Communication in Physical Sciences, 2024, 11(1): 136-148

Electrical Resistivity Tomography Investigation of Groundwater Contamination Pathway at Ahmadu Bello University Sewage Treatment Site

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Received: 18 October 2023/Accepted: 20 March 2024 /Published: 29 March 2024

Abstract: *The Two-dimensional electrical resistivity survey using Schlumberger array at 5m electrode spacing was carried out along three profiles at the Ahmadu Bello University sewage treatment site. The study aims to investigate the possible fracture and permeable zones that serve as the pathways for groundwater contamination. The ABEM SAS4000 terrameter was used in data collection. The field data obtained has been analyzed using RES2DIV inversion software which gives an automatic interpretation of apparent resistivity. The geologic sequence beneath the study area is composed of topsoil, weathered basement and fracture basement layers. The resistivity value of the first layers ranges from 15Ωm to 58Ωm, 12Ωm to 40Ωm and 9Ωm to 14Ωm. The low resistivity variations in the topsoil identify the presence of contaminated plume zones in the layer. However, the fracture basement underlying the weathered basement shows lateral variation in the basement resistivity. The result shows that the contaminated plume zones has the tendency to contaminate the groundwater.*

Keywords: *Contamination, Sewage, Groundwater, Topsoil and Fracture*

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1.0 Introduction

Sewage is water-carried wastes, in either solution or suspension that flow away from a community. It is also known as wastewater flows or used water supply of the community. It is more than 99.9% pure water characterized by its volume or rate of flow, its physical condition, its chemical constituents, and the bacteriological organisms that it contains (Asuerimen, *et al.*, 2012). Depending on their origin, wastewater can be classified as sanitary, commercial, industrial, or surface runoff. The spent water from residences and institutions, carrying body wastes, washing water, food preparation wastes, laundry wastes, and other waste products of normal living, are classed as domestic or sanitary sewage (Asuerimen, *et al.*, 2012). Liquid-carried wastes from stores and service establishments serving the immediate community, termed commercial wastes, are included in the sanitary or domestic sewage category if their characteristics are similar to household flows (Asuerimen, *et al*., 2012).

Investigating the level of groundwater contamination has become increasingly important because access to clean water is a human right and a basic requirement for economic development. (Reinhard, 2006). The importance of groundwater as a valuable source of potable potable water cannot be over-emphasized. Groundwater forms the most important natural resource of any region and compliments surface sources in the provision of portable water for domestic and industrial applications. (Nasir, *et al.*, 2010). Detecting Municipal Solid Waste Leachate Plumes through Electrical Resistivity Survey and Physicochemical Analysis of Groundwater Samples. (Nasir, *et al*., 2010)

Therefore, investigating the level of groundwater contamination becomes necessary because of the effect of the toxicity to human life. Waterborne diseases occur worldwide causing over 4% of all deaths and 5% of health loss to disability (World Health Organization Global Water Supply and Sanitation Assessment, 2000). During the peak of the rainy season, sewage treatment sites are covered by flood water and this contributes to the formation of leachate (water that has percolated through waste and contains various ions in solution). It is this contaminated liquid that forms a “plume” that moves outwards and downwards into the surrounding and underlying aquifers (Carpenter *et al.*, 2012).

Groundwater is the critical underlying resource for human survival and economic development in extensive drought-prone areas of south-eastern, eastern and western Africa, especially where the average rainfall is less than 1000 mm/a (Telford *et al.*, 1990). Rainfall tends to be variable from year to year, which creates difficulties in managing the quantity and quality of groundwater resources, and this variability is likely to increase with the growing impact of climate change (Fang, et, al. 2005). There are also several trans-boundary aquifers which require strategic management (Prem, *et al.*, 1997). The proximity of groundwater sources, and the related reduced infrastructure costs, make urban groundwater an ideal resource to target for development (Telford *et al.*, 1990). However, the susceptibility of groundwater to contamination in urban settings has to date received little attention compared to other regions globally (World Health Organization Global Water Supply and Sanitation Assessment, 2000).

