Research article

Geo-investigation on groundwater control in some parts of Ogun state using data from Shuttle Radar Topography Mission and vertical electrical soundings

Emmanuel S. Joel a,*, Peter I. Olasehinde b, Theophilus A. Adagunodo a, Maxwell Omeje a, Ifeanyi Oha c, Marvel L. Akinyemi a, Olukunle C. Olawole a

a Department of Physics, Covenant University, Ota, Nigeria
b Department of Geophysics, University of Ilorin, Ilorin, Nigeria
c Department of Geology, University of Nigeria, Nsukka, Nigeria

ABSTRACT

Groundwater is a vital natural resource that plays a significant function in sustainability of living things on earth. Its exploration requires special skill for optimum exploitation. Shuttle Radar Topography Mission (SRTM) and Vertical Electrical Sounding (VES) were used to detect the stratigraphy and subsurface structures controlling the groundwater system around Iju – Ota, Ogun State, Southwestern Nigeria. Nineteen (19) VES points were carried out where there were dense concentrations of lineaments and interconnected to establish the connection of the observed lineaments with groundwater occurrence in the study area using Schlumberger array, with electrode spacing of AB/2 varying from 180 to 320 m. The analysis of SRTM data revealed the dominating structural NE-SW and NW-SE trends, which control aquifer structure. The geoelectrical parameters from the VES results were used to map the stratigraphic sequences in the study area. Six (6) units that comprise the topsoil, lateritic clay, clayey sand, mudstone, sand (main aquifer), and shale or clay were identified in the study area. The aquiferous unit around Iju – Ota axis ranged from 30 to 80 m. The extracted from the hill shaded SRTM data and the result of VES revealed that the thickness of the aquifer is as a result of interconnectivity of the lineaments observed in the SRTM data suggesting that the groundwater occurrence in the study area is chiefly controlled by these fractures.

1. Introduction

It has been established that civilization and development of any nations (communities inclusive) have flourished due to reliable water supplies and have suffered setback as the water supplies failed (Troffen, 1973; Olasehinde, 2010). Water is an inevitable tool for life survival on earth (Chaplin, 2001; Jequier and Constant, 2010; Hansmeier, 2011; Oladejo et al., 2013; Adagunodo et al., 2018; Adejumo et al., 2015; SDG6, 2018; Westall and Brack, 2018). It occurs in three forms: as rain, surface flow and subsurface flow. In Nigeria, rain and surface water are easily contaminated due to negligence of the regulatory bodies on water conservation and treatment for its sustainability (Adagunodo et al., 2018; Joel et al. 2019a, b). As a result of this, groundwater is the major source of water for drinking (Adagunodo, 2017) and domestic usages (Olafisoye et al., 2012; Oladejo et al., 2015). Groundwater is cheap, safe, constant in quality and quantity, and abundant to man when properly explored (Umar et al., 2017). It is however essential to understand the stratigraphic structures of a terrain before its groundwater resource can be optimally harnessed, either through dug wells or boreholes (Olasehinde, 2010). Various methods have been employed in groundwater exploration globally, ranging from traditional methods such as fracture trace method and borehole drilling (Lattman and Parizek, 1964; Acharya et al., 2012) to the use of geophysical methods such as electrical resistivity, magnetics, electromagnetics, seismic, radiometric techniques and so on (McNeill, 1991; Bernard and Legchenko, 2003; Goldman and Neubauer, 1994; Hewaidy et al., 2015; Shishaye and Abdi, 2016; Helaly, 2017; Muhammad and Khalid, 2017; MuthamilSelvan et al., 2017; Poongothai and Sridhar, 2017; Umar et al., 2017; Gao et al., 2018). In addition, SUNMONU...
et al. (2016), Adagunodo et al. (2018) and Joel et al. (2019a) had established that geophysical methods are capable to map the depth to groundwater table. Groundwater has been successfully investigated on sedimentary and basement terrains using resistivity technique by number of researchers (Okereke et al., 1998; Nwankwo et al., 2004; Singh et al., 2006; Aroyi and Adeyemi, 2009; Al-Amoush, 2010; Nwankwo, 2011; Zarroca et al., 2011; Ikhan et al., 2012; Molli et al., 2015; Omeje et al., 2013; Omeje et al., 2014; Rotimi et al., 2014; Sunmonu et al., 2015; Aizebeokhai et al., 2016; Sunmonu et al., 2016; Joel et al., 2016; Muhammad and Khalid, 2017; Poongothai and Sridhar, 2017; Umar et al., 2017).

