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Groundwater Potential and Vulnerability Assessment from Integrated Geophysical Methods, Borehole Logging, and Hydrogeological Measurement

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ABSTRACT

Geophysical investigations and hydrogeological measurements were carried out in Akoko area of Ondo State, Nigeria which are characterized by rugged hills of Precambrian Basement Complex of Southwestern Nigeria comprising mainly of the Migmatite-Gneiss-Quartzite Complex of Archean-Proterozoic age. The study was aimed at evaluating the groundwater potential of the area and assess the vulnerability of the aquifers/water bearing units within the phreatic zone to contamination especially from surface activities/anthropogenetic sources. Seventy soundings were carried out along fifteen traverses where the VLF-EM measurement was also conducted. The hydrogeological measurement involved determination of static water level/vadose zone thickness from 138 wells. Also four borehole were drilled after thorough geophysical investigations in order to constrain the interpretation of the geophysical investigation. Findings show that the major water bearing units/aquifer in the area are the weathered layer (clayey in nature) and fractured basement as delinated on the geoelectric sections, borehole sections, and very low frequency electromagnetic. The combination of these aquifer units are common in Ikare and Akungba parts of the study area. The visible depth of groundwater exploitation in the area is between 10 – 40 m. The static water level is generally less than 5 m. The map of the overburden shows that Akoko area is generally made up of thin overburden thickness except at Irun, Ogbagi, Arigidi, and Oke Agbe that showed moderate overburden thickness (10 m – 20 m). The static water level measured in the study area ranged from 0.75 m – 16 m, with a modal range of 1.1 – 3.0 m as they constituted for about 78 % of the area. This generally showed that the static water level was shallow across the study area, thus suggesting that the surficial aquifers/water bearing units would be highly vulnerable to anthropogenetic/surface activities which are the major sources of groundwater contamination. Clay or silt, characterized by low resistivity (1 – 100 Ω-m) and very low permeability, and impervious or semi-impervious topsoil materials (laterite and lateritic sand), characterized by high resistivity values (>400 Ω-m) constitutedthe protective layers that cappedthe vadose zones in the area. The topsoil can provide protection to a reasonable extent, but limited due to its thin thickness across the area.

Keywords: *Vadose Zone, Contamination, Groundwater Prospect, Vulnerability, Fractured Zone, Anthropogenic*

1. INTRODUCTION

Many drillers and well developers exploring and exploiting for groundwater usually carry out their activities/operationswithout taking cognizance of the lithological units that could assist in proper delineation of aquifer or productive water bearing units and its vulnerability potential to contamination/pollution arising from anthropogenic sources.This has consequently leads to abortive boreholes, low yield wells, total failure of wells, and adulterated water. The quantity of groundwater recovered from an aquifer system is as important as its quality especially for domestic, irrigation, municipal water supply scheme etc.Therefore sustainable use of groundwater resource is highly expedient to prevent falling water tables, deteriorating water quality, environmental degradation, rising pumping costs of wells, and lower crop yields.In most developing countries, rapid development and increased population has raised the quantity of waste generated. However, little concern has been shown to the management of wastes in these developing countries like Nigeria, as piles/heaps of these wastes are recklessly dumped in public places, open sanitary landfills, which later precipitate into groundwater system. If there was a time we (Nigerians) needed extensive exploration of groundwater resources, it is now! This would facilitates government's frantic effort on diversification from oil to agriculture to engage teeming unemployment youths for extensive agriculture, which would invariably leads to improve household food security through irrigation during drought seasons and increase income or Gross Domestic Product of the nation.

It's worthy of note that groundwater currently supplies approximately 40 % of the world's irrigated area. It enables 13 % of total food production and groundwater contributes to about 44 % of irrigated food production [1]. Although groundwater may also be susceptible to drought, e.g. where groundwater storage is limited, meteorological drought risk is high and where population density is high, groundwater dependency are relatively high for both domestic and productive purposes. The focus of this research is to delineate water bearing unit and determine its vulnerability potential to contamination or pollution, using integrated geophysical methods (electrical resistivity and very low frequency electromagnetic), borehole logging, and hydrogeological measurement. These methods have provedtheir effectiveness over the years in groundwater investigation [2-7].The concept of aquifer vulnerability derives from the assumption that the physical geomaterials may provide some level of protection to groundwater, especially with regard to pollutants entering the subsurface [8-9]. Consequently, the lithologic variations and the thickness of the unsaturated zone (vadose zone) which determines the inaccessibility of the underlying aquifer units [10], constitute the focus in aquifer vulnerability assessment. Although the general concept of vulnerability has been in use for years, strict definition of the term and the conventional vulnerability assessment methodology are still evolving [8, 11].

1.1 STUDY AREA

The study area (Akoko) is located in Ondo State, Nigeria (Figure 1) which is predominantly an agricultural State with over 60 % of its labour force deriving their income from farming. Agriculture also constitutes the main occupation of the people of the Akoko Area, majorly subsistence farming. It is located within Lat. 7°15¹ and 7°50¹N and Long. 5°30¹ and 6°10¹E.The area is characterized majorly by rugged hills with granitic outcrops in several places, most of the hills are above 250 m above the sea level. The most outstanding characteristics of the drainage over the area is the proliferation of many small river channels. The channels of the smaller streams are dry for many months, especially from November to May. There are also occurrences of many devastating erosion gullies along hill slopes. The climate of the area is of the Lowland Tropical Rainforest Type, with distinct wet and dry seasons. The mean monthly temperature and its range are about 30 °C and 36 °C respectively. The mean monthly relative humidity is less than seventy percent (70 %). The vegetation of the area composed of Tectonagrandis (teak) and Gmelinaarborea (pulp wood) (Figure 2).

