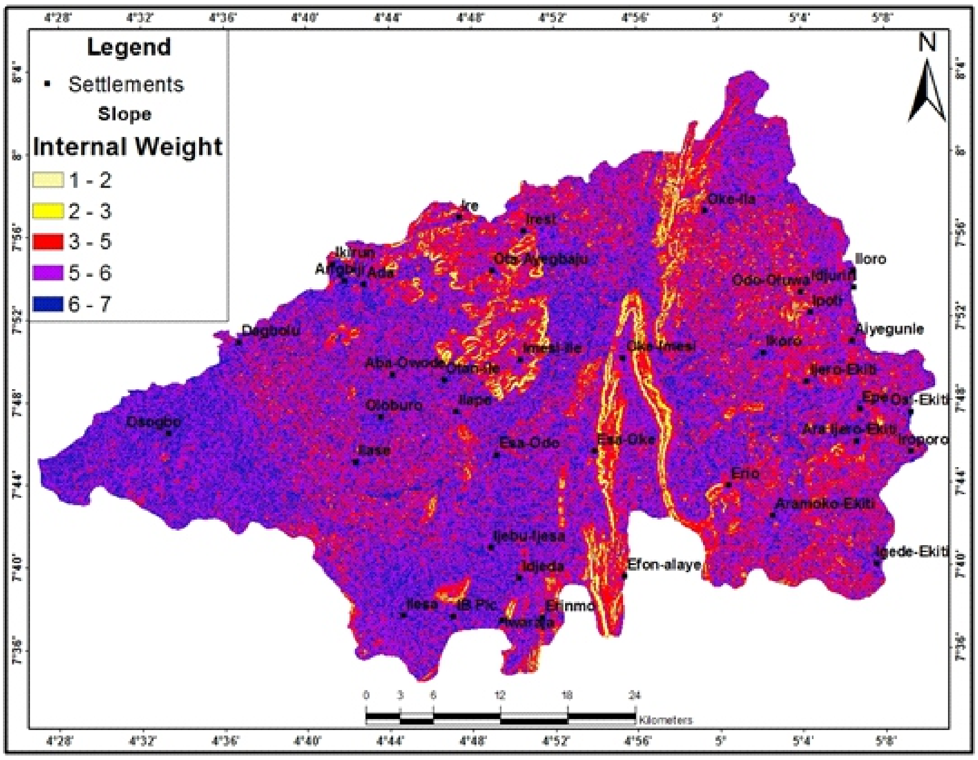

Figure 9: Weighted Slope Map

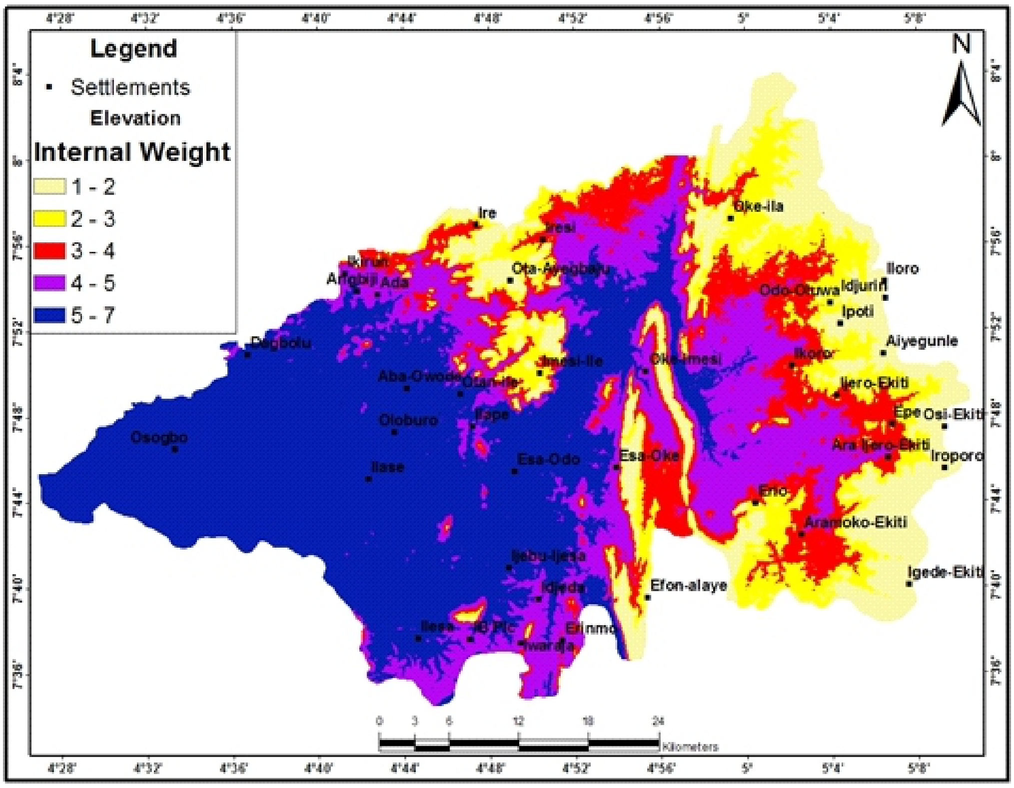

Figure 10: Weighted Relief Map

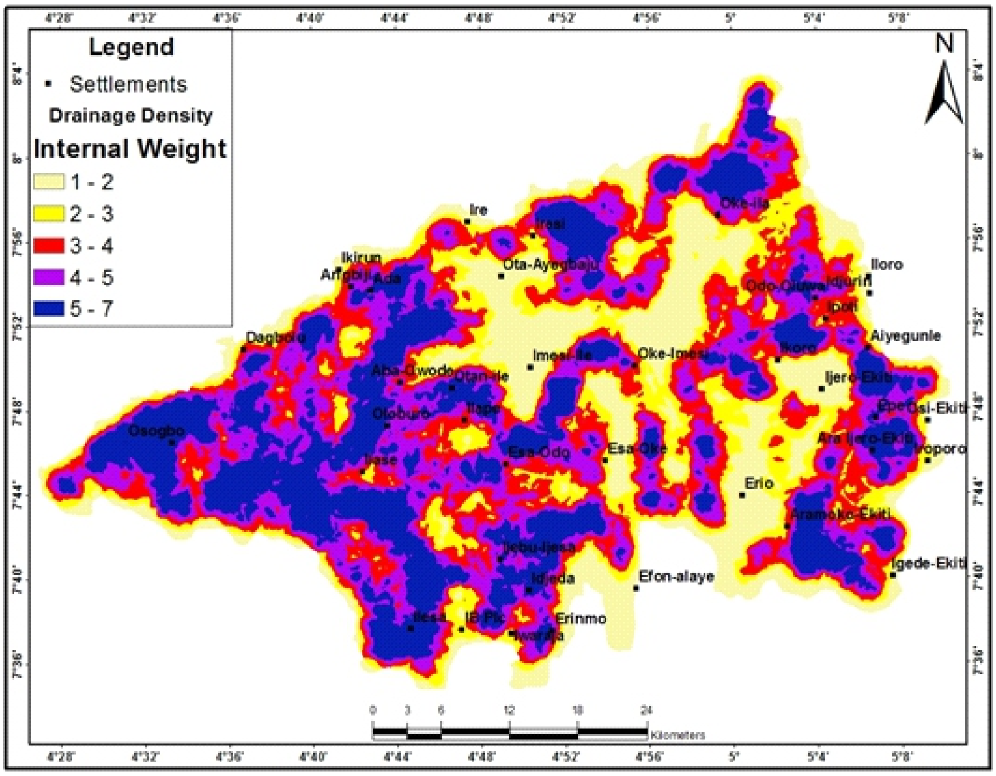

Figure 11: Weighted Drainage Density Map

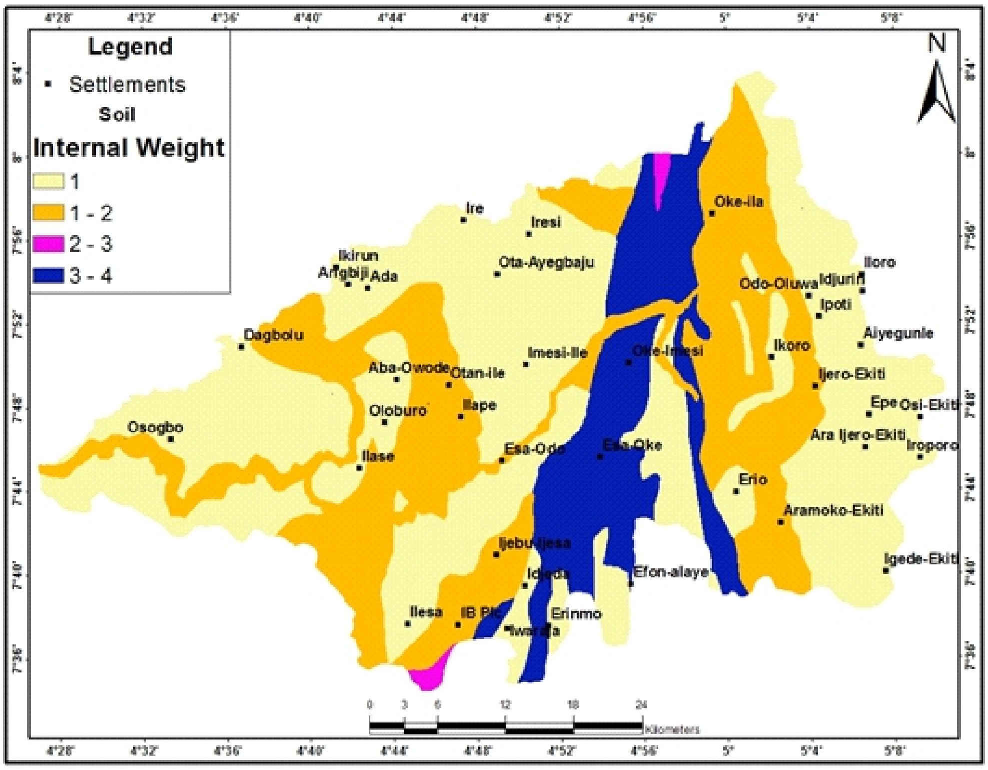

Figure 12: Weighted Soil Map

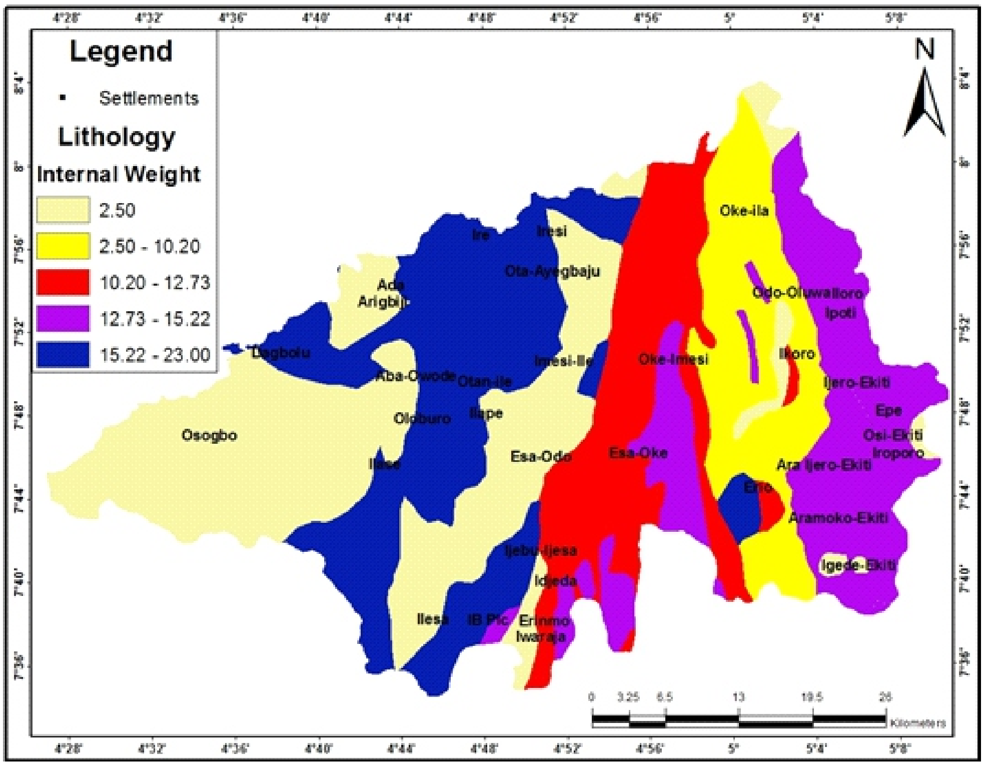

Figure 13: Weighted Lithologic Map

