Supported by tetfund

ASSESSING GROUNDWATER POTENTIAL AND AQUIFER VULNERABILITY USING GRTER AND GOD INDEX

Jane Bada[1], Joel Amosun[2*], Oreoluwa Komolafe[3], Oluwapelumi Agbebunmi[2], Titilayo Oluyemi[3]
[1]Department of Applied Geophysics, Federal University of Technology Akure, Ondo State, Nigeria
[2]Department of Geophysics, Federal University Oye Ekiti, Ekiti State, Nigeria.
[3]Department of Geology, Federal University Oye Ekiti, Ekiti State, Nigeria
*joelamosun@gmail.com;joel.amosun@fuoye.edu.ng,

Received: February 11, 2023 **Accepted:** April 15, 2023

Abstract

A multi-criteria model (GRTER), created as G (geology), R (resistivity), T (thickness of the aquifer), E (elevation) and R (bedrock relief) and groundwater occurrences (G), general lithology of the overlying strata (O) and depth to aquifer units (D) termed GOD index, were employed towards delineating the groundwater potential and aquifer vulnerability of Ilere Town, Ondo State, Southwestern Nigeria. Hydrogeologic measurement of fifty-two (52) wells, by measuring the column of water and static water level of all tested wells, was performed so as to identify groundwater flow direction. Thirty (30) Vertical Electrical Sounding (VES) data were acquired and the results displayed as tables, charts, and maps. The maps developed using the measurements of aquifer resistivity and thicknesses were further used to create the groundwater potential map. The results attest to a good correlation between maps of the bedrock relief and groundwater potential zones and indicate that the north-central and the south-eastern parts are the recharge zones, with elevation values ranging between 365m and 390m; while the north-western and the south-western regions are the discharge zones, with elevation values that vary from 325m to 360m. The GOD map shows area of vulnerability range: 0.0 - 0.1 (insignificant), 0.1 - 0.3 (low), 0.3 - 0.5 (medium) and 0.5 - 0.7 (high). This map, therefore, suggests that the groundwater potential and aquifer vulnerability index of Ilere town is moderate.

Keywords: elevation, geology, groundwater potential, resistivity, thickness, vulnerability

Introduction

Water is a natural resource that is vital for social and economic development of any state. Groundwater describes underground water, found in the cracks/spaces in soils and within fractures of rock formation (Amadi *et al.,* 2011). It is described as a viable yet harmless water source in several remote regions where surface water is uneconomically sustainable (Omosuyi, 2010). The cost of groundwater exploitation and development is relatively lower, providing highly potable water and easily available in most areas compared to surface water. Thus, groundwater resource is a key source of freshwater (Akintorinwa and Olowolafe, 2013).

The study area, Ilere town, near Akure in Ondo state, is a rapidly growing residential area with most homes depending on groundwater abstraction because there is no public water scheme in the area. Increase in population results in a rise in the challenge of accessing potable groundwater. Hence, there is a need to evaluate the groundwater potential and aquifer layers’ vulnerability of the area, as this will help in identifying the appropriate locations that are suitable for siting dumpsites or petrol stations towards not contaminating the groundwater resources in the area.

Although, crystalline basement rocks, such as amphibolites, migmatite gneisses, granites, schists and pegmatites, are generally impermeable with negligible water storage capacity, wells for accessing groundwater have been productively established within them in different parts of Nigeria and globally, resulting from the presence of porosity and permeability (secondary) ensuing via fracturing of rock and weathering processes (Omosuyi, 2010). In a characteristic setting of hard rock, the geology routinely comprises of a basement rock underlying unconsolidated, loose materials of variable thicknesses (that is, the overburden or regolith). It is, therefore imperative to ascertain if this water-table within the aquifer is well protected. It is important for aquifers to be well protected for sustainability, protection of several dependent ecosystems, and spatial planning and action plans. In other words, vulnerability is the key to quantifying how protected an aquifer is.

Aquifer vulnerability was described by Ogungbemi *et al.,* 2013, as its sensitivity or that of the excellence of its resource (groundwater) to the presence of contaminants, which is determined by its inherent characteristics. Therefore, aquifer vulnerability uniquely specifies whether the features-physical and biochemical- of the subsurface inhibits or supports the passage of pollutants into and within aquifers (Aweto, 2011), however, it disregards the definite loading mechanisms of pollutants within that area.

Geophysical methods, such as gravity, magnetic, seismic and electromagnetic techniques, have effectively discerned the character of groundwater, for instance, in mapping regional aquifers, fractured rock system, large scale basin features (Todd, 2004; Majumdar and Das, 2011; Karami *et al.,* 2009). However, the electrical resistivity method is most frequently employed in the basement complex terrains because hydrogeological properties, such as the porosity and permeability of rocks, can be accurately correlated with electrical resistivity signatures (Molua and Emagbetere, 2005).

Constraints such as thickness of overburden, resistivity values of both the weathered and bedrock layers, along with the thickness and resistivity of the aquifer are usually considered in isolation when evaluating the groundwater potential of a place (Clark, 1985; Omosuyi and Oseghale, 2012; Adeyemo *et al.*, 2014).