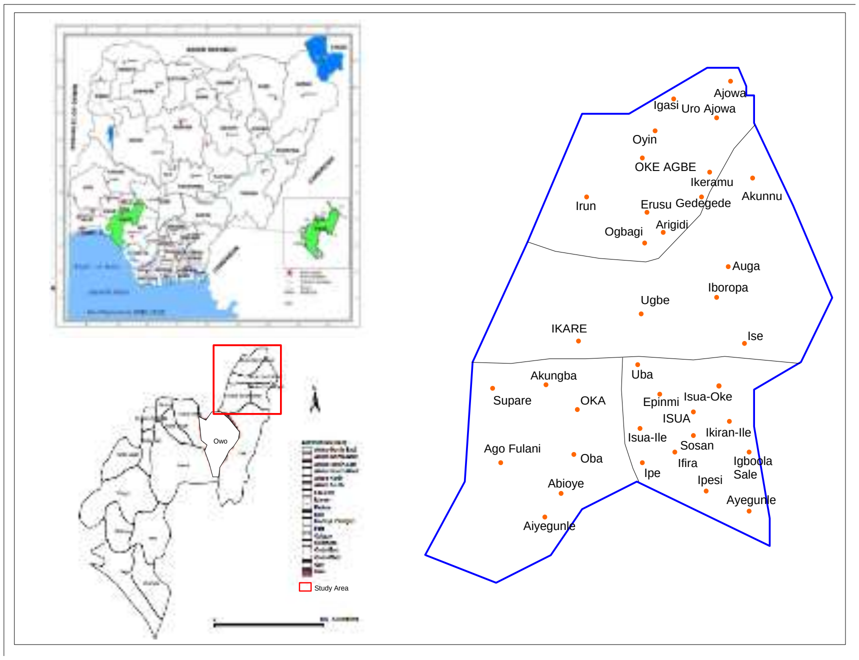


Figure 1: Location Map of the Study Area

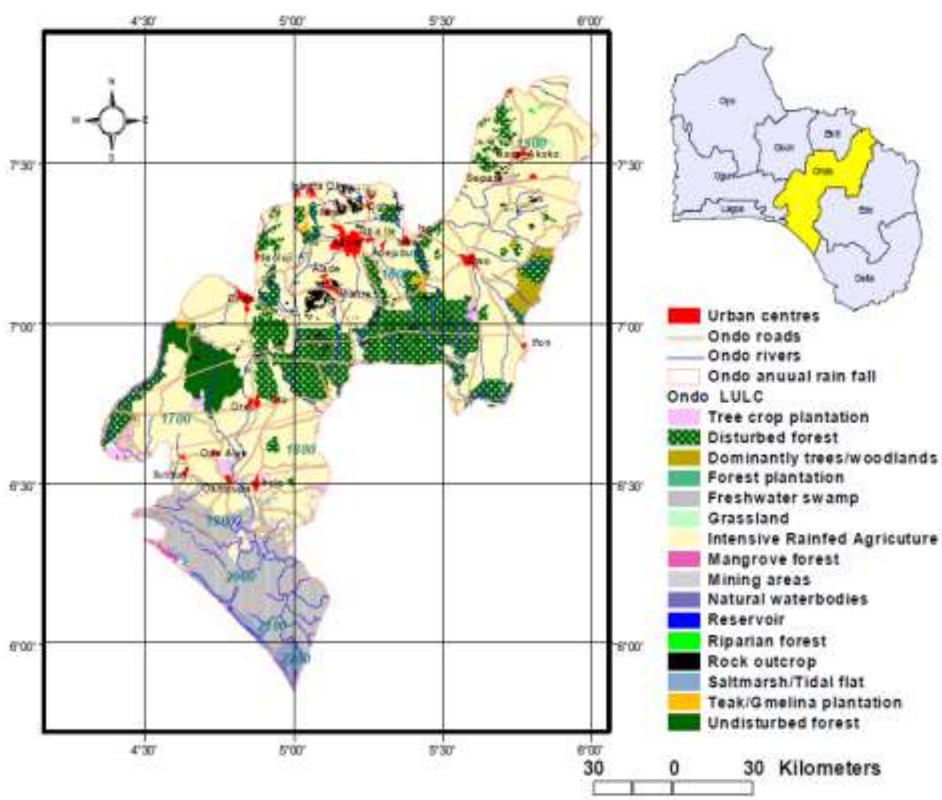


Figure 2: Land use Map of Ondo State showing Akoko at the Northern Part

1.2 Geology and Hydrogeology

Akoko area forms part of the Precambrian Basement Complex of Southwestern Nigeria, comprising mainly of the Migmatite-Gneiss-Quartzite Complex (Figure 3) which is of Archean – Proterozoic age averagely >2Ga [12-13], the Late Proterozoic SchistBelts [14-15] and the Older Granitoids of Pan-African age (500-750Ma) which intruded the former two units [16-18]. The area comprises mainly of gneisses in association with other rock types which include porphyritic granite, pegmatite, aplite, quartz vein and amphibolite. The gneisses are of two types: granite gneisses and grey gneisses. References [16] and [19] referred to the grey gneisses as early or quartzo-feldspathic gneisses and explained that they are granodioritic to quartz-dioritic or tonalitic in composition. The granite gneiss forms part of the felsic components of the Migmatite-Gneiss complex [16]. The grey gneisses are the second most abundant rock type in the area forming enclaves within the granite gneisses. They are dark grey in colour and are medium-coarse grained with well-developed mineralogical bands. The light coloured bands are quartzo-feldspathic while the dark bands are biotite-rich. The grey gneisses contain intrusions of pegmatites and quartzo-feldspathic veins and are regarded as the oldest rocks in the area into which all other rocks in the area were intruded. The granite gneisses are light coloured, medium-coarse grained and characterised by weak foliation defined by the alignment of streaks of light and dark coloured minerals. The granite gneisses contain xenoliths of the grey gneisses and amphibolites. This indicates that the granite gneisses post-date the grey gneisses in the study area. These gneisses (grey and granitic varieties) are widespread in the area constituting about 90% of the rock types found in the area and have been intruded by the Pan-African granites. They occur as massive rugged hills and rolling plains assuming batholithic dimensions and forming impressive outcrops which tower few hundred meters above the surrounding lowlands and showing different types of geological structures such as folds, faults, foliation, joints, veins, etc. These structures show that the area has been subjected to at least two phases of deformation. Metamorphism in this area is of granulite faces grade [19].

In tropical and equatorial regions, weathering process creates superficial layers, with varying degrees of porosity and permeability [2]. The unconsolidated superficial materials often constitute reliable aquifer units if significantly thick and appropriately porous and permeable [20]. The concealed crystalline basement rocks, on the other hand, may contain incipient joints, highly faulted, and fracture systems, derived from multiple tectonic events they have experienced. The delineation of these fissured zones may facilitate the delineation of groundwater prospect zones, since they are known to house abundant groundwater [2].

2. MATERIAL AND METHODS

The study involved two phases of measurements: the hydrogeological and geophysical measurements. The hydrogeological phase involved water level measurements in a total of one hundred and thirty eight (138) existing non-flowing wells across the study area. The measurements engaged steel tape whose lower end was marked with carpenter's chalk, as practiced in Moore [21]. This was to enable a reading to be taken from the submerged portion. To ensure accuracy, two measurements were taken at each well location, and the average values were determined whenever there was contrast. Since the depth to the static water level is considered an approximation of the interface between the vadose and phreatic zones in a non-confined aquifer setting [21], the measurements were used to compute the thickness of the vadose zone across the area.