The application of Shuttle Radar Topography Mission (SRTM), a remotely-sensed data for hydro-geophysical investigation is increasingly becoming well known most importantly in areas where orthodox method such as resistivity technique is inadequate. This is used for subjective estimation of ground-water resources through the extraction and studying of geological features, surface morphology and their hydrogeological attributes. In addition, better observation and systematic examination of groundwater, lineaments structure and land-forms which oversee the conditions of presence of water underneath the earth-surface are provided. Employed remote-sensing and GIS techniques to identify potential areas for groundwater in the Musi-basin by the use of various maps (these include hydro-geomorphological, structural, geological, slope, drainage, land use or land cover and slope. Other investigators that have used remotely-sensed data to carry out groundwater investigations either as stand-alone or as integrated technique with other geophysical techniques include Edet et al. (1994), Batalan and De Smedt (2000), Valeriano et al. (2006), Wright et al. (2006), Grohmann et al. (2007) and Sultan et al. (2017). The use of remotely sensed data in hydrogeological investigation has been able to provide complementary information about the subsurface of an area before borehole can be drilled (Goki et al. 2010; Anudu et al. 2011; Omeje et al., 2014; Sultan et al., 2017).

Due to the influx of people into study area (Iju – Ota community area of Ado-Odo/Ota Local Government Area, Ogun State), basic necessities of life (such as water) has been a concern as a result of uneven distribution of water in this zone. Inadequate water supply to the communities has been epileptic due to the inability of the government to meet demand of water resources needed by this ever-growing community as a result of absolute reliance on surface water. Therefore, the search for groundwater resource as a complimentary is needed in the community in order to meet the demand of water resources for domestic purposes and other related usages. Application of both Vertical Electrical Sounding (VES) and Shuttle Radar Topography Mission (SRTM) on this terrain will aid the mapping of groundwater potential system in Iju – Ota community, which will be insightful for borehole drilling. In addition, extracted lineaments from satellite imagery will aid the choice of VES point selection within the study area, such that these fracture traces will be the prospects for hydrogeophysical mapping in Iju – Ota community. Although some studies have reported significant deviations between the traced lineaments and the major fracture systems in some regions (Acharya et al., 2012; Acharya and Mallik, 2011; Degnan and Clark, 2002), integration of geophysical method (such as electrical resistivity method) with satellite imagery for groundwater exploration will assist one to locate the correct point that is suitable for groundwater exploitation (Omeje et al., 2014; Dafalla et al., 2015; Anbazhagan and Jothibasu, 2016). This present study, therefore, employed the integration of SRTM and VES with the aim to accurately investigate groundwater potential zones in an investigated area (conglomerates of sedimentary and shallow basement rocks) such as Iju – Ota community in Ogun State, in order to address the inadequate water supply being experienced in the area.

2. Geological and hydrogeology settings of the study area

The study region is generally a gently sloping low-lying area. It falls within the eastern Dahomey Basin of southwestern Nigeria which stretches along the continental margin of the Gulf of Guinea. The groundwater occurrence, movement and accumulation are chiefly controlled by geology. The geologic factors that control the groundwater system are stratigraphy, petrography, thickness, geomorphology and structure (Adagunodo, 2017). The local geology of Iju – Ota axis lies within the sedimentary rock sequence of Dahomey Basin which extends from the eastern part of Ghana through Togo and Benin Republic to the western margin of the Niger Delta (Oniho, 1999) (Figure 1). The sequence arrangement of the local geology undertaken by the study area is as follows: Recent Alluvium (Quaternary age) which trends towards south-east, east and central part of the study area and formed a boundary with Coastal Plain Sands in the west. This formation is followed by Coastal Plain Sands (Tertiary age – Pliocene) which is located in the west, south-west and eastern part of the study area and also formed boundary with Ilaro Formation in the north-west. Ilaro Formation (Tertiary age - Eocene) overlays both Coastal Plain Sands and Recent Alluvium and formed boundary with Ewekoro Formation/Oshosun Formation/Akinbo Formation. This formation cut across north-west to north-east of the study area. This geological formation is followed by Ewekoro Formation/Oshosun Formation/Akinbo Formation (Cretaceous – Paleocene). It cuts across north-north to north-east trend. The last geological formation which underlies Ewekoro Formation is Akerokuta Formation which is Cretaceous age (Senonia) and this formation formed boundary with Basement Complex in the north and Ewekoro Formation in the north-east (Omatosa and Adegoke, 1981). The Hydrogeology of Dahomey basin comprises Ogun River and Owena basin. The tectonic structure of the basin is simple, forming a monoclone against the basement outcrop the North, with only little evidence of faulting (Joel et al., 2019b). The area is characterized by two major climatic seasons, namely: dry season spanning from November to March and rainy (or wet) season between April and October. Occasional rainfalls are usually witnessed within the dry season, particularly along the region adjoining the coast. Mean annual rainfall is greater than 2000 mm and forms the major source of groundwater recharge in the area.