The geophysical survey method has been found very suitable for this kind of environmental study. This is because generally ionic concentration of leachate is much higher than that of groundwater and so when the leachate enters the aquifer, it’s results in a large contrast in electrical properties and the method will identify these zones as an anomaly which enable the leachate plume to be detected (Nasir, *et al.*, 2010).

Electrical resistivity tomography (ERT) is now a well-established tool for environmental and engineering site investigation, and is routinely applied to the detection of pollution the characterization of geologic and engineering structures and hydro-geologic studies (Grant *et al.*, 2007).

1.1 The study location

The area under study is located within the Samaru main campus of Ahmadu Bello University Zaria it is approximately bounded by latitude 11º10′12″N and 11º10′46″N and longitude 07º36′55″E and 07º44′12″E. and consists of a septic tank and six ponds that are about 2 m deep, unlined, separated and protected on all sides by earthen dikes. The site is underlain by Precambrian older granite that has been weathered to laterite. The lateritic outcrop exposed in a section by erosion is about two meters thick and becomes less compacted with depth. The site consists of numerous pits or ponds which are divided by functions mainly into 'Facultative lagoons' and 'Maturation lagoons forming a waste stabilization pond system (WSP). These ponds are connected by a structure of concrete pipes. Other structures on site include a filtration chamber and manholes which grant access to solve blockage in pipes. These ponds are expected to store the sewage for a period when natural biological processes of treatment might have occurred followed by the final application of chlorine to destroy pathogenic organisms before stabilized water is discharged as effluent down the slope, some few metres, into the downstream, which is connecting the spillway of the Ahmadu Bello University dam.

1.2 The geology of the study area

The study area is part of the Nigeria Basement Complex which according to McCurry (1973), is composed of two distinct rock types (Fig. 2). The Basement gneiss which outcrops mostly along stream channels/valleys in deeply weathered forms. Examples are found along Kubanni Valley. It is medium to coarse-grained and moderately to weakly foliated (Wright and McCurry, 1970). • The Older granite has two textural varieties, the porphyritic variety and the evenly-grained medium to coarse-grained type. It is weakly foliated and mostly occurs as inselbergs and low whalebacks. Its exposure is mostly cross-cutted by pegmatites and aplites. The rocks typically found within the basement complex of the northwest Nigeria include gneisses, migmatites, metasediments and some intercalation of amphibolite. The basement complexes accommodate the metasediments and are made up of gneisses. Exposures are scanty and highly weathered. The rock types are biotite, gneisses, granite gneisses and in parts with subordinate migmatites. The contact between the gneisses and metasediments is gradational (McCurry, 1970).

Granitic intrusions form a suite of batholiths (the Zaria Batholiths), part of which outcrops as the *Kufena Hill*.

Fig. 1: Location of the study (Source: Google satellite image, 2009)

The gneisses are found as small belts within the granite intrusions and are also found east and west of the batholiths. The biotite gneiss extends westwards to form a gradational boundary with the schist belt. The gneiss continues eastwards to some extent and is occasionally broken up by the Older Granite (McCurry, 1970). The Older Granite intrusion is supposed to have been formed at the bottom of a fold mountain belt (Wright and McCurry, 1970).

The thrusting imposed on the basement complex during the Pan African Orogeny movement is believed to have brought together rocks of different ages with different structural and metamorphic styles (Grant, 1969). The metasediment probably belongs to the sedimentary and granite facies that were formed in a geosynclinal trough which had earlier developed at the end of the Pan-African Orogeny (Tokarski, 1972). During the Pan African Orogeny, the sediments and igneous material, together with the former metamorphosed basement rocks behaved as one tectonic unit. Some of these metamorphosed rocks became assimilated into the granite intrusions that accompanied the last orogeny (Grant, 1969).