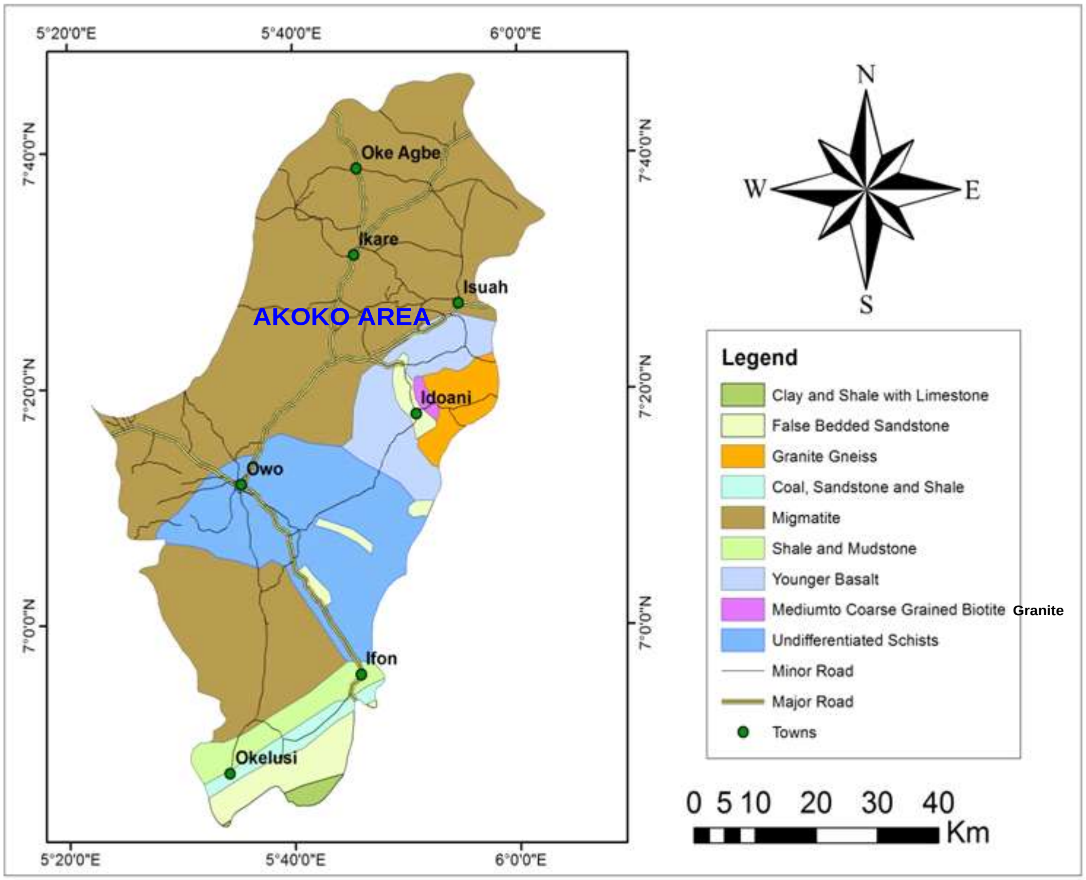


Figure 3: Geological Map of Northern Part of Ondo State showing a predominantly Migmatite Rock

The geophysical measurements involved electrical resistivity (vertical electrical sounding) and very low frequency electromagnetic (VLF-EM). The soundings were conducted at points of anomaly quantitatively delineated from the EM profiles. Seventy (70) depth soundings were conducted, with maximum half-current electrode spacing (AB/2) of 100 m. The field curves were manually interpreted [22], using master curves [23] and auxiliary point charts [24-25]. Geoelectric parameters obtained frommanual interpretation were later used as a starting model for computer-assisted interpretation [26]. The interpreter enters an initial geoelectric model, through an iterative process, the program varies the thickness and electrical resistivity of each layer, but not the number of layers, until it finds a final geoelectric model that satisfactorily best fits the data.From the interpretation results, geoelectric sections along the traverses were produced. The interpreted result was considered satisfactory where a good fit of RMS between the field curves and computer generated curves is generally less than 10 % [27].Information was also obtained from four (4) drilled boreholes after thorough geophysical investigations.

The EM response was measured using the ABEM WADI VLF-EM instrument. The instrument measures the electrical properties of subsurface materials as detailed in Mc Neil [28]. EM data were collected at 20m intervals along fifteen (15) profiles, with profile lengths ranging from 100m to 450 m. The VLF-EM data were presented as EM profiles, showing plots of raw real and filtered real values against station positions. The EM profiles were quantitatively analyzed [3, 28]. The quantitative analysis enabled the identification of profiles where positive amplitude of filtered real crossover the inflection points of the raw real as points of anomaly for vertical electrical sounding [29]. The VLF-EM sections are plotted as Karous-Hjelt filtered real component [30]. The VLF electromagnetic profiling data are presented as plots of filtered real and filtered imaginary (in %) against station position.

3. RESULTS AND DISCUSSION

Table 1 gives a summary of the results of the VES curves obtained from the study area. The number of layers varies between three (3) layers and four (4) layers. Four curve types have been identified: H, HA, KH, and A. The most occurring curve type identified is H, signifying a weathered layer aquifer/water bearing unit.

Table 1: Summary of the Curve Types obtained from the Study Area

Location/Curve Type	H	HA	KH	A
Akoko Area	25	9	1	8

Figures 4 – 8 along five (5) traversesshow the comparison of the Karous-Hjelt filtered real component; VLF-EM 2-D model, and the geoelectric sections along five major towns representing Oka, Ikare, Isua, OkeAgbe and Akungba respectively.A suspected strong conductive feature on the inverted VLF-EM model (Fig. 4b) at distances between 25 m and 50 m is identified as clay on the geoelectric model (Fig. 4c) along Traverse 1. The area is hilly. The topsoil has resistivity in the range of 968 Ω-m – 1267 Ω-m, and composed of sand and laterite. The water level along this traverse is less 3 m. The weathered layer is composed of clay material with resistivity in the range of 50 to 100 Ω-m, and thickness less than 20 m. It is thicker in the southwestern flank i.e. greater than 10 m.

Traverse 16 is characterized by steeply dipping linear features sandwiched within high resistive body on the inverted model of VLF-EM (Fig. 5b) which are genuine inflexion of the positive peaks amplitude of the profile (Fig. 5a). The geoelectric section (Fig. 5c) recognizes this feature as a fracture zone at distances between 300 m – 320 m. This feature has a depth extent greater than 30 m especially on VLF-EM model. The major water bearing unit along this traverse is the weathered layer of clayey composition (less than 50 Ω-m), with thickness of about 10 m at the eastern part. The western part is hilly, where a fracture aquiferous zone is delineated, with depth extent greater than 30 m, and corresponds to the positive peak on the VLF-EM profile. Therefore the combined thickness of topsoil, the weathered layer, and fracture aquifer are the potential water bearing units along this traverse. The water level is about 5 m at eastern flank and less than 3 m at the western flank.

Along traverse 3 (Figure 6) few conductive targets are delineated at distances between 20 m and 35 m, and 280 m and 320 m, which are represented by relatively low amplitudes on the VLF-EM profile. However on the geoelectric section, they are diagnostic of clayey material(less than 50Ω-m) with thickness of about 5 m. Moreover, the geoelectric section shows thin overburden thickness, hence groundwater potential along this traverse is expected to be low. However seasonally fluatuated shallow wells could be possible, as the static water level is less than 5 m.