Several models such as CALOD, SINTACS, GOD, COP and DRASTIC (Edet, 2004; Civita, 1994; Foster, 1988; Vias *et al.*, 2006; Aller *et al.*, 1987; Abdelmadjid and Omar, 2018; Olaseeni *et al.*, 2019; Alfred, 2016; Won *et al.*, 2017), with user-friendly interfaces have been developed and applied to ascertain the vulnerability of aquifers (Simsek, 2006). Although models such as DRASTIC, SINTACS, CALOD do not accommodate parameters that define contamination from the intrusion of seawater, that is, they do not recognise factors that are associated with water courses such as lakes or rivers which are connected to the aquifer (Olumuyiwa *et al.*, 2017). This essential attribute is available with the GOD and COP models which analyses the vulnerability alongside the perpendicular infiltration of contaminants within its unsaturated region, without allowing horizontal migration within the saturated area (Ferreira, 2004).

This research, created and adopted a multi-criteria GRTER modelling methodology for estimating the potential of groundwater, while the GOD model was however used for appraising the vulnerability of an aquifer in the basement complex terrain. The GRTER model was developed via five (5) fundamental hydro-geophysical considerations namely: geological characteristics, resistivity of identified aquifer layer, its thickness, elevation and bedrock relief.

Description and Geology of the Study Location

The study area (Ilere) is along Ijare road in Ondo State, Southwestern Nigeria; it occupies Eastings extending between 738700m to 739650m and Northings encompassing 808500m to 809600m within the (31N) Minna datum, of the Universal Traverse Mercator (UTM) and occupies a total area of 4.2 km square (Fig. 1).

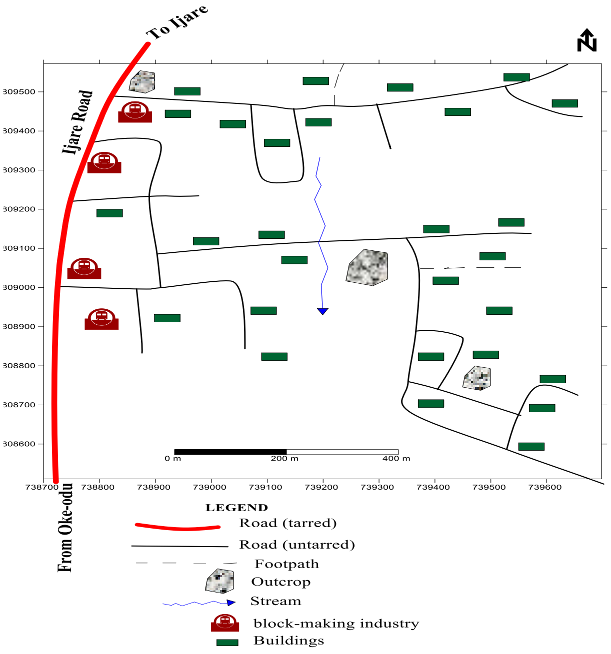

Fig. 1: Map of the study area

The elevation of the surface of the study area, of about 354m to 398m above the sea level, indicates a moderate to extremely undulating terrain (Fig. 2). The hot and humid climate is a result of the presence of southwest monsoon winds, originating from the Sahara desert, which bear the rains. Average rainfall of approximately 1524 mm per annum (Duze and Ojo, 1982) is experienced between April to October. The temperature and relative humidity during the harmattan in in the study area can vary depending on the specific time of day and weather conditions. However, generally speaking, the harmattan season typically occurs between November and February and is characterized by dry and dusty winds. During this period, the temperature can drop to as low as 16°C (60.8°F) in the morning and evening, while the relative humidity can range from 20% to 60% (NIMET, 2012). The natural vegetation is representative of a tropical rainforest.

Outcrops of migmatite-gneiss, with a sequence of low-lying rubbles of quartzite and pockets of charnockites are visibly prominent in the study location (Fig. 3). The Migmatite-gneiss appears as tightly disjointedly folded vein-like rocks with distinct isolations of light colored granitic regions. These light colored regions seem to contain quartz and feldspar while some dark colored areas which contain biotite are also observed. The low-lying quartzite debris occurs as boulders within this study area.