3. Material and methods

3.1. Shuttle Radar Topography Mission (SRTM)

The Shuttle Radar Topography Mission (SRTM) is an international research effort that obtains digital elevation models on a near-global scale from 56°S to 60°N to generate the most complete high-resolution digital topographic database of the Earth. SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during the 11-day STS-99 mission in February 2000 using older Space-borne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR). To acquire topographic data, the SRTM payload was outfitted with two radar antennas. One antenna was located in the Shuttle’s payload bay, the other – a critical change from the SIR-C/X-SAR, allowing single-pass interferometry – on the end of a 60-meter (200-foot) mast that extended from the payload bay once the Shuttle was in space. The technique employed is known as interferometric synthetic aperture radar. The elevation models are arranged into tiles, each covering one degree of latitude and one degree of longitude, named according to their southwestern corners. The resolution of the raw data is one arcsecond (30 m along the equator) and coverage includes Africa, Europe, North America, South America, Asia, and Australia. The elevation models derived from the SRTM data are used in geographic information systems and can tell how the surface of Earth changes due to the actions of glaciers, rivers and the processes.

The SRTM, a pass of single interferometer mission flown on February 2000, with generated Digital Elevation Model (DEM) data at 90 m of resolution, which is 80% of surface of the earth in C-band is presented in Figure 2. The shuttle radar topography mission digital elevation model data were obtained from the archives of United State Geological Survey Agency (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1). The extracted data are within the longitude 3°00’ to
These data were subjected to hill-shading using Idrisi 32 software to enhance the linear features that could be the major regional fractures (Valeriano et al., 2006). The analytical hill-shaded result was used to create the hill-shading image with the Sun azimuth angle set to 315° (NW) and the Sun elevation angle set at 30° as reported in Anudu et al. (2011) and Omeje et al. (2014). The lineaments and its orientations were digitized on-screen using GEORient 9.5.0 software.

### 3.2. Vertical Electrical Sounding

In this investigative study, nineteen (19) resistivity soundings were carried out both in NE–SW and NW–SE orientations, where lineaments were concentrated and interconnected (Lattman and Parizek, 1964; Acharya et al., 2012) as shown in Figures 5a and b. ABEM 4000 series equipment was used and this computes and displays mean apparent resistivity for the electrode configurations of choice. As adopted by other authors (Sunmonu et al., 2012; Adagunodo et al. 2017, 2018; Oyeyemi et al., 2018), Schlumberger Array was used for...
the present study with current electrode spacing that ranged from 180 to 320 m.

The obtained data were manually plotted using log-log graph. An automated iterative program (1D inversion algorithm) known as WinResist version 1.0 software was used to model the partial curve matching results (Aizebeokhai and Oyebanjo, 2013; Adagunodo et al., 2015), which greatly minimized the interpretation errors (Sunmonu et al. 2012, 2016; Adagunodo et al., 2017). The major VES curve types obtained in this study are presented in Figure 3.

4. Results and discussions

4.1. Interpretation of SRTM (digital elevation model) data

The SRTM data extracted from Hill shaded digital elevation model and Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS) software was used to infer the detailed hydrogeological features that control the groundwater system in the area. The purpose of using SRTM is to acquire possible knowledge of surficial features such as topographic information and/or lineaments, which could have originated as a result of joints, foliation, fractures, faults and other subsurface features (Wright et al., 2006; Anudu et al., 2011) in some parts of the study area. Understanding of these surficial features prior to localized geophysical survey(s) could enhance proper identification of suitable site for development of productive wells, corresponding to the zones of deformation in the subsurface (Akinluyi et al., 2018). Figure 2 presents the hydrogeological near-surface feature (in watershed form) of the study area. The watershed presented on the DEM is capable of revealing shallow underground tributaries, based on the relationship between the surficial and subsurface features (Valeriano et al., 2006; Zandbergen, 2008). The total numbers of lineaments extracted and digitized were fifty-eight (58) as revealed in Figure 4. The lineament map is presented in Figure 5a, while the map revealing the lineaments and the VES points is presented in Figure 5b. By comparing Figures 2, 5a and b, the lineaments...

Figure 3. Some of the VES curve types obtained in Iju – Ota axis (VESs 1 to 4 and VES 7).
Figure 4. Lineament orientation with strikes in NE – SW and NW – SE directions.