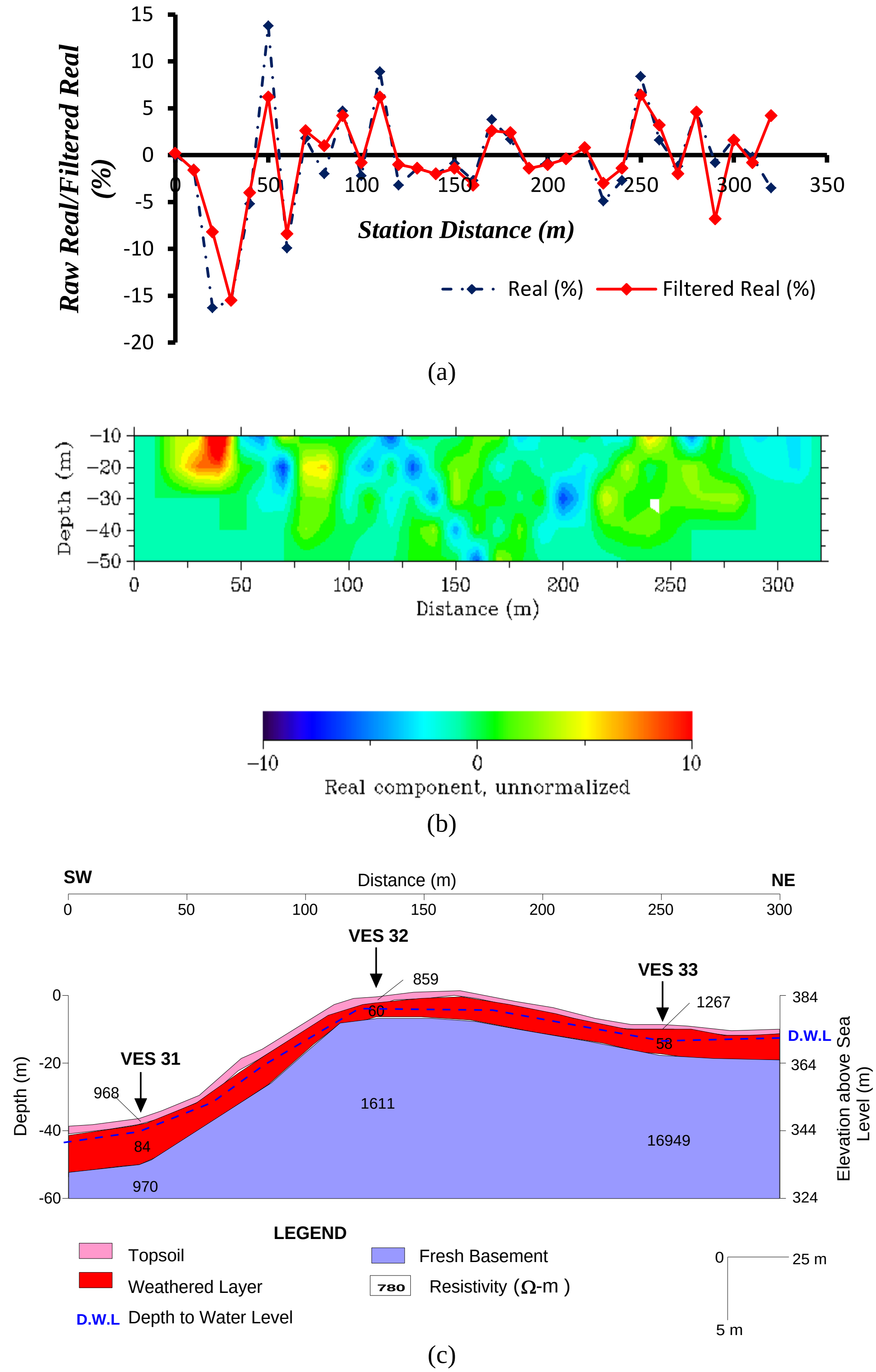
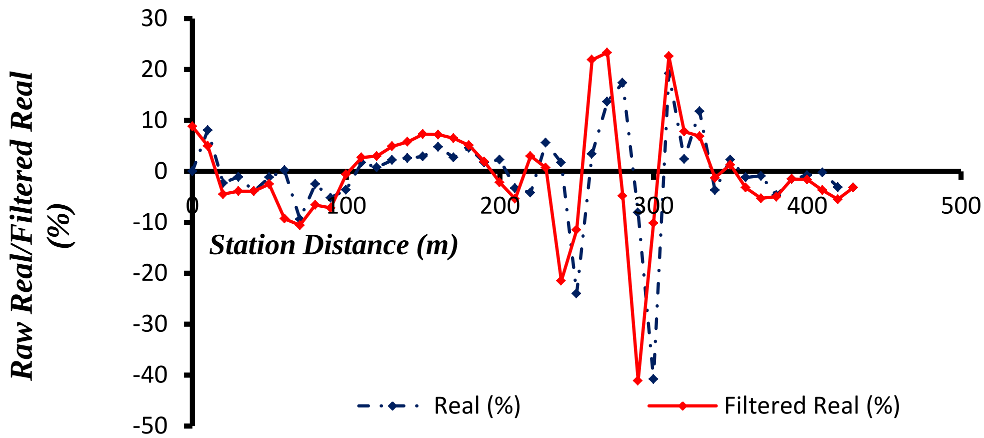
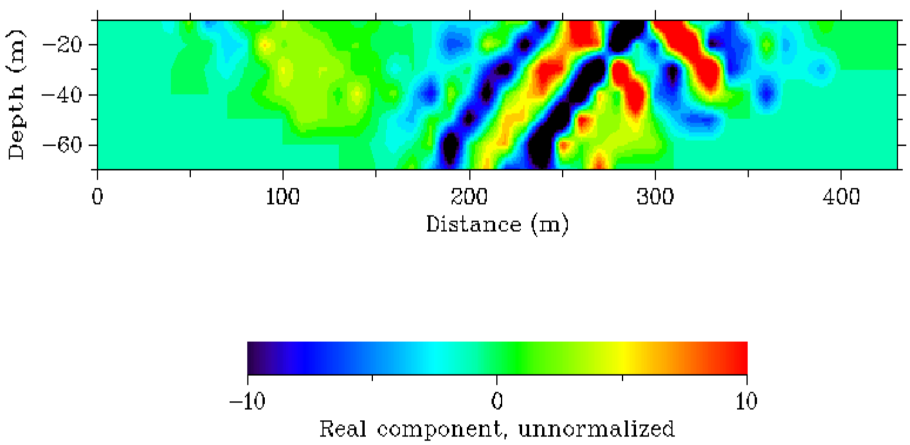


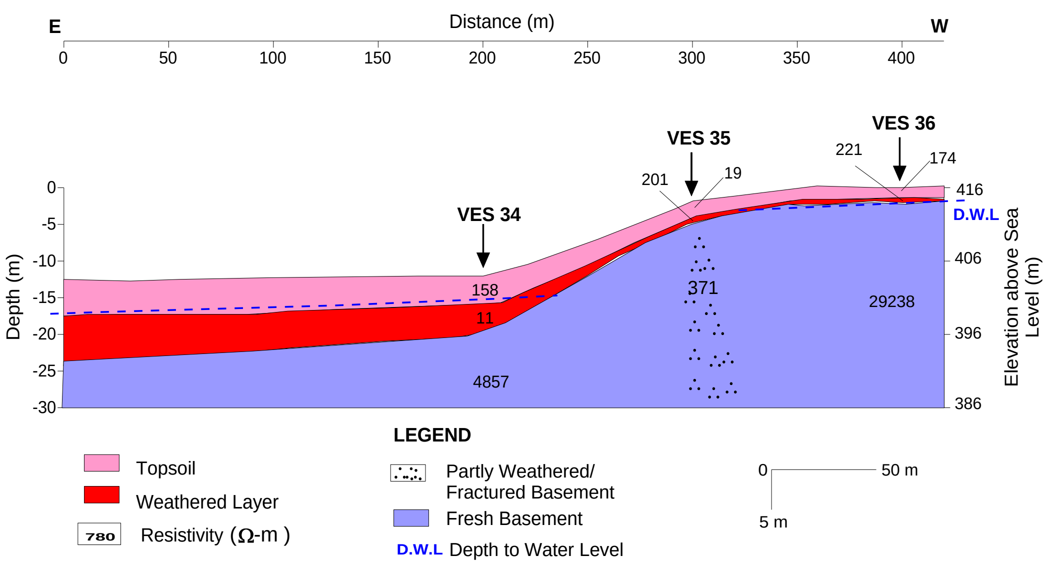
Figure 4: (a) VLF-EM profile (b) VLF-EM Model (c) Geoelectric section along Traverse 1 (Oka Akoko)