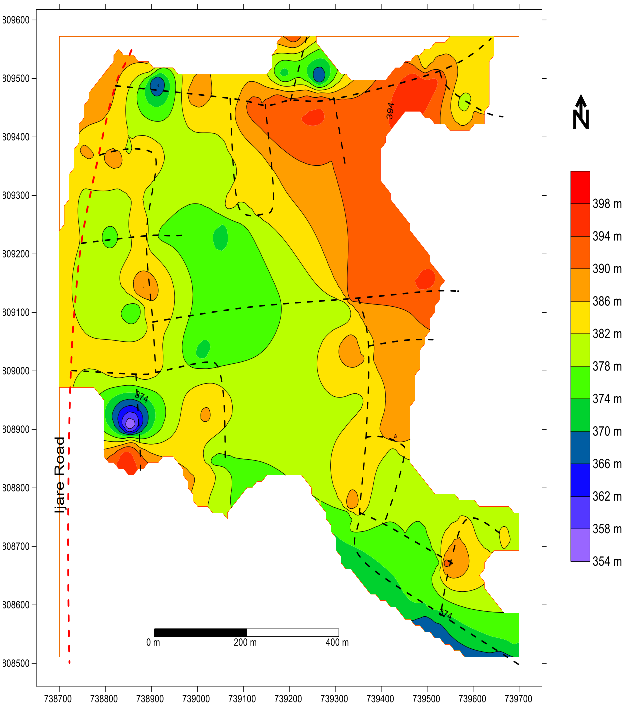

Fig. 2: Topographic map of the area of study

Fig. 3: Simplified Geologic map of the study area

Methodology

Hydrogeological investigation

With the aid of a well whistle, the static water level (SWL) was obtained by measuring the depth of the well to the top of the water table on all the accessible hand-dug wells (Fig. 4). The tail of the well whistle was attached to a graduated tape to know the distance (level of the water) from the surface of the ground when submerged. Maps were generated using Surfer 12 software, to show variation in the depth of the water table.

From the static level of water map, the area with a shallow depth between 1 to 5 m indicated a low static water level, which occupies almost the entire section of the map areas with a depth of 5 to 8 m have considerable static water level. This map is also the vadose zone thickness map and all things being equal the vadose zone thickness is one of the factors that determine how vulnerable an aquifer layer can be. Areas of low vadose zone thickness are more vulnerable and offer low protection to the overlying aquifer while areas of moderate vadose zone thickness are less vulnerable; therefore offers moderate protection for the overlying aquifer.

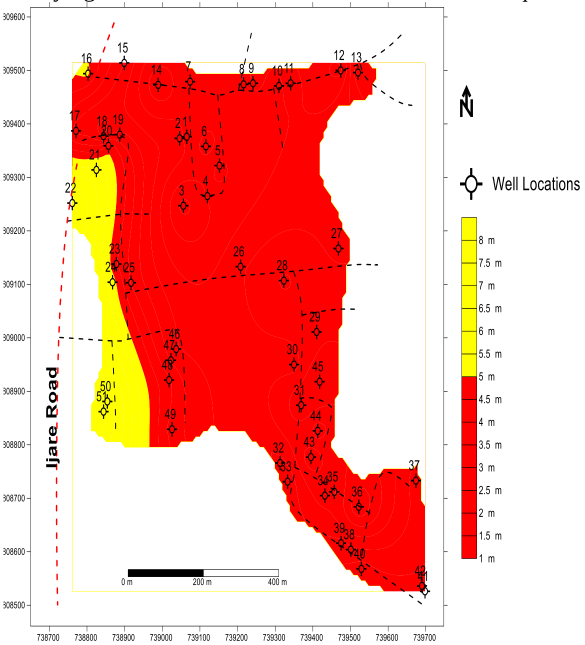

Fig. 4: Static water level map displaying the well locations

Geophysical Investigation

The geophysical investigation was performed using Vertical Electrical Sounding (VES) technique. Thirty (30) VES points were established with half current electrode spacing (AB/2) ranging from 1 m to a maximum length of 100 m. Interpretation of VES data were done quantitatively and qualitatively and plotted as sounding curves, by correlating the values derived for apparent resistivity against AB/2 on a bi-log graph.

The VES data was then analyzed qualitatively and quantitatively in other to establish geoelectric limits of the underlying sequences. The quantitative results from the geoelectric soundings are displayed as chart, table and maps.

GRTER Model

GRTER indicators assist with the quantitative rating of essential groundwater parameters (Table I). These indicators, as proposed by (Olumuyiwa, 2017), are assembled using numbers to rank the aquifer potential of each VES location and also to generate the groundwater potential map using SURFER 12 software.

Table I: Indicator weight (Adeyemo *et al.*, 2017)

S/N	Indicators	Weights
1	Geology	4.5
2	Aquifer resistivity	4
3	Aquifer thickness	3.5
4	Elevation	1.5
5	Bedrock relief	1.5

The steps involved for developing GRTER model include the following:

1) Identify the significant elements inducing groundwater potential.

2) Derive indicator weights which portray the comparativerank of each parameter to the estimation of groundwater potential.

3) Derive of diverse rankings for all identified indicators.

The maximumsubstantial indicators have weights of 4.5 and the least significant elements are assigned weights of 1.5 in a four and half (4.5) -point scale.

The five (5) major factors were combined applying the relationship proposed by Adeyemo *et al.,* 2017:

$$\text{GRTER value} = [(Wt_{geology} * Rt_{geology}) + (Wt_{resistivity} * Rt_{resistivity}) + (Wt_{thickness} * Rt_{thickness}) + (Wt_{elevation} * Rt_{elevation}) + (Wt_{bedrock\ relief} * Rt_{bedrock\ relief})]$$

Where, Wt = Weight; Rt = Rating.