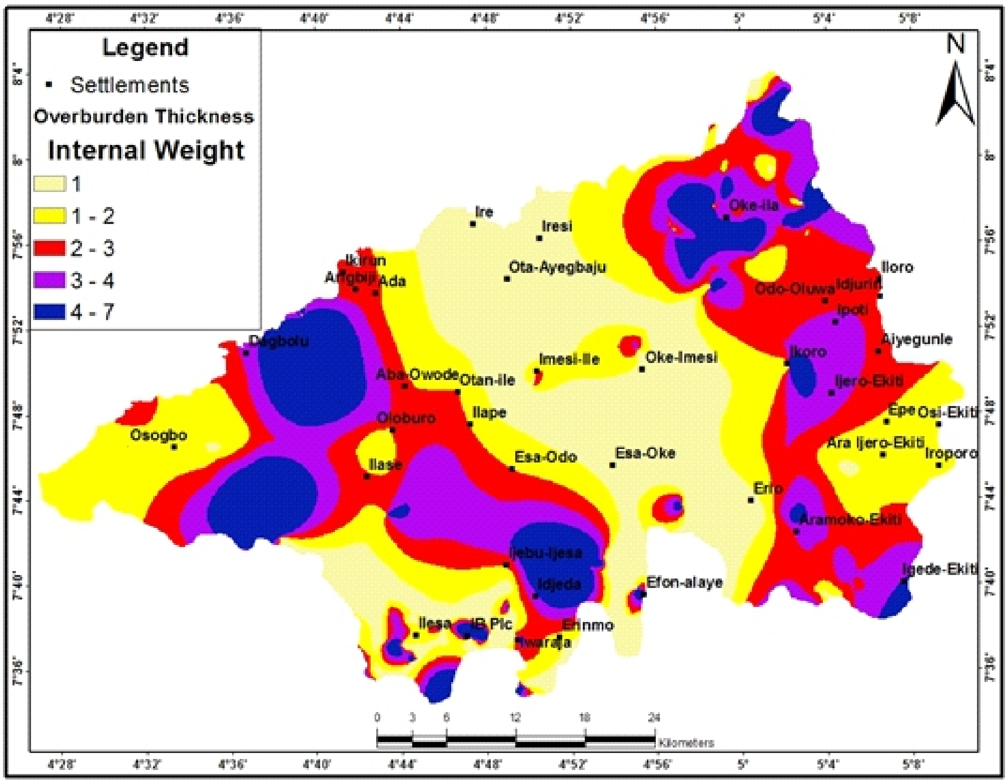

Figure 14: Weighted Overburden Thickness Map

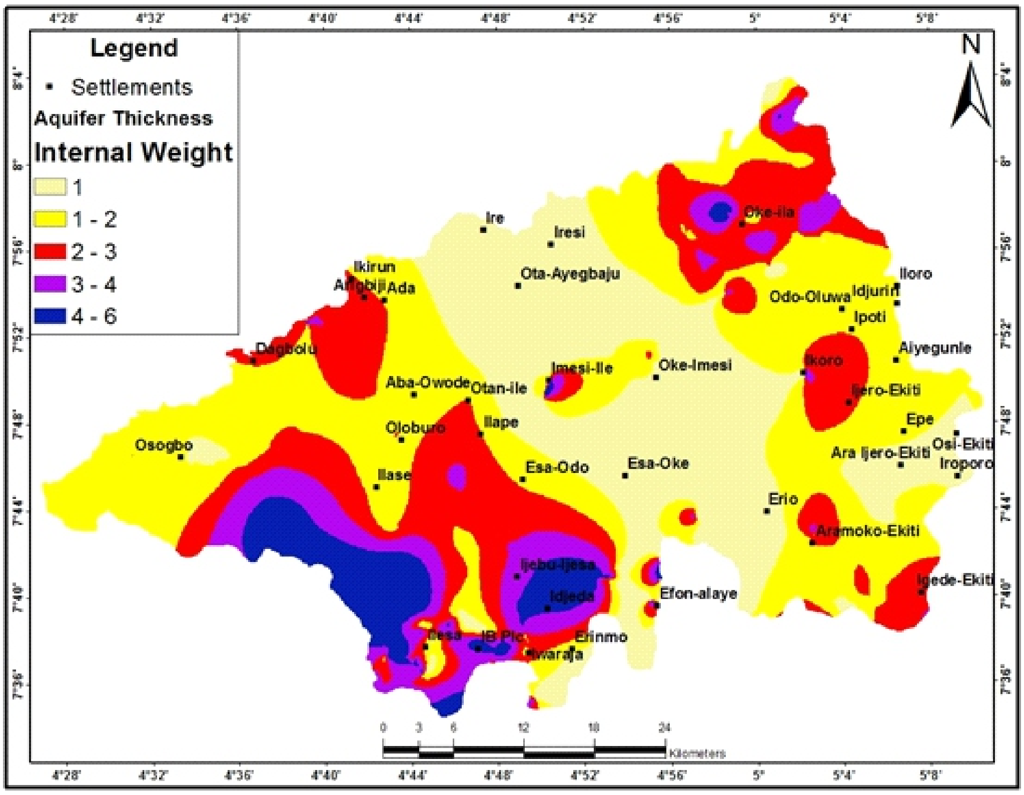

Figure 15: Weighted Aquifer Thickness Map

The attributes of these aquifers are summarized in Table 4. Sixty three (63) percent of the VES locations were underlain by weathered layer aquifers with thicknesses ranging from 2 to 89.2 m. Thirty one (31) percent of the locations constituted fractured aquifers with thicknesses ranging from 4.4 to 126 m. The remaining 6 percent of the sampled VES locations was devoid of aquifer with layer resistivity values greater than 1000 ohm-m (fresh basement). The prosperity of an aquifer is highly dependent on its storativity and transmissivity.

Table 4: Summary of Delineated Aquifer Types

	Aquifer Thickness (m)				
Aquifer Type	Population	Minimum	Maximum	Mean	Standard Deviation
Weathered Layer Aquifer	140	2	89.2	27.02	18.95
Fractured Layer Aquifer	69	4.4	126	37.51	28.02

Groundwater Potential Assessment

All the generated thematic layers were subjected to fuzzy logic procedure, which culminated in the final groundwater potential map. The fuzzy membership-based groundwater potential map and the corresponding potential classes as well as their percentage area extents are presented in Figure 16. The final groundwater potential map was the output of the classification of the original fuzzy membership values using the potential class interval as presented in Table 5a, which was generated based on borehole yield ranges in a typical Basement Complex terrain (Table 5b).