Figure 5. a: Lineament map of the study area. b: Map of lineaments with VES points.
are concentrated and interconnected both at the eastern and the western parts of the study area. It was observed further that some of the lineaments were interconnected; signifying that the groundwater system in Iju – Ota is chiefly controlled by fractures (Edet et al., 1994). In the western and eastern parts of the study area, a dominance of groundwater channels reflects the high concentration of lineaments which suggests the zones of high groundwater potential (Grohmann et al., 2007; Anudu et al., 2011; Omeje et al., 2014). The extracted lineaments were used to produce the lineaments’ orientations, which are presented in Figure 4. The orientations of the lineaments trend in NE – SW and NW – SE directions. This suggests that groundwater potential could be very high along the lineaments (Edet et al., 1994; Valeriano et al., 2006; Wright et al., 2006; Omeje et al., 2014).

4.2. Vertical Electrical Sounding (VES) data interpretation

The lithological layers were named and classified based on the resistivity contrasts among the layers, as classified by Keller and Frischnecht (1970), Sunmonu et al. (2015), Sunmonu et al. (2016), and Kure et al. (2017). The most common and basic classification of the resistivity curve in Precambrian basement terrain belongs to the three-layer type. This type reveals that three (3) different resistivity values ($\rho_1$, $\rho_2$, and $\rho_3$) correspond to three lithological variation in the subsurface. Three-layer geo-sounding curves are fundamentally grouped into four (4) categories:

i. Minimum type: When $\rho_1 > \rho_2 < \rho_3$. This is referred to as H-type (associated with the name of Hummel).

ii. Double-ascending type: When $\rho_1 < \rho_2 < \rho_3$. This is also known as A-type (corresponding to term anisotropy).

iii. Maximum type: When $\rho_1 < \rho_2 > \rho_3$. This is known as K-type or is sometimes referred to as DA-type (meaning displaced or modified anisotropy).

iv. Double descending type: When $\rho_1 > \rho_2 > \rho_3$. This is known as Q-type and is sometimes referred to as DH-type (meaning displaced Hummel or modified Hummel). Figures 6a and b showed the diagrammatical representations of all these type curves for the three-layer cases.
However, in sedimentary basin, more than three-layered lithological settings (such as four, five-layer curves and so on) corresponding to multiple curve types could be achievable. For example, in order to classify a 4-layered resistivity curve, its classification can be done by analyzing the first 3 resistivity values ($\rho_1, \rho_2,$ and $\rho_3$) and the last three resistivity values ($\rho_4, \rho_5,$ and $\rho_6$), such that eight (8) categories of four-layered curves (that is, HA, HK, AA, AK, KH, KQ, QH, and QQ) are possible as shown in Figures 6c, d, e, f. Further classifications can be done using this basic approach as documented by Patra and Nath (1999) and Sunmonu et al. (2015). Five (5) different curve types were identified in the study area, which are AAKQ-curve, HKHQ-curve, AKQK-curve, KHAK-curve, and QHKQ-curve types (Table 1). The percentage distribution of the curve types in the order of appearance from the curve types are as follow: 15.8% are of AAKQ-type, 26.3% are of HKHQ-type, 42.1% are of AKQK-type, 10.5% are of KHAK-type, and 5.3% are of QHKQ-type respectively. Classification of the VESs to their respective types, curve models and their frequencies are summarized in Table 1. The interpretation of geoelectrical results revealed six lithological layers in the study area, which are AAKQ-curve, KHKQ-curve, AKQQ-curve, KHAK, and QHKQ types (Table 2). The resistivity value of this layer ranges from 263.7 to 1564.4 $\Omega$m with an average value of 550.4 $\Omega$m and varying thickness of about 1.4–6.6 m. Beneath the lateritic clay is clayey sand with mean value of 770.7 $\Omega$m which is continuous laterally from second layer. The resistivity value of this layer ranges from 263.7 to 1564.4 $\Omega$m, with a thickness of about 2.3–19.7 m. Both second and third layers have different degree of water saturation and compaction, which are impermeable, most especially area where percolation are poor as a result of compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction. These layers once a while always form parched aquifer and as a result the areas experience fluvial compaction.
4.2.1. Geoelectric section