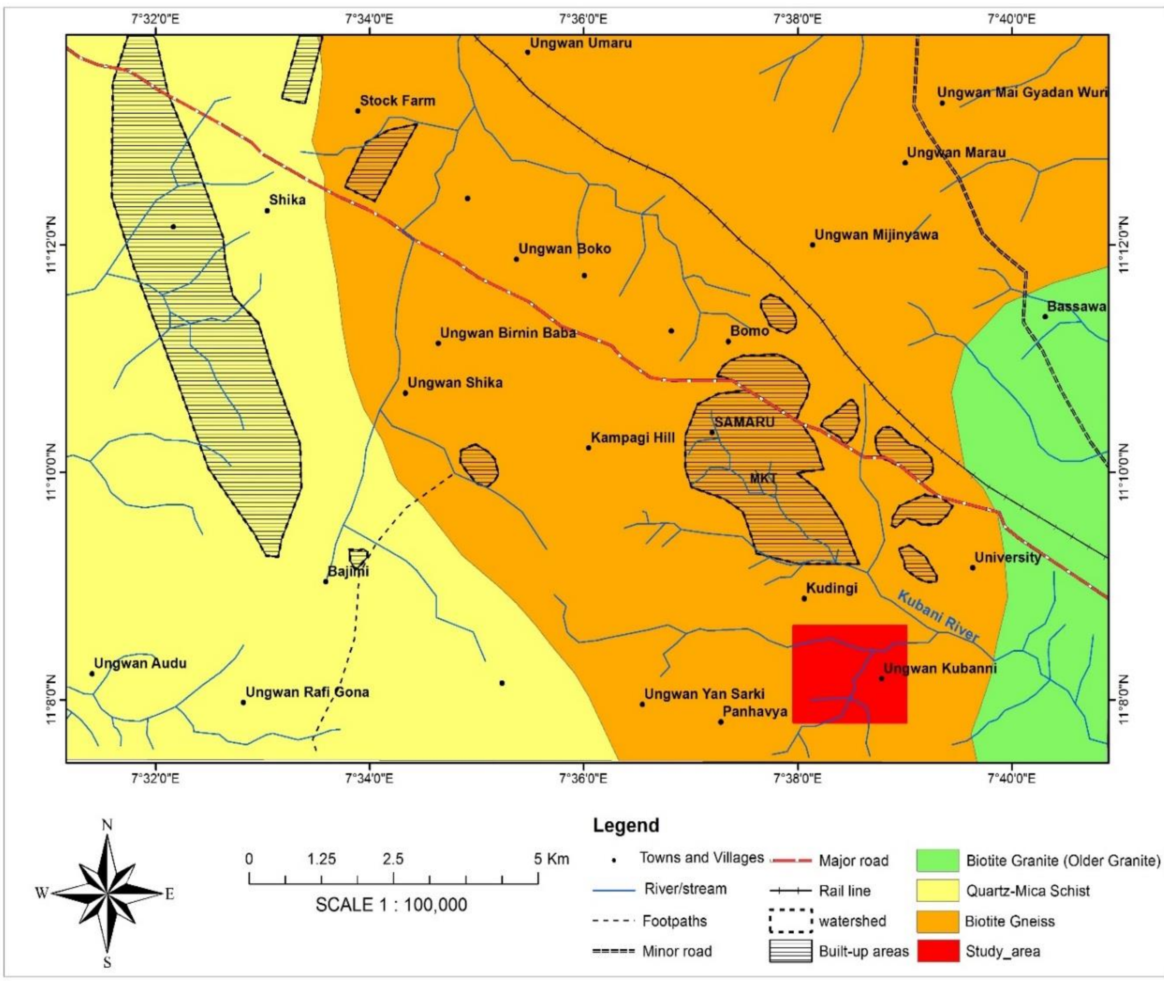


Fig. 2: Geological map of the Kubanni Basin (Adapted from McCurry, 1970)

1.3 Principle of the resistivity method

In the electrical resistivity method, anomalies of the subsurface conduction depend on the electrical conductivity contrast between the conductor and the host rock. Details on the conductivity (electrical property) of earth material can be found in Telford *et al* (1976), and Keller and Frischnecht (1977). There are many methods of observing these anomalies in electrical surveying some of these materials make use of naturally occurring fields within the earth while others require the introduction of artificially generated sources into the ground. The resistivity method uses an artificial source field. Artificially generated electric current are driven into the ground any variation in the subsurface resistivity (conductivity) alters the distribution of the electric potential the resulting potential differences are measured at the surface any variation observed from the pattern of potential differences expected from uniform earth are deviation from the uniform earth these deviations represent the geological target of resistivity exploration.