GOD Model

The GOD model for the estimation of aquifer vulnerability as an index, as suggested by (Foster, 1988), helped to evaluate the vulnerability of aquifers in the area of study, by focusing on three major parameters, viz: the groundwater occurrence (G) - which emphasizes on the overlying and underlying strata, regardless of presence or level of confinement, the overlying strata lithology (O) and the aquifer layer depth (D). The product of the assigned values of these three elements in each VES location gives the GOD index which helps to generate the vulnerability of aquifer map. The GOD indexes, following (Boufekane, 2013) are separated into five groups of 0 to 1 values (see Table II).

Table II: Interval values of GOD index and corresponding classes (Boufekane, 2013).

Class Vulnerability	Very low (negligible)	Low	Medium	High	Very high
Index	0 – 0.1	0.1 – 0.3	0.3 – 0.5	0.5 – 0.7	0.7 - 1

Results

Aquifer's Resistivity and Thickness

Four- to six – layer types of curves were recognized during this research. The four-layer curve comprises of the KH, AK, AA, HK and HA curve types. The five-layer curve comprises of the KHA, AKH, KHK, HKH, QHA and the HKQ curve types while the six layer curve types include HKHA, KQQH, AAKH and the AHKA. The dominant curve types (KH and AA) account for 20% each of the study area, AK curve types account for 10%, KHA, AKH, KHK curve types account for 6.7% of the study area each. The HK, HA, HKH, QHA, HKQ, HKHA, KQQH, AAKH and the AKHA curve types account for 3.3% of the study area each.

The study area shows four to six geoelectric layers. The first layer is the top soil, with resistivity value between 28 Ohm-m to 1150 Ohm-m and thickness values that range between 0.2 and 1.3 m, while the second, partially weathered layer has a resistivity value that varies from 43Ohm-m to 598Ohm-m and thickness range of 0.4 m and 9.5 m. The weathered basement (third layer) gave values of resistivity varying from 25 Ohm-m to 5399 Ohm-m and thickness ranging from 0.7 m to 30.4 m, the fourth layer of highly weathered/fractured basement which has a resistivity values ranging between 21 Ohm-m and 11092 Ohm-m and a thickness of 2.2 m and 21.9 m respectively. The fifth layer is also the fractured/fresh basement in some parts of the Ilere town with a resistivity value that varies between 164 Ohm-m and 13739 Ohm-m, and a thickness that varies from 1.6 m to 46.8 m, while the sixth layer (completely fresh basement) displayed values of resistivity vary between 578 Ohm-m and 6058 Ohm-m and infinitely thick.

Aquifer Vulnerability Index

The GOD model for evaluation of aquifer vulnerability index was used to evaluate the vulnerability of the study area. This index was obtained by multiplying the assigned values of the groundwater occurrence (G),i.e. either the aquifer is confined, semi confined or unconfined considering the overlying and the underlying strata, with the lithology of the layers overlying the aquifer (O) and the depth to the aquifer layer (D) together. The multiplication of the assigned value of these three parameters in each VES location gives the GOD index. The calculated GOD index for the study area is shown in Table III.

Table III: Calculated GOD Index of the Study Area

GROUNWATER OCCURENCES	OVERALL LITHOLOGY	DEPTH	G	O	D	GOD INDEX
Semi-confined	Silty sand and gravel	4.5	0.4	0.7	0.9	0.252
Unconfined	Sand and clayey gravel	4.4	1	0.5	0.9	0.45
Unconfined	Sand and clayey gravel	7	1	0.5	0.8	0.4
Unconfined	Silty sand and gravel	4.5	1	0.7	0.9	0.63
Unconfined	Silty sand and gravel	0.2	1	0.6	1	0.6
Unconfined	Sand and clayey soil	0.5	1	0.5	1	0.5
Semi-confined	Sandy gravel	1.3	0.4	0.7	1	0.28
Unconfined	Sand and clayey soil	2.7	1	0.5	0.9	0.45
Unconfined	Silty sand and gravel	6.6	1	0.6	0.8	0.48
Unconfined	Sandy gravel	2.4	1	0.7	0.9	0.63
Unconfined	Sand and clayey gravel	25.8	1	0.6	0.6	0.36
Confined	Lateritic soil	10.4	0.2	0.8	0.7	0.112
Semi-confined	Sandy gravel	20.5	0.4	0.7	0.6	0.168
Semi-confined	Clayey gravel	6.3	0.4	0.8	0.8	0.256
Unconfined	Silty sand and gravel	5.2	1	0.6	0.8	0.48
Semi-confined	Sandy gravel	1.2	0.4	0.7	1	0.28
Unconfined	Sand and clayey gravel	1.4	1	0.5	1	0.5
Unconfined	Gravel	3.8	1	0.7	0.9	0.63
Unconfined	Silty sand and gravel	2.3	1	0.6	0.9	0.54
Unconfined	Sandy gravel	2.1	1	0.7	0.9	0.63
Unconfined	Silty sand and gravel	0.4	1	0.6	1	0.6
Unconfined	Sand and clayey gravel	6.6	1	0.6	0.8	0.48
Semi-confined	Sandy gravel	2.3	0.4	0.7	0.9	0.252
Unconfined	Sand and clayey soil	6.3	1	0.5	0.8	0.4
Semi-confined	Sand and clayey gravel	2.4	0.4	0.6	0.9	0.216
Unconfined	Silty sand and gravel	0.9	1	0.6	1	0.6
Unconfined	Silty sand and gravel	2.5	1	0.6	0.9	0.54
Confined	Gravel	10.8	0.2	0.6	0.7	0.084
Unconfined	Silty sand and gravel	3.7	1	0.6	0.9	0.54
Unconfined	Silty sand and gravel	3.4	1	0.6	0.9	0.54