The result presented showed the geospatial features of the subsurface layers according to their depths and stations. The geoelectric sections of six traverses, as revealed on Figures 1 and 5b were plotted in order to map the depth to the main aquifer (Figures 7a, b, c, d, e, f). The importance of geoelectric sections is to map the variations of geoelectrical parameters along a linear path (Adagunodo et al. 2015, 2017; Sunmonu et al., 2015, 2016; Raji and Adeoye, 2017). The six traverses were grouped as follow: traverse 1 contained VESs 1, 19, 2, 3, 4, 5 and 7 in NE – SW direction, traverse 2 contained VESs 18 and 6 in NE – SW direction, traverse 3 contained VESs 17, 16 and 15 in N – S direction, traverse 4 contained VESs 11, 13, 15 and 14 in NW – SE direction, traverse 5 contained VESs 13, 8 and 7 in NW – SE direction, and traverse 6 contained VESs 11, 13, 10 and 9 in NS direction. Each traverse was chosen according to how the two-dimensional (2D) signatures of the subsurface variations can be imaged conveniently (Adagunodo et al., 2017). The 2D imaging is also capable of revealing both lateral and vertical variations within the subsurface. The top of the main aquifer in the study area fluctuates from 11.9 to 50.5 m while the aquifer bottom fluctuates from 27.5 to 80.1 m. This reveals that the depth to the main aquifer in Iju and Ota is approximately 25.0 m. The aquifer thickness varies from point to point with minimum thickness of about 8.6 m and maximum thickness of 32.0 m. The thickness of the aquifer in Iju and Ota community is a result

Figure 7. a. Geoelectric section of traverse 1. b. Geoelectric section of traverse 2. c. Geoelectric section of traverse 3. d. Geoelectric section of traverse 4. e. Geoelectric section of traverse 5. f. Geoelectric section of traverse 6.
of the fractures (lineaments) that are interconnected, which will defi-
nitely result to good yield at this depth.

Traverse 1 revealed that aquifer may be reached at depth of 28.0 m
for VES 1, for VES 19 the depth to the aquifer ranged between 35.0 m
and 55.0 m, as well as VES 3. But at VES 2, the depth to the aquifer is
between 50.0 m and 80.0 m while is 40.0 m at VES 4 and VES 5 and 35.0 m at VES 7 respectively in the NE-SW direction (Figure 7a)
Transverse 2 showed the variations in the aquifer to be between 28.0 m and 50.0 m in NE-SW direction (Figure 7b). Transverse 3 in the N-S direction further revealed the thickness of aquifer towards the southern part of the study area to be approximately 30.0 m thick and the depth to reach the aquifer in tha-
torientated ranged between 40.0 m and 80.0 m (Figure 7c). Transverse 4 in the NW-SE direction unfolds the depth to the aquifer that ranged between 20.0 m and 80.0 m with deep aquifer observed at VES 4 (Figure 7d) while transverse 5 revealed similar trend but at the depth to the aquifer that ranged between 20.0 m and 50.0 m with observed thick overburden (Figure 7e). Also transverse 6 discloses the trend of the aquifer to be N-S direction at the depth that varied between 20.0 m and 60.0 m at VES 11, VES 13, VES 10 and VES 9 respectively (Figure 7f).

5. Conclusions

The lineaments and the production of the rose diagram indicate the trend of the structural features that control the groundwater system in the area which invariably suggests high groundwater potential of the study area, where water can be tapped and served for long period of time. Resistivity technique (geoelectric section) revealed good aquifers features with variation in depths of about 25.0 m–80 m for a good yield in the study area. The use of resistivity technique and SRTM for geo-
hydrological investigation revealed significant subsurface features of a better groundwater characterization in the study area. Significantly, the combinations of these two techniques serve a better scientific idea for undisclosed nature of groundwater featuresin sedimentary terrain where fractures are buried in the subsurface. It is therefore recommended that thickness of aquifers should be determined from geo-electric studies before recommending the drilling locations in the study area.

Declarations

Author contribution statement

Emmanuel S. Joel: Conceived and designed the experiments; Per-
formed the experiments; Analyzed and interpreted the data; Wrote the paper.
Peter Olasehinde: Conceived and designed the experiments. Theophilus Adagunodo: Analyzed and interpreted the data. Maxwell Omeje, Ifeanyi Oha, Marvel L. Akinyemi, Olukunle C. Ola-
wole: Contributed reagents, materials, analysis tools or data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors are thankful to Covenant University Ota, for providing enabling environment. Furthermore, authors are also grateful to Open Transaction on Geosciences for the permission given to reproduce Figure 6 from Sunmonu et al. (2015).