Generally, four electrode arrays are used at the surface, one pair for introducing current into the earth and the potential difference established in the earth by the current is measured in the vicinity of current flow with the second pair.

A great number of electrode arrangements have been used for resistivity exploration (Whitely 1973). The most used electrode arrangement is Warner and Schlumberger, three-point speed, lee-partition spread and dipole-dipole spread method (Telford *et al* 1976). Any of these electrode arrangements may be used to study the lateral variation of resistivity or variation in resistivity with depth (Keller and Frischnecht, 1977). In studying lateral variations such as those associated with dyke-like structures of faults a fixed separation is maintained between the various electrodes and the array is moved as a whole along the transverse line this is called horizontal profiling or trenching. In studying the variation of resistivity with depth as in case of layered medium, the center of electrodes spread is often kept fixed while the electrode spacing is changed. This is called the vertical electrical sounding (VES) the electrical resistivity method employed in this work is the VES a brief description of the theoretical basis of the method is highlighted in sub-section 1.4

1.4 Theory of resistivity method

The simplest approach to the theoretical study of the earth resistivity method is to consider first the case of a completely homogenous isotropic earth. The equation which gives a potential due to a single point source of current at the surface is developed according to Keller and Frischknecht (1977) from two basic considerations.

Ohms law

$$E = \rho j \qquad (1)$$

Where E= potential gradient, J= current density ρ= resistivity of the medium and Divergence condition

$$\nabla . \mathrm{j}=0 \qquad (2)$$

This states that all current going into a chunk of material must leave the other side. Unless there is a source or sink for current within the chunk. The divergence of the current density vector must be zero at every place but at the current electrode source (Keller and Frischknecht 1977).

Combining equations (1) and (2) we obtain the Laplace's equation.

$$j = \sigma E \qquad (3)$$

But $\sigma = {}^{1}/_{\rho}$ indicating that

$$j = {}^{1}/_{\rho}\, E \qquad (4)$$

Where j=current density, σ=conductivity, ρ =resistivity and E=electric field.

The component of an electric field in any direction is the negative of the value of change of the potential in that direction

$$E = -\nabla v \qquad (5)$$

Put equation 2.5 into 2.4

$$j = -\sigma \nabla v \qquad (6)$$

$$j = -{}^{1}/_{\rho}\, \nabla v.$$

The divergence of current density

$$\nabla . \mathrm{j}=0 \qquad (7)$$

Put equation (2.6) into (2.5)

$$\nabla .\mathrm{j} = \nabla\, (\sigma \nabla v)$$

$$(\nabla v)\nabla \sigma + \sigma \nabla^2 v = 0 \qquad (8)$$

Since σ is constant the first term varnishes, (Keller and Frischknecht 1977).

$$\sigma \nabla^2 v = {}^{1}/_{\rho} \nabla^2 v = 0 \qquad (9)$$

In spherical polar coordinates, the Laplace equation can be expressed as $\sin^2 \theta$

$$\nabla^2 V = {}^{1}/_{\mathrm{r}^{2}} \frac{\partial}{\partial r}(\mathrm{r}^2 \frac{\partial v}{\partial r}) + \frac{1}{\mathrm{r}^{2} \sin\theta} \frac{\partial}{\partial \theta}(\sin\theta \frac{\partial v}{\partial \theta}) + \frac{1}{\mathrm{r}^{2} \sin^2\theta} \frac{\partial^2 v}{\partial \varphi^2} = 0 \qquad (10)$$

where θ = azimuthal polar coordinate, φ = azimuthal angle. For the single current electrode source placed at the surface, there is complete symmetry of current flow concerning θ and ϕ direction and the derivative for this direction are zero, (Keller and Frischknecht, 1977).

Thus

$\nabla^2 V = {}^1/_{r^2} \frac{\partial}{\partial r}(r^2\frac{\partial v}{\partial r})=0$ since $r \neq 0$

$$=\frac{\partial}{\partial r}(r^2\frac{\partial v}{\partial r})=0 \quad (11)$$

The equation can be integrated directly, thus

$$r^2\frac{\partial v}{\partial r} = C \quad (12)$$

$V=-\frac{C}{r} + D$

Where C and D are constant and r is the distance from the current electrode. V = 0 when $r \rightarrow \infty$ Then D = 0 and

$$V=-\frac{C}{r} \quad (13)$$

The current flows azimuthally through a hemisphere surface in the lower medium

$$I=2\pi r^2 j \quad (14)$$

$$j = -\frac{1}{\rho}\nabla V = -\frac{1}{\rho}\frac{\partial v}{\partial r} \quad (15)$$

Combining 13 and 14 we have, Keller and Frischknecht (1977).