(a)

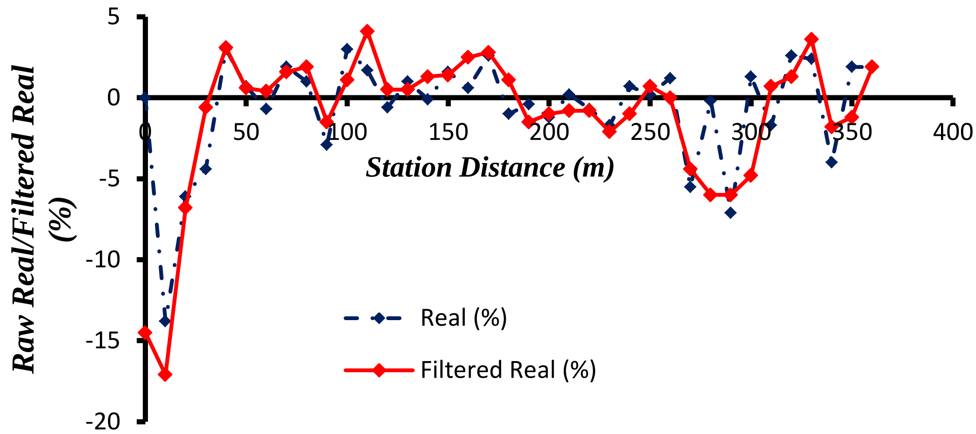


(b)

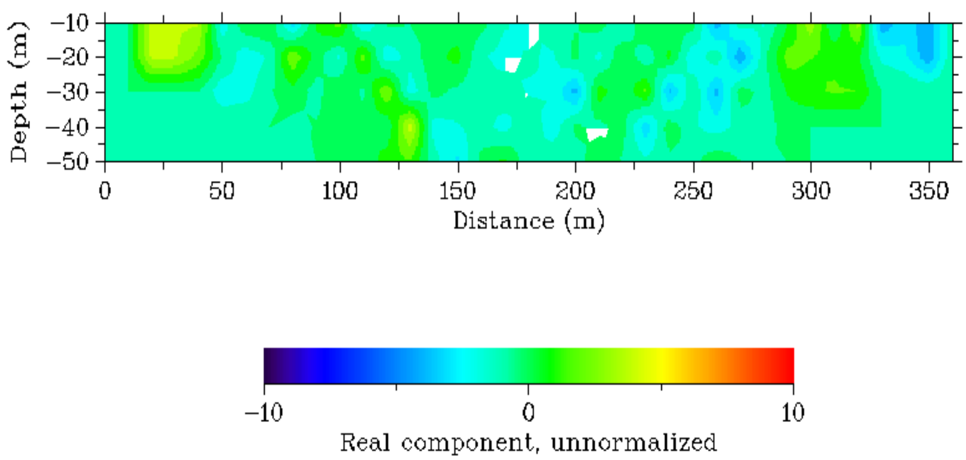


(c)

Figure 5: (a) VLF-EM profile (b) VLF-EM Model (c) Geoelectric section along Traverse 2 (Ikare Akoko)



(a)



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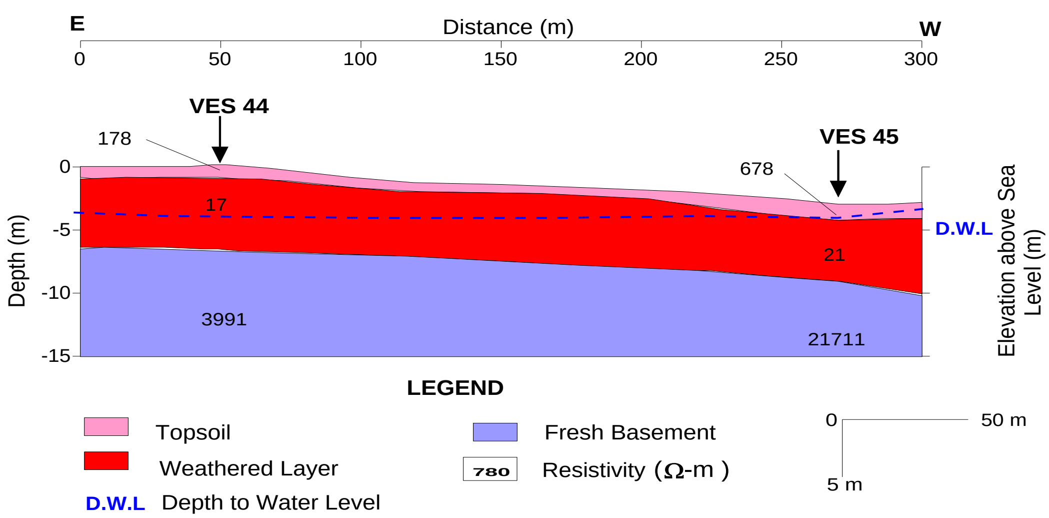

(c)

Figure 6: (a) VLF-EM profile (b) VLF-EM Model (c) Geoelectric section along Traverse 3 (Isua Akoko)