References

Acharya, T., Mallik, S.B., 2011. Analysis of lineament swarms in a Precambrian metamorphic rocks in India. J. Earth Syst. Sci. 121 (2), 453-462.
Acharya, T., Nag, S.K., Basumallik, S., 2012. Hydraulic significance of fracture correlated lineaments in precambrian rocks in purulia district, West Bengal. J. Geol. Soc. India 80 (5), 723-730.
Adagunodo, T.A., 2017. Groundwater Contamination/Performance, Effects, Limitations and Control. Chapter 3 in Book: Groundwater Contamination: Performance, Limitations and Impacts, 1–135. In: Anna L. Powell © 2017. Nova Science Publishers, Inc., pp. 33-64.
Adagunodo, T.A., Adeniji, A.A., Erinle, A.V., Akinyemi, S.A., Adewoyin, O.O., Joel, E.S., Kayode, O.T., 2017. Geophysical investigation into the integrity of a reclaimed open dumpsite for civil engineering purpose. Inter. J. 42 (11), 324-339.
Adagunodo, T.A., Akinloye, M.F., Sunmonu, L.A., Aizebeokhai, A.P., Oyeyemi, K.D., Abdurani, F.O., 2018. Groundwater in aso residential area of akure, Nigeria. Front. Earth Sci. 6, 66.
Adagunodo, T.A., Sunmonu, L.A., Adeniji, A.A., 2015. Effect of dynamic pattern of the napolitic zone and its basement on building stability: a case study of a high-rise building in ogbomoso. J. Appl. Phys. Sci. Int. 3 (3), 106-115.
Adejumo, R.O., Adagunodo, T.A., Bility, H., Lukman, A.F., Isibor, P.O., 2018. Physicochemical constituents of groundwater and its quality in crystalline bedrock. Nigeria. Int. J. Civ. Eng. Technol. 9 (8), 887-902.
Aizebeokhai, A.P., Oyebanjo, O.A., 2013. Application of vertical electrical soundings to characterize aquifer potential in Ota, Southwestern Nigeria. Int. J. Phys. Sci. 8 (46), 2077-2085.
Aizebeokhai, A.P., Oyeyemi, K.D., Joel, E.S., 2016. Groundwater potential assessment in a Sedimentary terrain, southwestern Nigeria. Arab. J. Geosci. 9, 1-15.
Akinluyi, F.O., Oluronfemi, M.O., Bayowa, O.G., 2018. Investigation of the influence of lineaments, lineament intersection and geology on groundwater yield in the basement complex terrain of Ondo state, southwestern Nigeria. Appl. Water Sci. 8, 49.
Al-Amouth, H., 2010. Integration of vertical electrical sounding and aeromagnetic data using GIS techniques to assess the potential of unwatered natural and natural basalt caves for groundwater artificial recharge in NE-Jordan. Jordan. J. Civ. Eng. 4 (4), 389-408.
Azbazhagan, S., Jothibau, A., 2016. Geoinformatic in groundwater potential mapping and sustainable development: a case study from southern India. Hydro. Sci. J. 1 (61), 1109-1123.
Anud, G.K., Essien, B.I., Osum, L.N., Ipokonte, A.E., 2011. Lineament analysis and interpretation for assessment of groundwater potentiality at Wamba and adjoining areas, Nassarawa state, north-central Nigeria. J. Appl. Technol. Environ. Sanit. 1, 185-198.
Ariyo, S.O., Adeyemi, G.O., 2009. Role of electrical resistivity method for groundwater exploration in hard rock areas: a case study from Fidiowo/Ajobro areas of Southwestern Nigeria. Pacif. J. Sci. Technol. 10, 483-486.
Batalan, O., De Smedt, F., 2000. Using Landsat imagery in the assessment of groundwater resources in the crystalline rocks around Dutsin-Ma, northwestern Nigeria. J. Min. Geol. 36, 85-92.
Bernard, J., Legenhoko, A., 2003. Groundwater exploration with the magnetic resonance sounding method. ASEG Extend. Abstr. 2, 1-5.
Chaplin, M.F., 2001. Water: its importance to life. Biochem. Mol. Biol. Educ. 29, 54-59.
Daftalla, D.S., Khirallah, K.M., Dahab, M.A.H., 2015. Groundwater exploration using integration of electrical resistivity data with remote sensing and GIS data, northern state – Sudan. Int. J. Sci. Res. Eng. Technol. 4 (7), 736-746.
De’gnaan, J.R., Clark JR., F.S., 2002. Fracture-correlated Lineaments at Great Bay, Southeastern New Hampshire. U.S.G.S. Open-File Report 02-13.
Elder, A.E., Tema, C.S., Okereke, C.S., Ese, E.O., 1994. Lineament analysis for groundwater exploration in precambrian oban massif and obudu plateau, south-east Nigeria. J. Min. Geol. 30, 87-95.
Gao, Q., Shang, Y., hassan, M., Jin, W., Yang, P., 2018. Evaluation of a Weathered rock aquifer using ERT method in south Guangdong, 357 China. Water 10, 293.
Goki, N.G., Ugodulunwa, F.X.O., Ogunmola, J.K., Oha, L.A., Ogbole, J.O., 2010. Geological controls for groundwater development in the basement rocks of Kanke, central Nigeria from geophysical and remotely sensed data. Afr. J. Basic Appl. Sci. 2, 104-110.
Goldman, M., Neubauer, F.M., 1994. Groundwater exploration using integrated geophysical techniques. Surv. Geophys. 15 (3), 341-361.
Grohmann, H.C., Riciomini, C., Machado-Alves, F., 2007. SRTM-based morphotectonic analysis of the Pocos de Caldas Alkaline massif, Southern Brazil. Comput. Geosci. 33, 10-19.
Hansmeier, A., 2011. Life and Water. Chapter 2 in Book: Water in the Universe, 368. Astrophysics and Space Science Library, pp. 25–36. http://www.springer.com
Helaly, A.S., 2017. Assessment of groundwater potentiality using geophysical techniques in Wadi Allaqi Basin, Eastern desert, Egypt-case study. NIRAG J. Astron. Geophy. 6, 408-423.
Hewaidy, A.G.A., El-motaal, E.A., Sultan, S.A., Ramdan, T.M., El-khafeef, A.A., Soliman, S.A., 2015. Groundwater exploration using resistivity and magnetic data at the northern part of the Gulf of suez, Egypt. Egypt. J. Petrol. 24, 255-263.
Ikhan, P.R., Omosanya, K.O., Akinmosin, A.A., Odugbese, A.B., 2012. Electrical resistivity imaging of slope deposits and structures in some parts of Eastern Dahomey basin. J. Appl. Sci. 12, 716–726.