$I = - -\frac{2\pi r^2}{\rho}\frac{\partial v}{\partial r}$ and $I = -\frac{2\pi}{\rho}r^2\frac{\partial v}{\partial r}$. However,

$r^2\frac{\partial v}{\partial r} = C$, $I = -\frac{2\pi}{\rho}C$. Therefore,

$$C = -\frac{I\rho}{2\pi} \quad (16)$$

Put (14) in (12)

$$V = \frac{I\rho}{2\pi r} \quad (17)$$

Equation 15 is the potential at distance r from a single current electrode placed at the surface, (Keller and Frischknecht 1977). The application of equation (15) to the general four electrode configuration is shown below.

(Fig 2) shows two electrode c_1 and c_2 placed at finite distance and two inner potential electrodes p_1 and p_2 can be shown as thus:

$$\Delta v = \frac{I\rho}{2\pi}\left\{\left[\frac{1}{r_1} - \frac{1}{r_2}\right] - \left[\frac{1}{r_3} - \frac{1}{r_4}\right]\right\} \quad (18)$$

From equation 14 above, all the quantities can be measured directly from the ground except the apparent resistivity, if we make apparent resistivity (ρ) the subject of the formula we have;

$$\rho = \frac{2\pi\Delta v}{I}\left\{\left[\frac{1}{r_1} - \frac{1}{r_2}\right] - \left[\frac{1}{r_3} - \frac{1}{r_4}\right]\right\}^{-1} \quad (19)$$

$$V_1 = \frac{I\rho}{2\pi}\left(\frac{1}{r1} - \frac{1}{r2}\right) \quad (20)$$

Since the current at the two current electrodes are equal and opposite in direction (one current electrode acts as source and the other sink)

Where B_1 is distance from P_1 to C_1

B_2 is the distance from C_2 to P_1

Similarly, the potential at p_2 due to C_1 and C_2 is

$V_2 = \frac{I\rho}{2\pi}\left(\frac{1}{r3} - \frac{1}{r4}\right)$

Where is the distance of C_1 from P_2

The potential difference between P_1 and P_2 is

$V_1 - V_2 = \frac{I\rho}{2\pi}\left(\left(\frac{1}{r1} - \frac{1}{r2}\right) - \left(\frac{1}{r3} - \frac{1}{r4}\right)\right) = \nabla V$

$\rho = \frac{2\pi}{\left(\left(\frac{1}{r1}-\frac{1}{r2}\right)-\left(\frac{1}{r3}-\frac{1}{r4}\right)\right)}\frac{\nabla V}{I}$

$$\rho = K\left(\frac{\nabla V}{I}\right) \quad (21)$$

$$\text{where} \quad k = \frac{2\pi}{\left(\left(\frac{1}{r1}-\frac{1}{r2}\right)-\left(\frac{1}{r3}-\frac{1}{r4}\right)\right)} \quad (22)$$

Equation (16) is an expression for an ideal case of an isotropic homogeneous uniform earth, (Keller and Frischknecht 1977). When the earth is uniform, resistivity calculated with (16) should be constant and independent of electrode spacing.

In real situations the earth is inhomogeneous (not uniform). Inhomogeneous earth, the resistivity will vary with the relative position of the electrodes. Any computed value of resistivity is then known as the apparent resistivity and will be as a function of the homogeneity equation (16) is the basic relation for calculating the apparent resistivity (ρ_a) of any electrode configuration and can be used to define ρ_a as (Keller and Frischknecht 1977).

$$\rho_a = K\left(\frac{\nabla V}{I}\right) \quad (23)$$

Where k is the geometric factor in both (16) and (18) and depends on the electrode configuration used for field measurement. For this study, the objective Schlumberger electrode configuration was used for field measurement. Schlumberger configuration is convenient to use in this field and the potential electrodes are not usually moved or when moved they are moved in a minimum number of times during a given sounding compared to frequent movement of other electrode configuration this configuration is therefore cost effective since it saves time and man power (Aboh, 2011).