Discussion

Geology

Underlain of the study area is migmatite-gneiss, with a sequence of low-lying quartzite rubbles in certain portions and some pockets of Charnockites. The Charnockite suites, vary as meager and adequate groundwater potential regions, while prominent groundwater producing zones comprise Migmatite-Gneiss-Quartzite complex are (Adeyemo *et al.,* 2017). Thus, a rating of 0.6 and 1.0 is applied to Charnockites, and Migmatite-Gneiss-Quartzite respectively in the GRTER model.

Resistivity Map of Aquifer Layers

The map showing the resistivity of aquifer layers displays the disparity in the values of resistivity of the various aquifers (Fig. 5) by sub-classing them into high, moderate and low based on their resistivity contrast. Mogaji *et al.,* 2011, explains that groundwater flows from region of greater resistivity to those of lower values; it implies that areas with lower values of resistivity will exhibit higher saturation levels. Therefore, areas with values between 20 Ohm-m to 100 Ohm-m are expected to have higher water saturation, and are rated 1.0 and 0.8 respectively. These areas exist mostly in the north-central and some parts of the north-eastern regions. Areas with moderate resistivity values, 100 to 300 Ohm-m are rated 0.6 and 0.4 and found in parts of the north-eastern region, north-western part and tail of the south-eastern region. High resistivity values that range from 300 Ohm-m to 580 Ohm-m, reflect poor saturation potential and are ranked 0.2; and were discovered in part of the north-western side, the south-western side downward part and tail of the south-eastern part of the study area.

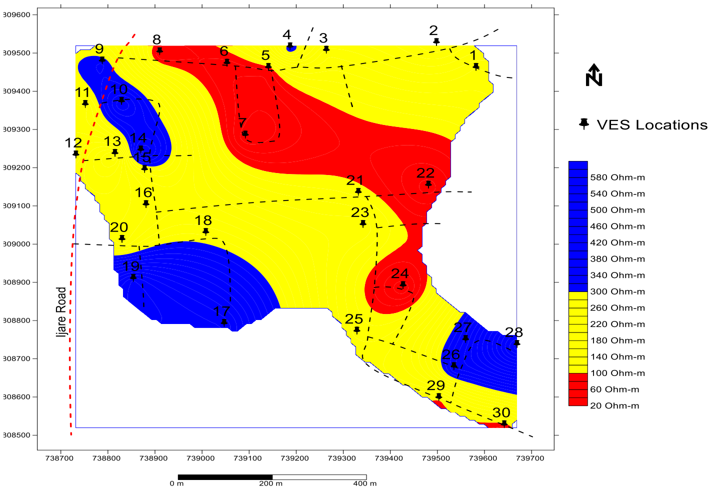

Fig. 5: Map of Aquifer Resistivity

Portions of the area of study with higher values of resistivity indicate lower conductivity and subsequently lower moisture content; while areas with moderately low resistivity value indicate areas with moderately high conductivity which indicates high moisture content. Hence, the study area is of moderate hydrogeological significance. The GRTER model (see Table I) estimates the weighted value of resistivity as 4 out of a maximum grade of 4.5.

Aquifer Layer Thickness Map

Fig. 6 is a map that shows the thickness of aquifer within the study area; and depicts regions with thickness ranging from 2m to 5m as areas of low aquifer thickness with a rating of 0.2. These areas comprise of a minor part of the south-eastern and northern regions. The north central, and major portion of the study region have moderate thickness that ranges from 5 to 15 m, and are ranked 0.4 and 0.6 respectively. The areas with high aquifer thickness have thickness that ranges from 15 to 48 m, and are rated 0.8 to 1.0. These areas occupy parts of the north-western, south-central and south-eastern tail. Within an aquifer layer, the aquifer thickness directly relates with the level of groundwater potential. Areas with higher aquifer thickness and moderately high resistivity value are of good hydrogeological significance. The aquifer thickness is weighted as 3.5 out of 4.5.