Jequier, E., Constant, F., 2010. Water as an essential nutrient: the physiological basis of hydration. Eur. J. Clin. Nutr. 64, 115–123.

Joel, E.S., Olasehinde, P.I., De, D.K., Omeje, M., Adeyemi, G.A., 2018. Estimation of aquifer transmissivity from geophysical data: A case study of Covenant University and Environworks, southwestern Nigeria. Sci. Int. (Lahore) 28 (4), 3379–3385.

Joel, E.S., Olasehinde, P.I., Adagunodo, T.A., Omeje, M., Akinmi, M.O., Ojo, J.S., 2019a. Integration of aeromagnetic and electrical resistivity imaging for groundwater potential assessment of Coastal Plain sands area of Ado-Odo/Ota in southwest Nigeria. Groundwater Sustain. Develop. 9, 100264.

Joel, E.S., Maxwell, O., 2020. Relationship between fracture traces and the occurrence of ground water in carbonate rocks. J. Hydrod. 2 (2), 73–91.

McNeill, J.D., 1991. Advances in electromagnetic methods for groundwater studies. Geoexploration 27, 65–80.

Molut, G., Adewo, M., Manzella, A., Bonini, L., Botti, F., Menichini, M., Montanari, D., McNeill, J.D., 1991. Advances in electromagnetic methods for groundwater studies. Geoexploration 27, 65–80.

Muther, S., Doveri, M., Manzella, A., Bonini, L., Botti, F., Menichini, M., Montanari, D., McNeill, J.D., 1991. Advances in electromagnetic methods for groundwater studies. Geoexploration 27, 65–80.

Nagao, S., Fujii, H., 1998. Determination of potential groundwater sites using geological and geophysical techniques in cross river state, Southeastern Nigeria. Br. J. Appl. Sci. Technol. 19 (1), 1–9.

Nagao, S., Fujii, H., 1998. Determination of potential groundwater sites using geological and geophysical techniques in cross river state, Southeastern Nigeria. Br. J. Appl. Sci. Technol. 19 (1), 1–9.

Nagao, S., Fujii, H., 1998. Determination of potential groundwater sites using geological and geophysical techniques in cross river state, Southeastern Nigeria. Br. J. Appl. Sci. Technol. 19 (1), 1–9.

Omeje, M., Huisin, W., Nooordin, L., Oa, I.A., Owekaka, O.S., Sheih, S., 2014. Integrated geoelectrical and structural studies for ground-water investigation in parts of Abuja, North Central Nigeria. Near Surf. Geophys. 12, 515–521.

Omeje, M., Huisin, W., Nooordin, L., Oa, I.A., Owekaka, O.S., Uwekwe, P.E., Meladu, O., 2013. Geoelectrical investigation of aquifer problems in Gosa area of Abija, North Central Nigeria. Int. J. Phys. Sci. 6, 549–559.