2.0 Materials and Method

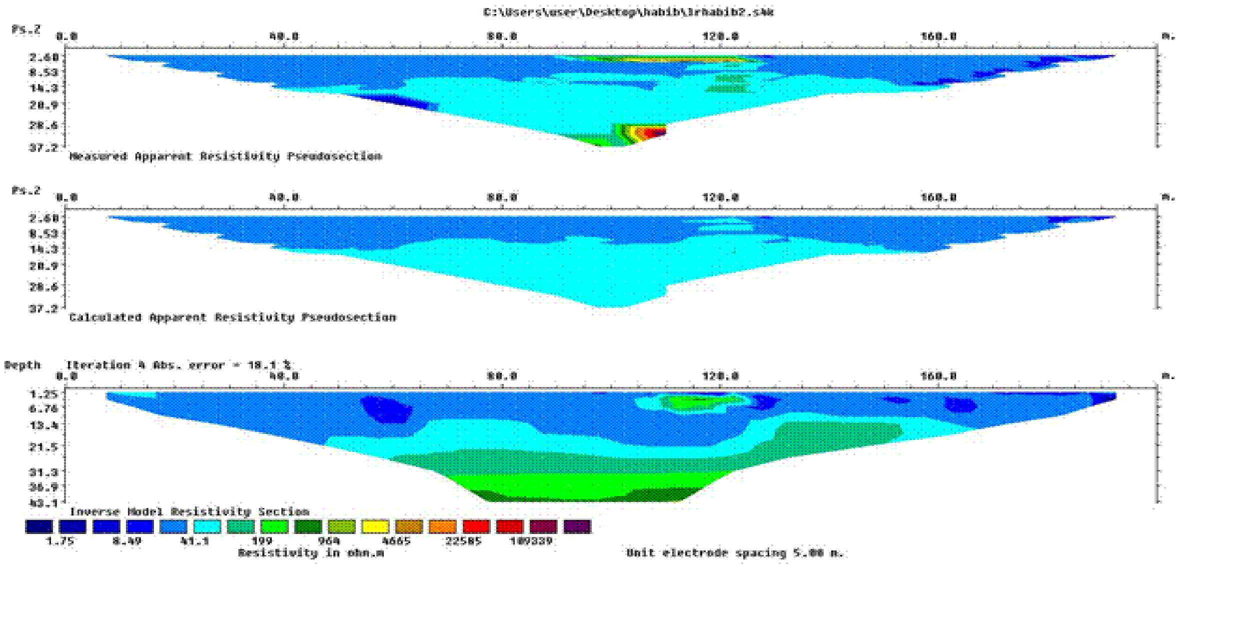
The 2D-Resistivity data were recorded on the Terrameter. The complete equipment of ABEM Lund Imaging system consists of SAS4000 Terrameter, electrode selector, ES464, 2 Lund cables, 5 meters spacing, 21 take-out with addresses 1-21 (cable no. 1) and 22-42 (cable no. 2), totaling 42 smart electrodes, 2 reels, 42 stainless steel electrodes and 42 jumpers. A detailed 2d-resistivity survey was carried out on each of the three profiles identified from the pre-field work study. The profiles were LundDam01, LundDam02 and LundDam03. Three of the profiles (LundDam01, LundDam02 and LundDam03) lie around the wastewater stabilization ponds and are positioned such that they fall on the footpath as much as possible.

3.0 Results and Discussion

The -pseudo-section plot obtained by contouring the apparent resistivity values is a convenient means to display the data. The pseudo section gives a very approximate picture of the true subsurface resistivity distribution. However, the pseudo section gives a distorted picture of the surface because the shapes of the contours depend on the type of array used as well as the true subsurface resistivity. The pseudo section is useful as a means to present the measurement of apparent resistivity values in a pictorial form and as an initial guide for further quantitative interpretation and also for picking out bad apparent resistivity. Such bad measurements usually stand out as points with unusually high or low values (Loke, 2004).