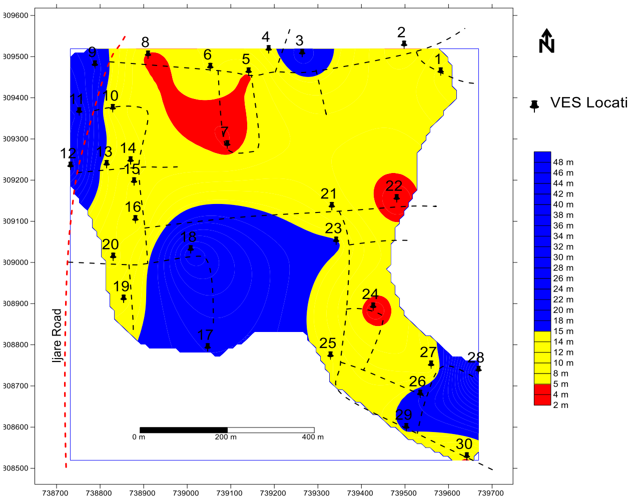

Fig. 6: Map showing the Aquifer Thickness

Elevation Map

Areas of depression and ridges can be delineated from the topographic map (also called surface elevation map) in Fig. 2. This map shows elevation that ranges from 354 to 402 m. Areas with high elevation are possible hilly areas with surface elevation values that ranges from 386 to 402 m mainly in the eastern portion of the study region and they are rated 0.2 to 0.4. The areas with low elevation ranging from 354 to 382 m are around the central portion and south-western portion of the study region rated 0.8 to 1.0 respectively. Elevation is weighed 1.5 from possible 4.5 in the GRTDER model.

Bedrock Relief Map

Bedrock relief map (Fig. 7) was created by estimating, plotting and contouring the difference between the depths to aquifer layer and the surface elevation. The map displays the bedrock subsurface topography across the area of study. The areas with high bedrock thickness are delineated as the zones of recharge and they inhabit the south-eastern and the north-central regions of the study area, which has elevation ranging from 365 to 390 m and are respectively ranked as 0.2 to 0.4. The regions with low bedrock thickness are recognized as zones of discharge and they occupy part of the north-western and the south-western parts of the map. They have elevation that ranges from 325 to 365 m, rated 0.8 to 1.0 respectively. Bedrock relief is weighed 1.5 from possible 4.5 in the GRTER model.

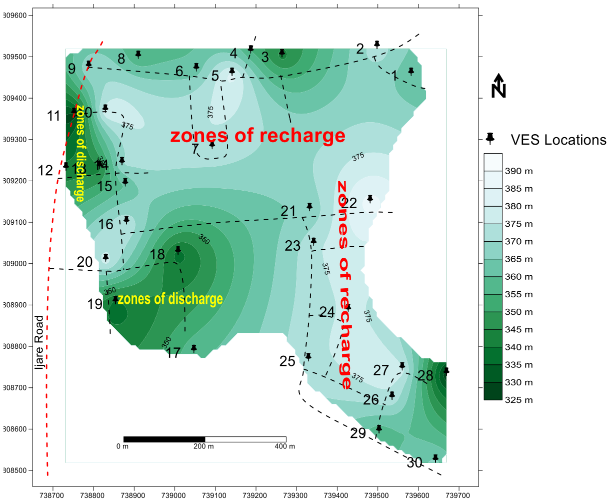

Fig. 7: Bedrock Relief Map

Map of Groundwater Potential

Map of the GRTER model (Fig. 8) incorporates maps of the aquifer thickness, geology, elevation, aquifer resistivity and bedrock relief. It indicates directly the groundwater potential of the study area and expresses the contrast of groundwater potential across several parts. Three groundwater potential areas are identified, namely; low/insignificant, moderate and high groundwater potentials. Small portion of the south-eastern and northern regions are described as low groundwater potential areas (0 – 0.3.) These areas have low aquifer resistivity value that can accommodate water but occurs at a very shallow depth within the aquifer layer and will result in a low groundwater yield. The areas with moderate groundwater potential are located in the southeast, northeast, some portion of the north central and part of the south eastern tail. These areas occupy a high percentage of the study area (0.3 – 0.7). They have moderate aquifer resistivity value and moderate aquifer thickness that can give a moderate yield of groundwater. North western part, a portion of the south central, and a portion of the south eastern tail are areas identified as high groundwater potential (0.7 – 0.97). These regions have moderately high aquifer resistivity value and high aquifer resistivity thickness, thereby resulting in high groundwater potential because they are thick enough to accommodate water. A hydrogeological measurement was also carried out by investigating some wells in the area. This was used to define the direction of flow and the water volume present in each well. The results obtained by taking the static water level and water columns of all tested wells indicates that groundwater flows from the northeastern to the southwestern part of the area of study.