Table 5: (a) Classified Fuzzy Membership Values (b) Borehole Yield Ranges in Typical Basement Complex Terrain

a

Zone	Class Interval	Groundwater Potential
1	0.0 – 0.5	Very Low
2	0.5 – 0.6	Low
3	0.6 – 0.7	Moderate
4	0.7 – 0.8	High
5	0.8 – 0.99	Very High

b

Class	Class Interval (l/s)	Groundwater Potential
1	0.0 – 0.5	Very Low
2	0.5 – 1.0	Low
3	1.0 – 1.5	Moderate
4	1.5 – 2.5	High
5	>2.5	Very High

The model predicted very high groundwater potential for 11 percent of the study area. Twelve (12) percent of the study area was rated high while 16 percent of the study area had moderate groundwater potential. Thirty (30) percent was rated low while 31 percent of the study area was rated very low. The summary is that 61 percent of the study has poor groundwater potential while only 23 percent of the study area is adjudged to have high/very high groundwater potential and 16% with moderate potential rating. The observed pattern of groundwater potential across the basin corroborates the groundwater prospect of a typical Basement Complex terrain (Olorunfemi and Fasuyi, 1993; James *et al.,* 2002; Solomon and Quiel, 2003; Afolayan*et al.,* 2004; Ayolabi*et al.,* 2009; Alisiobi and Ako, 2012; Ariyo and Adeyemi, 2009, 2012; Martin, 2012; Mbiimbe, 2012; Joseph and Olorunfemi, 2012; Abdulahi and Iheakanwa, 2013; Akinluyi, 2013; Bayowa, 2013; Ganapathi *et al.,* 2013).

The spatial organization of various groundwater potential zones as depicted in the final groundwater potential map obviously reflect regional patterns of lineaments, lithology, aquifer and overburden thicknesses across the study area. Spatially, the very high and high groundwater potential areas coincided with areas with high lineament density and foliated metamorphic rocks. In this case, very high groundwater potential areas are confined along lineament buffer zones with decreasing potential rating with increasing distance from the lineaments. The implication is that high groundwater prospect is only guaranteed within the area of influence of a given fault line, which is not always beyond 250 meters away from the center of the fault line (Solomon, 2003). The categories of low to very low groundwater potential areas were associated with areas of very low bedding depth, extremely low or zero lineament density and dense rocks. The upper axis of the heavily fractured metamorphic rocks (quartzite/quartz schist) that lie across the study area (approximately N-S orientation) and porphyritic granite area within Iresi sub-basin were classified as very high groundwater potential areas. Majority of the zones that were rated low to very low lie in the areas of poor groundwater prospecting rocks such as mica schist and amphibolite. The moderate groundwater potential rating of Oke-Ibode-Egbeda area is associated with the occurrence of thick overburden (on mica schist), which does not signify high groundwater prospect.

The spatial relationship between the groundwater potential model and borehole yield is presented in Figure 17 and the summary of the spatial model result is expressed in Table 6. The cross plot indicates a strong positive relationship (with correlation value of 0.87) between borehole yields and the fuzzy membership values. Table 6 shows that the fuzzy membership values for 92 percent of the locations of very low yielding boreholes ranged between 0.0 and 0.5.