Figure 1 below shows the results obtained from the 2D resistivity array at 5m electrode spacing. The profile runs along the sewage site in the NW-SE direction. The first layer is the topsoil consisting of sandy, clay, silt and lateritic soil with a thickness of approximately 14m. The resistivity of the layer ranges from 15ohm-meters to 58ohm-meters. The area of the low resistivity within the layer is suspected to be contaminant plume zones with high conductance. The second layer below the top soil is the weathered basement layer with the thickness of approximately 15meters and resistivity range of approximately 58 to 260ohm-meters. The third layer is the intrusion of the fracture basement with the approximate thickness of 15 m at a distance of 110 m to approximate thickness of 15 m and a distance of 110meters to 140 m. The resistivity of the layer is approximately 268 ohm-meters.

Figure 2 below shows the results obtained from 2D resistivity array at 5 m electrode spacing. The profile runs along the Centre of the sewage lagoon in approximately NW-SE direction. The first is the topsoil with approximate a thickness of 18 m and a resistivity ranging from 12 to 40 ohm-meter. The areas within the layers with low resistivity are suspected to be contaminant plume zones with high conductance. The second layer is the weathered basement with approximate a thickness of 13 m and a resistivity which ranged from a 42 to 180 ohm-meters. The third layer is fracture basement layer with approximate a thickness of 13 m and a resistivity ranging from 190 to 900 ohm-meters.



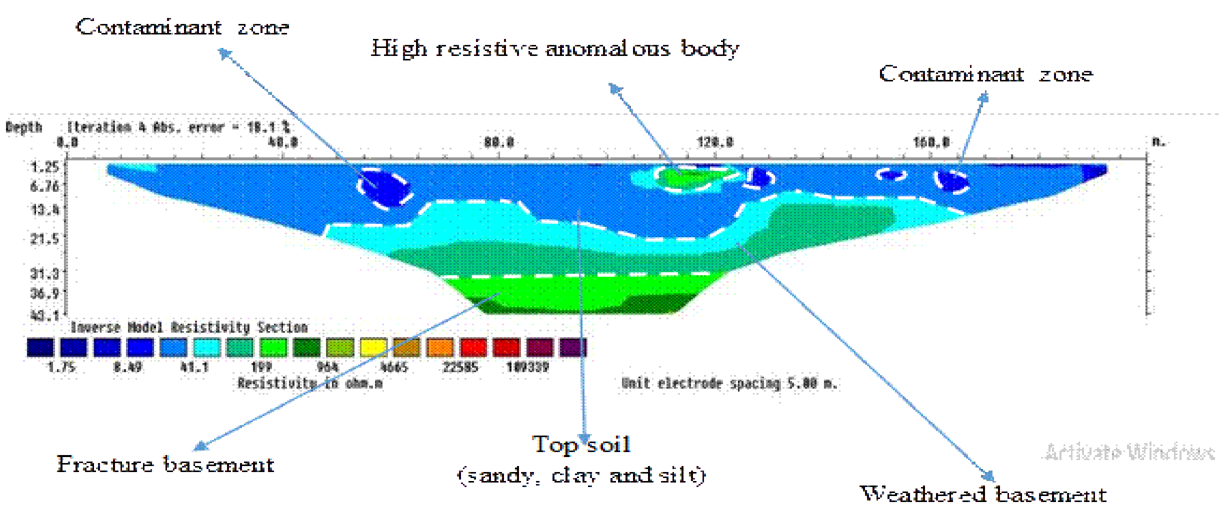


Fig. 1: Profile LunDam 02

Fig. 3 below shows the result obtained from 2D resistivity array at 5m electrode spacing the profile runs along the Centre of the sewage lagoon in approximately NW-SE direction. The first layer is the topsoil consisting of clay, sandy and silt with varied thicknesses of 1.25 to 19 m and resistivity which ranged from 9 to 14 ohm-meter. The areas of high resistivity are the anomalous body of low conductance. The resistivity of this layer shows the high conductance of the layer which may be contaminant zones and clay nature of the area. The second layer is the weathered basement layer with varied thicknesses of 1.25 to 28 meters and a resistivity ranging from 46 to 140 ohm-meter. The third layer is the fracture basement layer with a resistivity in the range of 156 to 540 ohm-meter. The resistivity of the result agreed with Abdullahi *et al.*, (2011), Samuel, *et al*., (2022), Ganiyu, *et al.*, (2015).