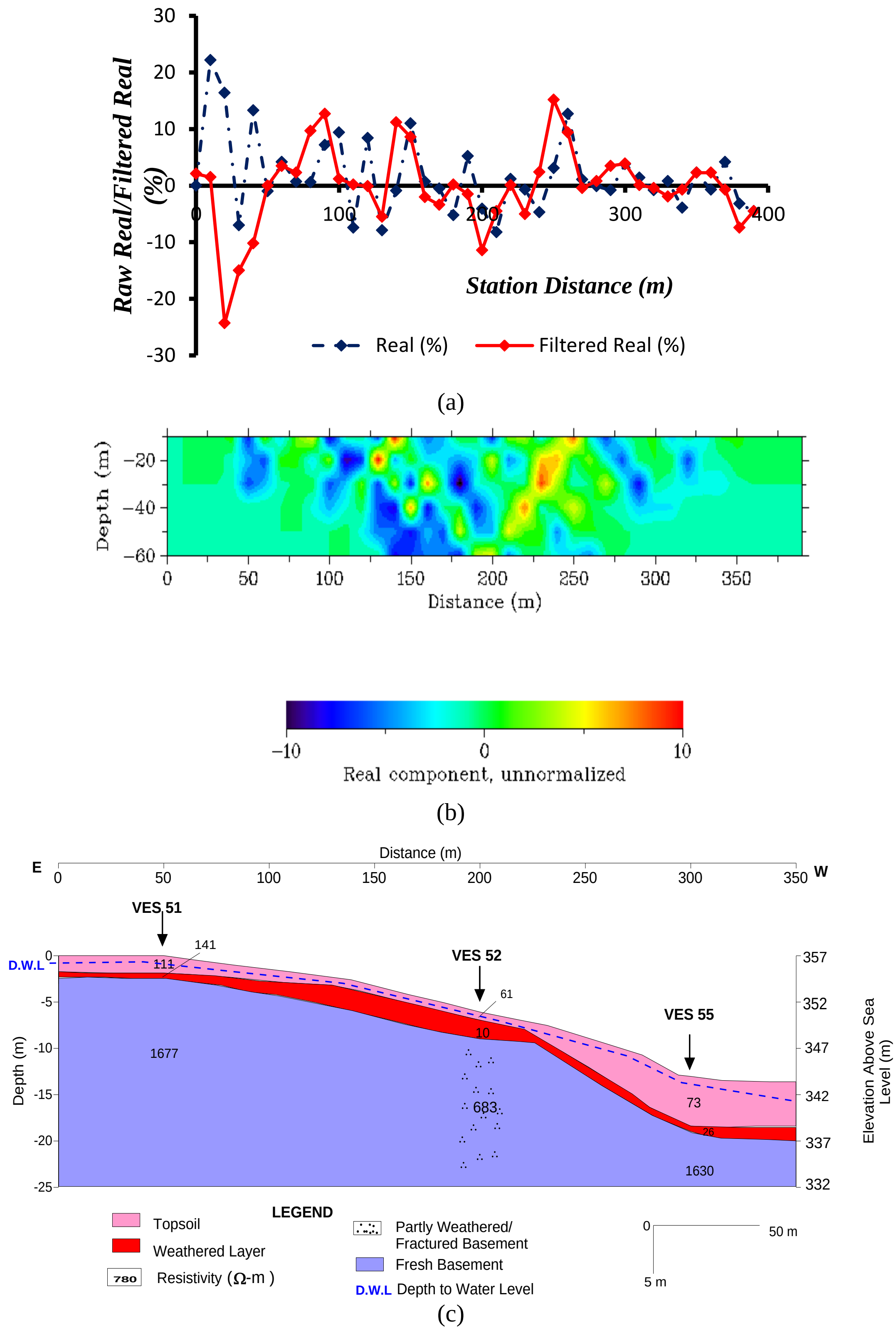

Figure 7: (a) VLF-EM profile (b) VLF-EM Model (c) Geoelectric section along Traverse 4 (Oke Agbe)

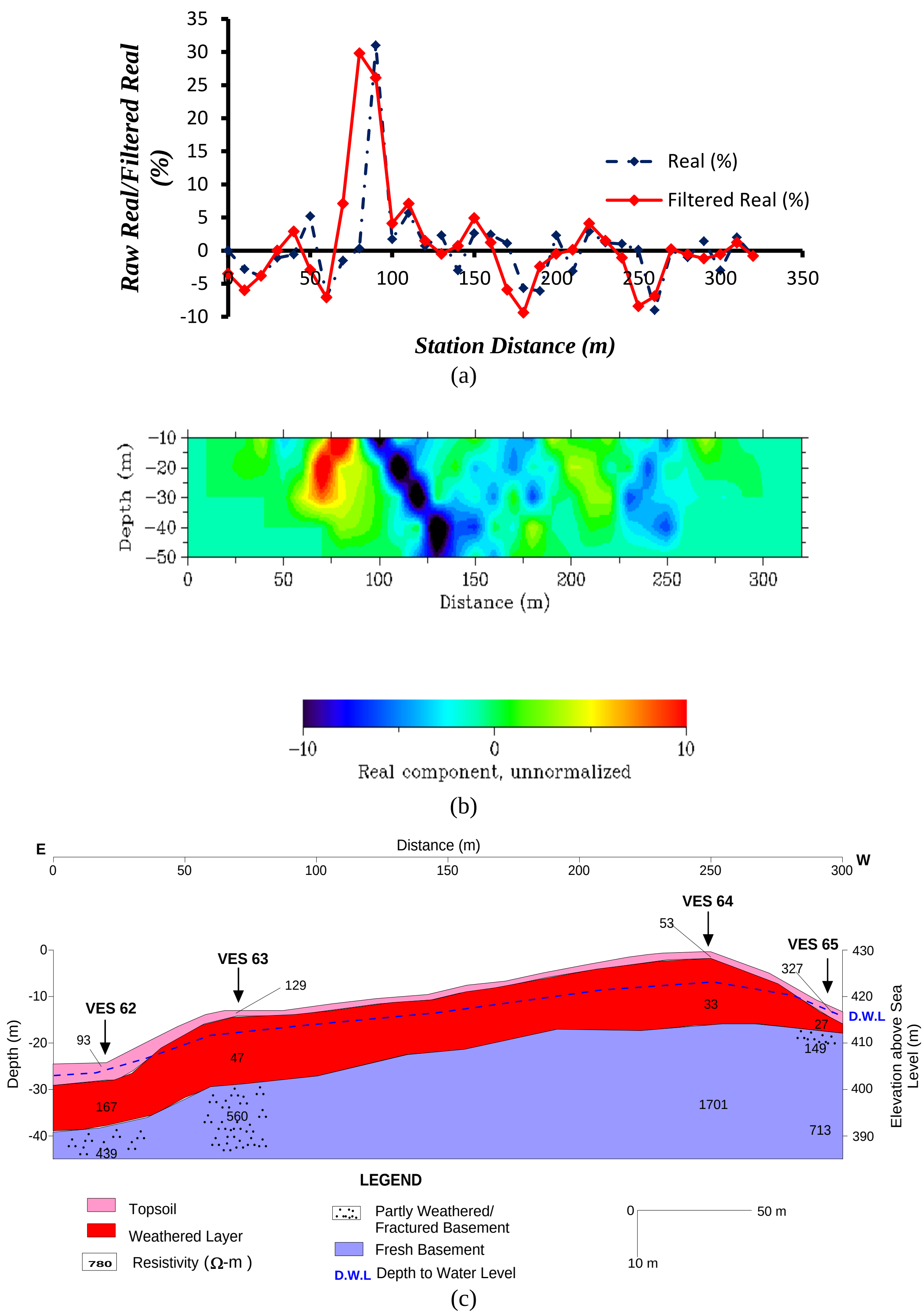

Figure 8: (a) VLF-EM profile (b) VLF-EM Model (c) Geoelectric section along Traverse 5 (Akungba Akoko)

At Oke Agbe which is represented by Traverse 4 (Figure 7) shows a slopy ground disposition. Most of the weathered and eroded soil material are deposited at the western part. This makes the combined topsoil and weathered layer greater than 10 m than what is obtainable at the hilly eastern part. Therefore the major water bearing units along this traverse are the fractured basement under VES 52 and the overburden under VES 55. The VLF-EM profiles and model show some level of heterogeneity along this traverse. A slightly dipping linear feature with its top at distance 250 m coincided/correlate the fracture zone delineated under VES 52. The static water level is less than 3 m.

Along traverse 5, a strong conductive water filled geological formation on the VLF-EM profile and model correlate with the fracture basement on the geoelectric section with resistivity range betweeen 400 – 600 Ω-m with thickness greater than 15 m (Figure 8). VES 62 and VES 63 show good groundwater prospect by the combined weathered layer and fracture basement, which is the best groundwater geological configuration, as the fracture zone would help in recharging the weathered layer aquifer. However, along the western part, the weathered layer with resistivity less than 50 Ω-m and thickness of about 20 m is the only realistic water bearing unit at the western part.