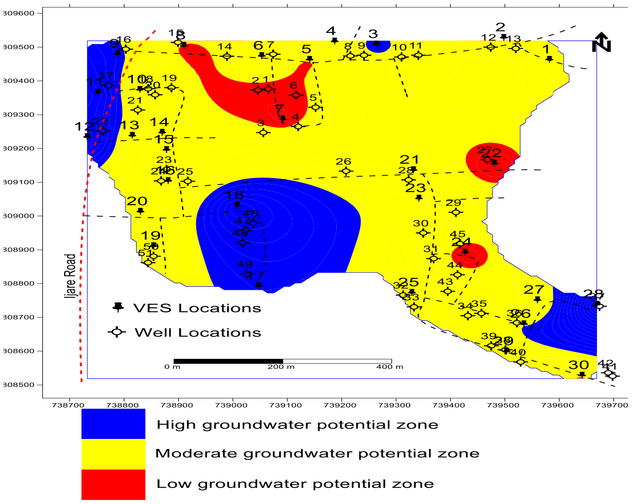

Fig. 8: Study Area Groundwater Potential Map

Aquifer Vulnerability Evaluation

Areas with negligible vulnerability with GOD index ranging from 0.0 to 0.1 are few within the study area and are found around VES 28 and VES 12 (Fig. 9). These are areas where the aquifer is highly protected from pollution because the overlying materials are capable of offering a high protection. Areas with low vulnerability with GOD index between 0.1 and 0.3 are scattered within the study area. They are identified in the upper part of the north-eastern region, some portions of the northwest and southeast and offer moderately high aquifer protection.

Regions with GOD index between 0.3 and 0.5 signify a moderate vulnerability to the underlying aquifer layer. These areas occupy the north and south central, the north and southeast and part of the southeastern tail. The aquifers in these areas are moderately protected from pollution. Areas with high vulnerability offer low protection to the underlying aquifer unit. These occupy portions of the south-western, south-eastern, northern region and south-eastern tail.

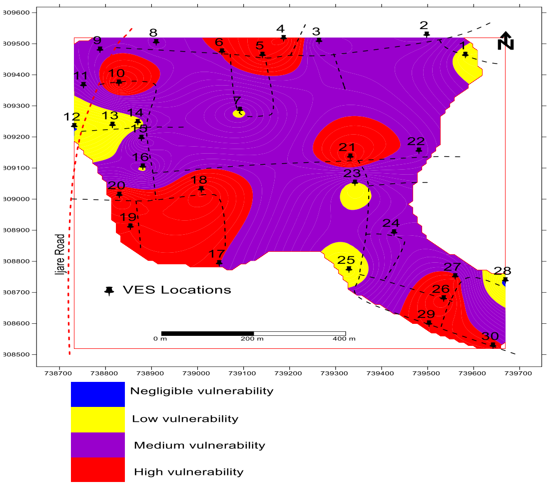

Fig. 9: Aquifer Vulnerability (GOD) Map

Conclusion

The groundwater potential map was generated from the aquifer resistivity and aquifer thickness maps. These maps correlate with bedrock relief map. Areas where we have high groundwater potential occurs in the north western regions and part of the south western region which are zones of discharge while areas with moderate groundwater potential occupies mostly the northern regions and the south eastern regions signifying area of recharge. The low groundwater potential zones also occur within the zones of recharge. This means that the water is accumulated mostly in the zones of discharge and the groundwater flow in this area is from the northern part and the south eastern part to the north western regions and part of the south western regions. This study shows that the groundwater potential in the study area is high in the north western regions and part of the south western regions; it is moderate in the northern regions and most of the south eastern regions. The groundwater potential is low in a small portion of the south eastern region and a small portion of the northern region. From the aquifer vulnerability map, the aquifer units are moderately protected. Based on the reliability of this model as observed in this study, it is suggested that multi-criteria techniques should be employed for assessing the groundwater potential regardless of the geologic setting.

Declarations

Funding: This research work is self-funded

Conflicts of interest: The authors declare that they have no conflict of interest.

References

Abdelmadjid, B. and Omar, S. (2018). Application of Groundwater Vulnerability Overlay and Index Methods to the Jijel Plain Area (Algeria). Groundwater, 56(1): 143 – 156.

Adeyemo I.A, Omosuyi G.O, Ojo B.T and Adekunle A (2017). Groundwater potential evaluation in a typical basement complex environment using GRT index, a case study of Ipinsa-Okeodu area, near Akure, Nigeria. Journal of Geoscience and Environment Protection, 5, 240-251

Adeyemo I.A, Omosuyi G.O, Olayanju G.M and Omoniyi G.K (2014).Hydro-geologic and Geoelectric determination of Groundwater flow pattern in Alaba- Apatapiti Layouts Akure, Nigeria. The International Journal of Engineering and Science (IJES), 3, 44-52.

Akintorinwa O.J Olowolafe T.S (2013). Geoelectric Evaluation of Groundwater Prospect within Zion Estate, Akure, Southwest, Nigeria. International Journal of Water Resources and Environmental Engineering, 5, 12-28.

Alfred, M. (2016). An Assessment of Groundwater Potential and Vulnerability in the Upper Manyame Sub-Catchment of Zimbabwe. Master of Science Thesis at University of Zimbabwe, 1 – 104.

Aller L, Bennet T, Lehr JH, Petty RJ and Hackett G (1987) DRASTIC: A standard system for evaluating groundwater pollution potential using hydrogeologic settings. EPA/600/2-85/018, US Environmental Protection Agency, Ada, Oklahoma, 455pp.