Ozumba, K.O., 1999. Structural features of Nigeria’s coastal margin: an assessment based on age data from wells. J. Afr. Earth Sci. 29 (3), 485–499.

Oyeyemi, K.D., 2013. The groundwater potential of major lineament and groundwater exploration using geological and geophysical techniques in cross river state, Southeastern Nigeria. Asian J. Geol. Geophys. 6, 1.

Patra, H.P., Nath, S.K., 1999. Schumberger Geoelectrical Sounding in Ground Water (Principle, Interpretation and Application). A.A. Balkema Publishers, Old Post Road, Brookfield, VT 05006-9704, USA.

Poonghothi, S., Sridhar, N., 2017. Application of geoelectrical technique for groundwater exploration in lower Pennayar sub-watershed, Tamilnadu, India. IOP Conf. Ser. Earth Environ. Sci. 80, 1–10, 012071.

Raji, W.O., Adeyoe, T.O., 2017. Geophysical mapping of contaminant leachate around a reclaimed open dumpsite. J. King Saud Univ. Sci. 29, 348–359.

Rotimi, O.J., Atehji, J.F., Ogunuga, B., 2014. Groundwater prospecting using electrical resistivity profiles over Jubilee Homes Parkland, Southwest, Nigeria. J. Emerg. Trends Eng. Appl. Sci. 5 (3), 188–196.

SDGe (Sustainable Development Goal 6), 2018. Synthesis Report 2018 on Water and Sanitation. United Nations Publications, New York, USA.

Sibih, H.A., Adib, S., 2016. Groundwater exploration for water well site locations using geophysical survey methods. Hydrol. Curr. Res. 7, 1.

Singh, K.K., Singh, A.K.S., Singh, K.B., Sinha, A., 2006. 2D resistivity imaging survey for siting water-supply tube wells in metamorphic terrains: a case study of CMRI campus, Dhanbad, India. Lead. Edge 25, 1450–1456.

Sultan, S.A., Essa, K.S.A., Khalil, M.H., El-Nabry, A.E.H., Galal, A.N.H., 2017. Evaluation of groundwater potentiality survey in south Ataga-Northwestern part of Gulf of Suez by using Resistivity data and site-selection modelling. NRIAG J. Astron. Geophys. 6, 230–243.

Summonu, L.A., Adagunodo, T.A., Olafisoye, E.R., Oladejo, O.P., 2012. The groundwater potential evaluation at industrial estate ogbomoso southwestern Nigeria. RMZ Mater. Geoeenviron. 59 (4), 363–390.

Summonu, L.A., Adagunodo, T.A., Adeniji, A.A., Oladejo, O.P., Alagbe, O.A., 2015. Geoelectrical delineation of aquifer pattern in crystalline bedrock. Open Trans. Geosci. 2 (1), 1–16.

Summonu, L.A., Adagunodo, T.A., Bayowa, O.G., Erine, A.V., 2016. Geophysical mapping of the proposed Ogun state housing estate, Oshipona for subsurface competence and groundwater potential. J. Basic. Appl. Res. 2 (2), 27–47.

Trofen, P.F., 1973. Groundwater utilization in hard rocks atlas copco MCT AB-stockholm Sweden. AHB 48, 35 – 15, Printed Matter no. 15317a.

Umar, A.B., Ladan, B., Gadu, A.A., 2017. Groundwater evaluation study using electrical resistivity measurements in Bunza area of KebbiState, Nigeria. Int. J. Enviren. Bioenergy 12 (2), 100–114.

Valeriano, M.M., Kuplich, T.M., Storiño, M., Amaral, D.D., Mendes, J.N., Lima, D.J., 2006. Modelling small watersheds in Brazilian amazonia with shuttle radar topographic mission 90 m data. Comput. Geosci. 32, 1169–1181.

Westall, F., Frack, A., 2018. The importance of water for life. Space Sci. Rev. 214, 50.

Wright, R., Garbeil, H., Baloga, S., Mougin-Mark, P., 2006. An assessment of Shuttle Radar Topographic Mission digital elevation data for studies of volcano morphology. Rem. Sens. Environ. 105, 41–53.

Zandbergen, P., 2008. Applications of shuttle radar topography mission elevation data. Geogr. Compass 2–5, 1404–1431.

Zarco, M., Bach, J., Linares, R., Pellicer, X.M., 2011. Electrical methods for identifying, mapping and monitoring different saline domains in a coastal plain region (Ait Emporda, Northern Spain). J. Hydrod. 409, 407–422.