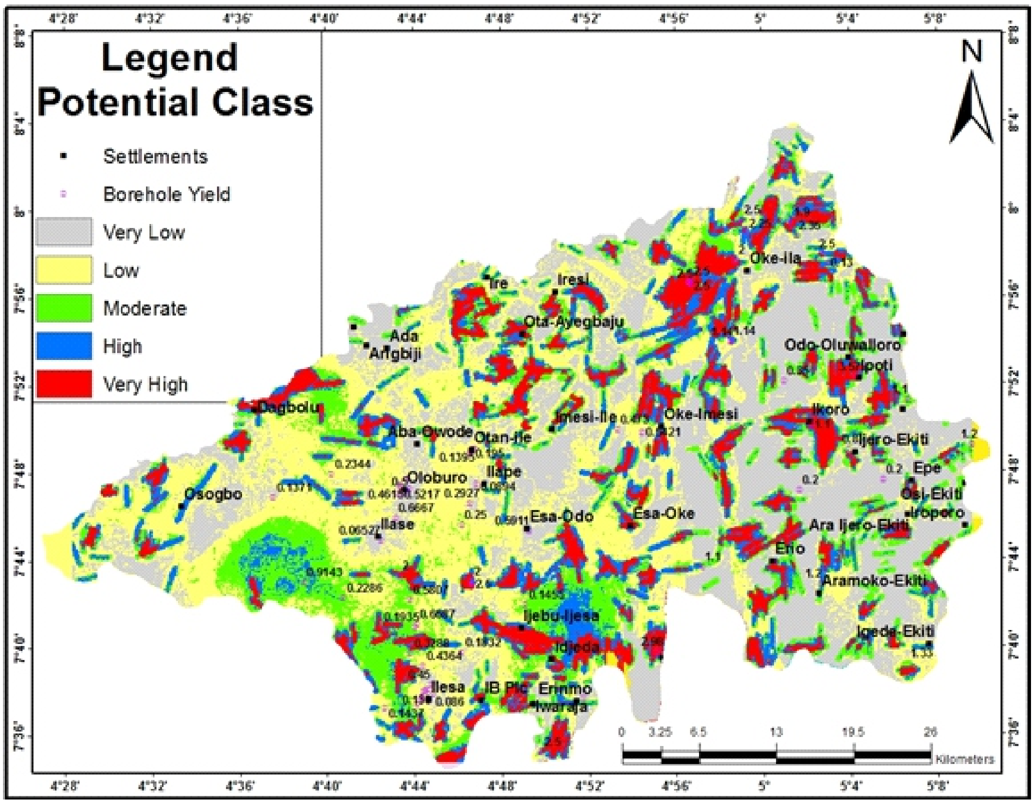

Figure 16: Groundwater Potential Map of Osun Drainage Basin

Seventy five (75) percent of the locations of low yielding boreholes have fuzzy membership values within the range of 0.5 and 0.6. Similarly, 71 percent of the locations of moderate yielding boreholes are having fuzzy membership values ranging between 0.6 and 0.7.The model result showed that all the locations of high to very high yielding boreholes were predicted with fuzzy membership values greater than 0.7. The interpretation of this result is that very low groundwater potential is peculiar to the areas that are having fuzzy membership value that is less than 0.5 while the high to very high rated groundwater potential areas are having fuzzy membership value that is greater than 0.7. The model result showed that 68 percent of the sampled boreholes are located within low groundwater potential areas while only 21 percent ofthe boreholes are situated within high to very high groundwater potential zones.The analysis revealed that borehole yield increases as the fuzzy membership values increase but with decreasing borehole population, meaning that groundwater potential of the current study area is generally low. GIS-based and SPSS Ordinary Least Square method revealed that the fuzzy membership values (the basis of the final groundwater potential map) can predict borehole yields within the study area. The computed correlation value (0.872 with p value of 0.000) implies that borehole yield (to a large extent) is controlled (directly or indirectly) by the examined groundwater potential factors.