In crystalline basement terrains, aquifers/water bearing units may occur within the overburden and/or the fractured bedrock. The thickness, the lateral extent and the resistivity parameters of any of these aquifer units are important groundwater evaluation parameters in the area. The map of the overburden in Figure 9 shows that Akoko area is generally made up of thin overburden thickness except at Irun, Ogbagi, Arigidi, and Oke Agbe that show moderate overburden thickness (10 m – 20 m) and the combined weathered layer and fractured basement constitute the aquifer units in these areas.

The results of the borehole sections generated through the recording of the cuttings ejected during drilling are presented in Figure 10. The drilling points were chosen after a thorough geophysical survey. Four major geological units are delineated, which comprises sandy clay, clay sand, laterite, sand, and basement rock. However the borehole sections agree very well with the geoelectric sections. From the section the uppermost 5 m is made up of clay sand, sandy clay, and laterite (in some cases hardpan). The groundwater levels in Akoko areas are generally less than 10 m. The overburden thickness varies from 20 m – 30 m, especially at OkeAgbe and Ikeramu. The weathered layer composed of clay-sand and sandy clay.

Figures 11- 13 represent Line Graph of the Static Water Level sampled from 138 Wells, Bar-chat of the Static Water Level/Vadose Zone Thickness Frequency Distribution, and Static Water Level/Vadose Zone Thickness Map for the study area respectively. The line graph of the static water level measured in the study area ranges from 0.75 m – 16 m, with a modal range of 1.1 – 3.0 m as they constitute for about 78 % of the area. This generally shows that the static water level is shallow across the study area, thus suggesting that the surficial aquifers/water bearing units are highly vulnerable to anthropogenetic/surface activities which are the major sources of groundwater contamination [31-32]. However well No. 80 – 100 representing Oke Agbe, Arigidi, Ogbagi, Irun, and part of Ikare are characteized by moderately deep water levels (greater than 5 m) around the north central part. Although the thickness of the vadose zone is an important consideration in vulnerability assessment [33-34], the composition of the soil media and the lithology/physical properties of materials capping the vadose zone also constitute important parameters in vulnerability assessment [35]. Clay or silt, characterized by low resistivity (1 – 100 Ω-m) and very low permeability, and impervious or semi-impervious materials (laterite and lateritic sand), characterized by high resistivity values (>400 Ω-m) constitute protective layers where they cap vadose zones. They are known to effectively slow down contaminants percolation in the vadose zone, thus allowing time for natural degradation. Permeable materials like sand and gravel readily allow access of contaminants. Therefore from the geoelectric sections the topsoil (which cap the vadose zone) resistivity ranges from 50 – 1300 Ω-m composed of clay, sandy clay, clay sand, lateritic clay/sand, laterite, and sand. The most frequently occurring resistivity class is in the range of 50 – 200 Ω-m diagnostic of clay/silt, sandy clay impervious material, can provide protection to a reasonable extent, but still limited due to its thickness across the area.

4. CONCLUSION

Findings show that the major water bearing units/aquifer in the area are the weathered layer (clayey in nature) and fractured basement as delinated on the geoelectric sections, borehole sections, and very low frequency electromagnetic profiles/2-D model. The combination of these aquifer units are common in Ikare and Akungba parts of the study area. The visible depth of groundwater exploitation in the area is between 10 – 40 m. The static water level is generally less than 5 m. The map of the overburden shows that Akoko area is generally made up of thin overburden thickness except Irun, Ogbagi, Arigidi, and Oke Agbe that show moderate overburden thickness (10 m – 20 m). The line graph of the static water level measured in the study area ranges from 0.75 m – 16 m, with a modal range of 1.1 – 3.0 m as they constitute for about 78 % of the area. This generally shows that the static water level is shallow across the study area, thus suggesting that the surficial aquifers/water bearing units are highly vulnerable to anthropogenetic/surface activities which are the major sources of groundwater contamination. Clay or silt, characterized by low resistivity (1 – 100 Ω-m) and very low permeability, and impervious or semi-impervious topsoil materials (laterite and lateritic sand), characterized by high resistivity values (>400 Ω-m) constitute the protective layers where they cap vadose zones in the area. The most frequently occurring topsoil resistivity class is in the range of 50 – 200 Ω-m diagnostic of clay/silt, sandy clay impervious material, can provide protection to a reasonable extent, but still limited due to its thin thickness across the area.