Amadi AN, Nwawulu CD, Unuevho CI, Ako TA (2011). Evaluation of the Groundwater Potential Pompo Village, GidanKwano, Minna Using Vertical Electrical Resistivity Sounding. British Journal of Applied Science & Technology, 1 (3): pp 53-66.

Attoui B, Kherci N, Bousnoubra H (2012). State of vulnerability to pollution of the big reservoirs of groundwater in the region of Annaba Bouteldja (NE Algeria). Geographia Technica. 2:1-13.

Aweto K.E (2011) Aquifer Vulnerability Assessment at Oke-Ila area, Southwestern Nigeria. InternationalJournal of the Physical Sciences, 6(33): 7574 – 7583.

Boufekane A and Saighi O (2013) Assessment of groundwater pollution by nitrates using intrinsic vulnerability methods: A case study of the Mill valley groundwater, Jijel, North-East Algeria. African Journal of Environmental Science and Technology, vol. 7(10), pp. 949-960.

Civita M (1994) Vulnerability maps of aquifers subjected to pollution: theory and practice, PitagoraEditrice, Bologna (in Italian) .pp 206-212.

Clark L (1985). Groundwater Abstraction from Basement Complex Area of Africa. Quarterly Journal of Engineering Geology and Hydrogeology, 18, 25-34.

Duze M and Ojo A (1982) Senior School Atlas. Macmillian. pp 113

Edet AE (2004) Vulnerability evaluation of a coastal plain sand aquifer with a case example from Calabar, southeastern Nigeria. Environmental Geology, 45, pp. 1062−1070.

Ferreira OM (2004). Groundwater vulnerability assessment in Portugal. Geofísica Internacional. 43(4):541-550.

Foster S.S (1988). Groundwater recharge and pollution vulnerability of British aquifers: a critical overview. Geological Society Special Publication, No 130, London.

Karami B, Dhumal K.N, Golabi M and Jaafarzadeh N (2009). Optimization the Relationship between Water Quality Index and Physical and Chemical Parameters of Water in Bamdezh Wetland, Iran. J. Applied Sci., 9: 3900-3905.

Majumdar R.K and Das D (2011). Hydrological Characterization and Estimation of Aquifer Properties from Electrical Sounding Data in Sagar island region, South 24 Parganas, West Bengal, India. Asian J. Earth Sci., 4: 60-74.

Mogaji, K. A., Aboyeji, O. S., and Omosuyi, G. O. (2011). Mapping of lineaments for groundwater targeting in the basement complex region of Ondo State, Nigeria, using remote sensing and geographic information system (GIS) techniques. International Journal of water resources and environmental engineering, 3(7), 150-160.

Molua O.C and Emagbetere J.U (2005). Determination of Water Table using Electrical Sounding Technique: A Case Study of Afuze, Edo State, Nigeria. J. Nig. Assoc. Math. Phys., 5: 457-464.

NIMET (2012) Seasonal Rainfall Prediction and Socio-Economic Implications for Nigeria. Nigerian Meterological Agency 2012.SRP. pp 22.

Ogungbemi O.S, Badmus G.O, Ayeni O.G, Ologe O (2013). Geoelectric Investigation of Aquifer Vulnerability within Afe Babalola University, Ado –Ekiti, Southwestern Nigeria. IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) Volume 1, pp. 28-34

Olaseeni, O.G., Oladapo, M.I., Olayanju, G.M., Dada, O.J. and Oyebamiji, A.R. (2019). Groundwater Vulnerability Assessment using Electrical Resistivity Method in the Northern part of Ado-Ekiti, Southwestern Nigeria. Journal of Physics: Conference Series, 1299, 1 – 21.

Olumuyiwa O Falowo, O. O., Akindureni, Y., and Ojo, O. (2017). Groundwater Assessment and Its Intrinsic Vulnerability Studies Using Aquifer Vulnerability Index and GOD Methods. International Journal of Energy and Environmental Science, 2(5), 103 – 116.

Omosuyi G.O and Oseghale A (2012). Groundwater Vulnerability Assessment in Shallow Aquifers using Geoelectric and Hydrogeologic Parameters at Odigbo, Southwestern Nigeria. Journal of Scientific and Industrial Research, 3,501-51.

Omosuyi GO (2010). Geoelectric assessment of groundwater prospect and vulnerability of overburden aquifers at Idanre, Southwestern Nigeria. Ozean Journal of Applied Sciences, 3, 19-28.

Simsek C, Kincal C and Gunduz O (2006). A Solid Waste Disposal Site Selection Procedure Based on Groundwater Vulnerability Mapping. Journal of Environmental Geology, 49, pp. 620−633.

Todd D.K (2004). Groundwater Hydrology. 2nd Edition, John Wiley and Sons, New York.

Vías J.M, Andreo B, Perles J.M, Carrasco F and Vadillo I (2006). Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method Application in two pilot sites in Southern Spain, Hydrogeology Journal, 14 (6), pp. 912-925.

Won, S. J., Bernard, E., Jon, H. and Larry, T. (2017). Aquifer Vulnerability Assessment for Sustainable Groundwater Management Using DRASTIC. Water, 9, 1 – 20.