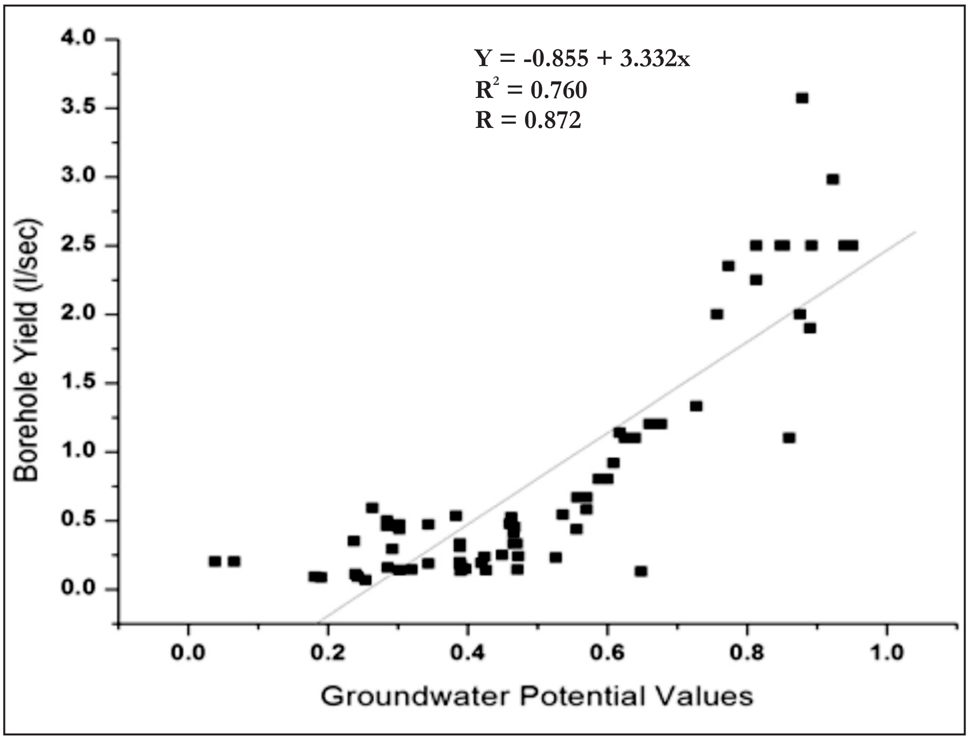

Figure 17: Cross plot of Borehole Yield and Groundwater Potential Values

Table 6: Summary of the Spatial Model Result

Yield Range (l/s)	0 – 0.45	%	0.5 – 0.99	%	1 – 1.49	%	1.5 – 2.5	%	> 2.5	%
Boreholes in Areas of ≤ 0.5 Fuzzy Membership Values	36	92.3	3	7.7	-	-	-	-	-	-
Boreholes in Areas of > 0.5 ≤ 0.6 Fuzzy Membership Values	2	25	6	75	-	-	-	-	-	-
Boreholes in Areas of > 0.6 ≤ 0.7 Fuzzy Membership Values	1	14.3	1	14.3	5	71.4				
Boreholes in Areas of ≥ 0. 7 Fuzzy Membership Values	-	-	-	-	3	16.7	13	72.2	2	11.1
Boreholes in Areas of ≥ 0. 7 Fuzzy Membership Values	-	-	-	-	-	-	-	-	2	100
Total Number of Boreholes in each Potential Class	39	54.2	10	13.9	8	11.1	13	18.0	2	2.8

The relationship between the yield of borehole and the fuzzy membership value is explained by the equation below:

Y = -0.855 + 3.322X……..................................*(3)*
Fuzzy Membership Value
(R^2 = 76.0 %; SE = 0.446)

This relationship explained 76 percent of the regression plain, which is quite significant at α = 0.01. The Adjusted R^2 value (0.757) revealed that, in actual sense, 75.7 percent of borehole yield wasactually explained by fuzzy membership value. In this case, the difference between the R^2 and Adjusted R^2 value (0.3) is very low, emphasizing the efficiency of the regression model generated in this study. Hence, the potential factors that were considered in this study are strong variables that can give meaningful explanation of borehole yield in the study area. Therefore, the explanation of borehole yield in the study area can best be done by examining all relevant environmental variables particularly within the domain of geology.

CONCLUSION

This study employed GIS procedures to integrate a set of environmental factors (lineament density, lineament proximity, drainage density, vegetation index, slope, elevation, landforms, overburden thickness, aquifer thickness, lithology and soil) with a view to assessing groundwater potential across Osun Drainage Basin, Southwestern Nigeria. The study showed that hydrolineament (depicting faults and fractures) is the most influencing determinant factor of groundwater potential in the study area. The spatial pattern of groundwater prospect also reflects the influence of lithology on the groundwater potential of the study area. However, all the examined factors exerted their individual influence at varying degrees on the groundwater potential of the study area. The study identified and delineated five groundwater potential classes comprising very low, low, moderate, high and very high potential zones. A significant positive relationship was observed between final groundwater potential map and spatial pattern of borehole yields across the study area. In this case, the environmental factors that were considered in this study are strong enough to give meaningful explanation of borehole yield across the study area.

The study concluded that groundwater potential is generally low across Osun Drainage Basin. However, isolated areas of good groundwater potential were evident particularly in the upland area of the basin. Thus, the observed groundwater prospect is only suitable for small-scale groundwater development scheme.

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