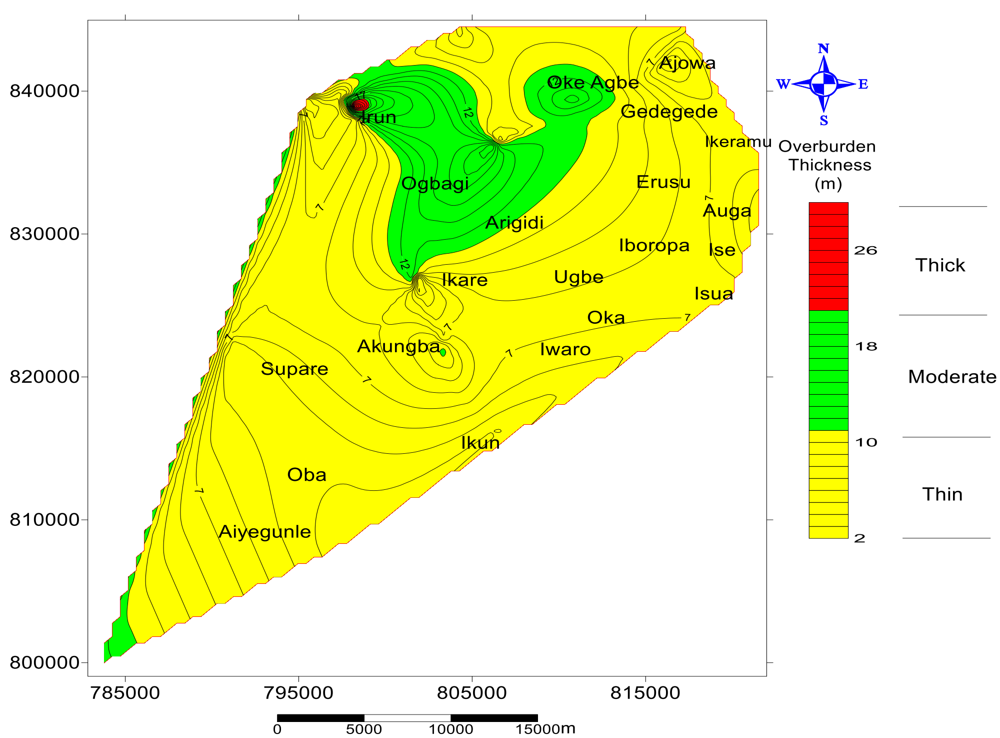

Figure 9: Overburden Thickness Map of the Study Area

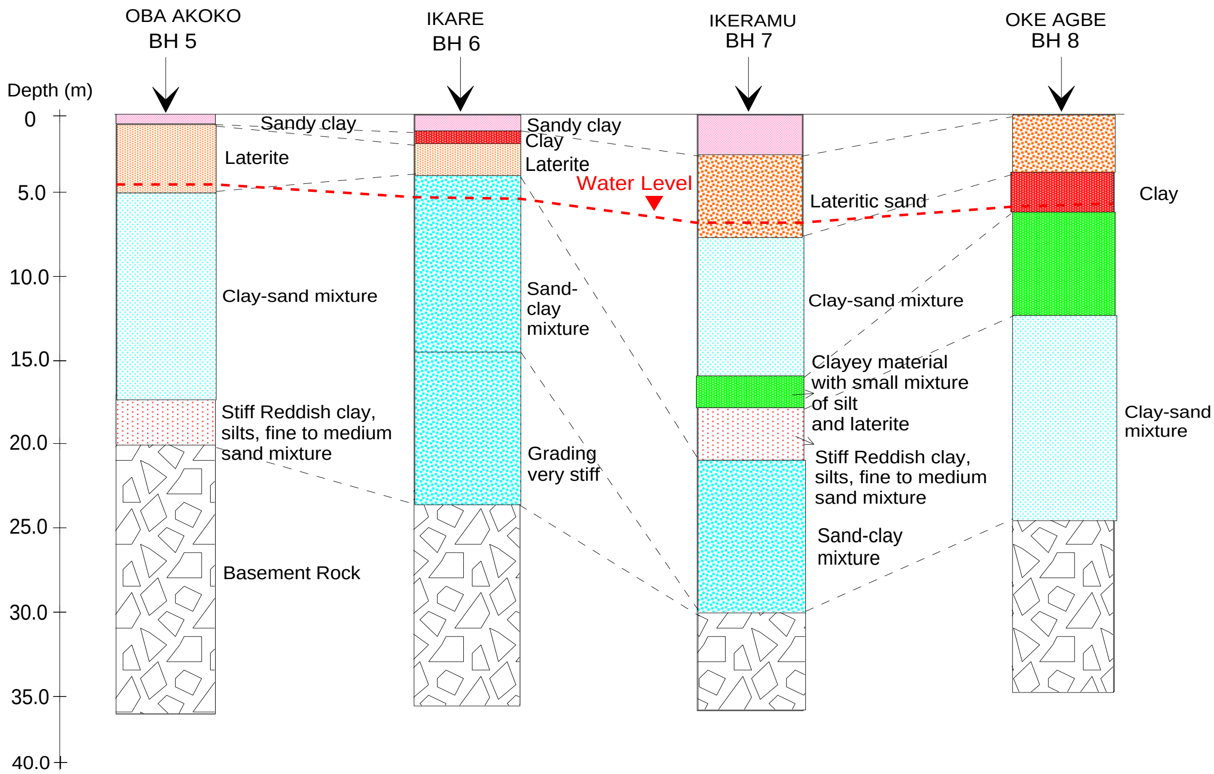

Figure 10: Borehole Sections obtained from 4-Drilled Boreholes

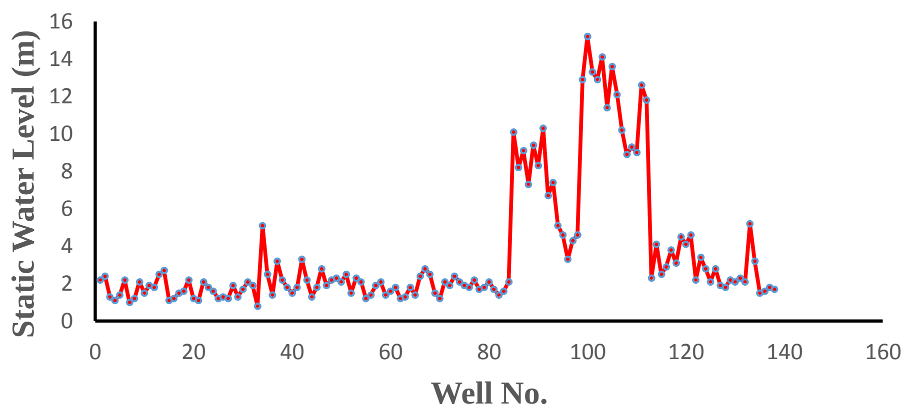

Figure 11: Line Graph of the Static Water Level sampled from 138 Wells

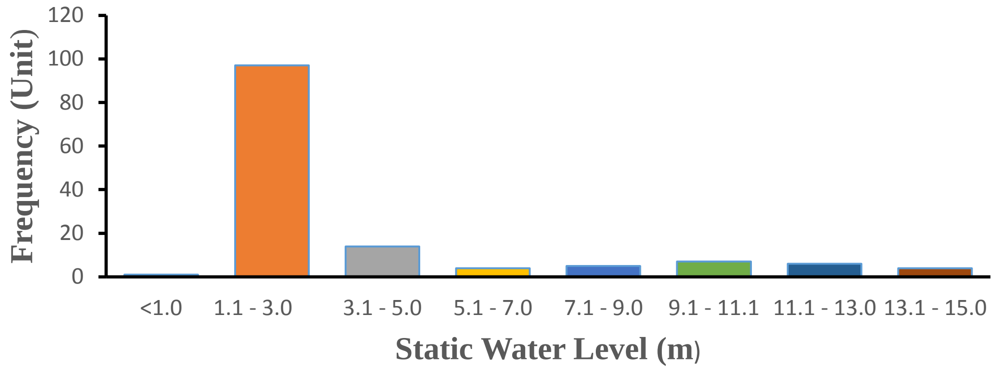

Figure 12: Bar-chat of the Static Water Level/Vadose Zone Thickness Frequency Distribution

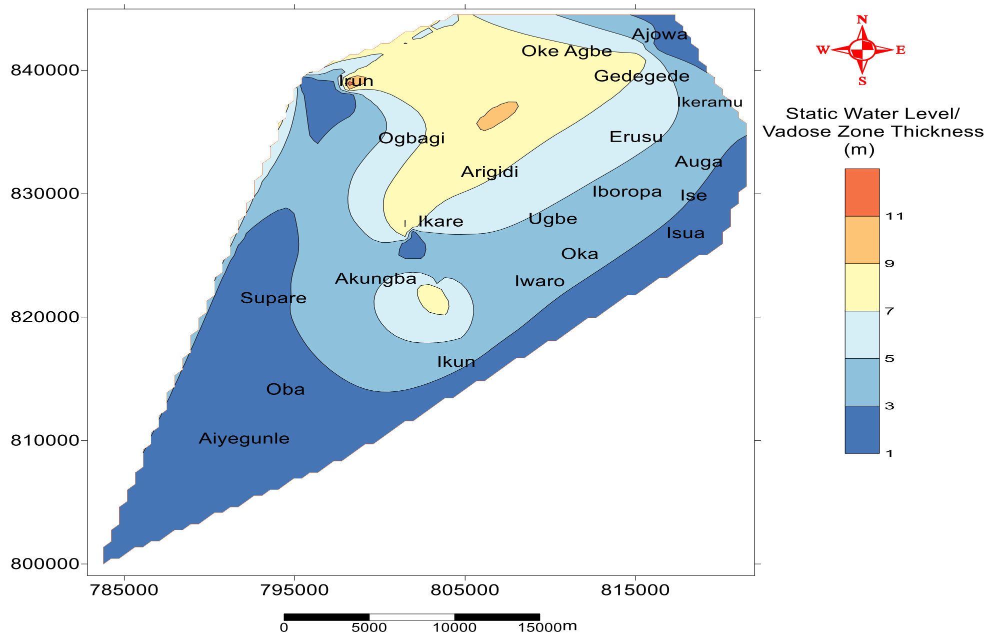

Figure 13: Static Water Level/Vadose Zone Thickness Map for Akoko Area

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