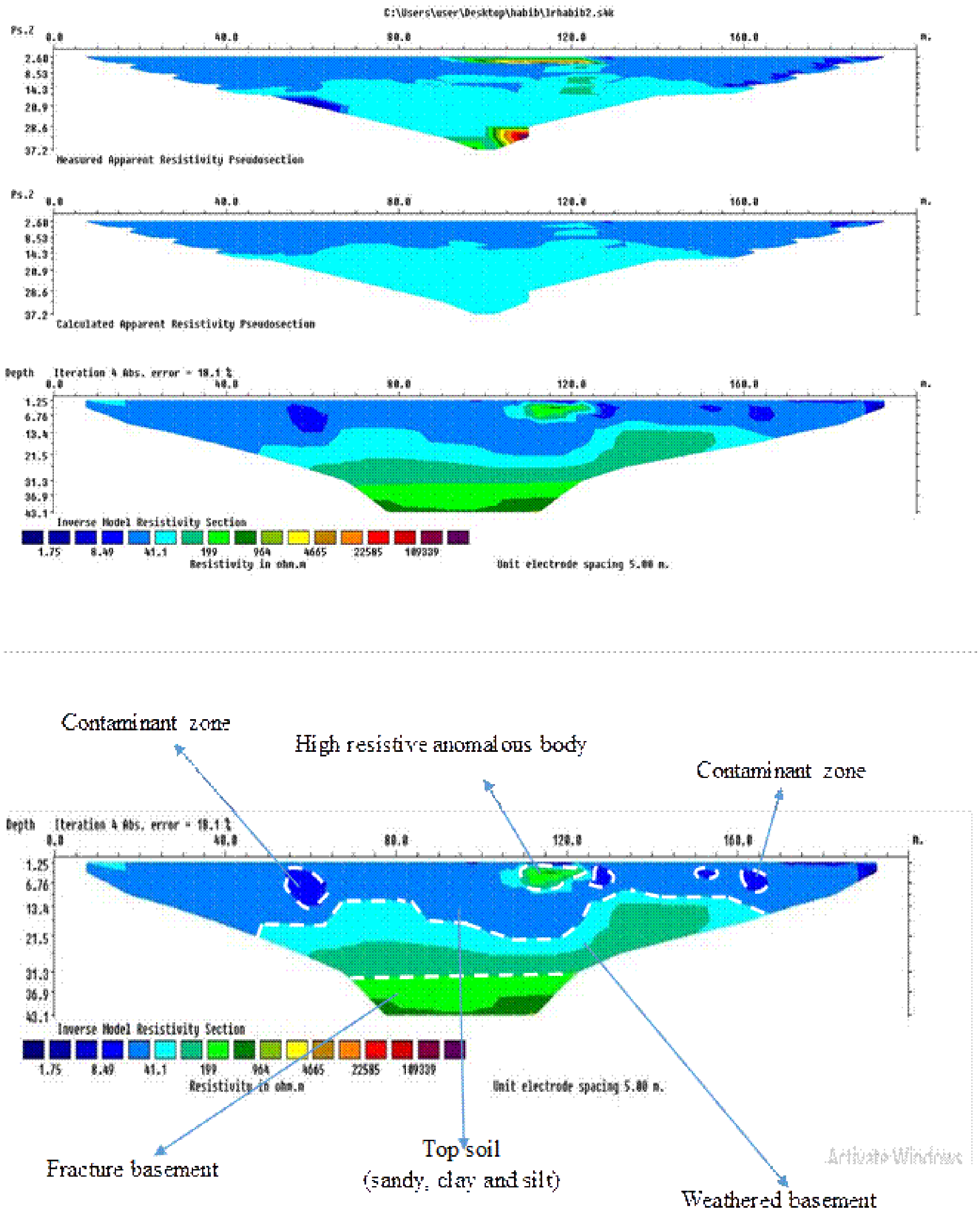


Fig. 2: Profile LunDam02

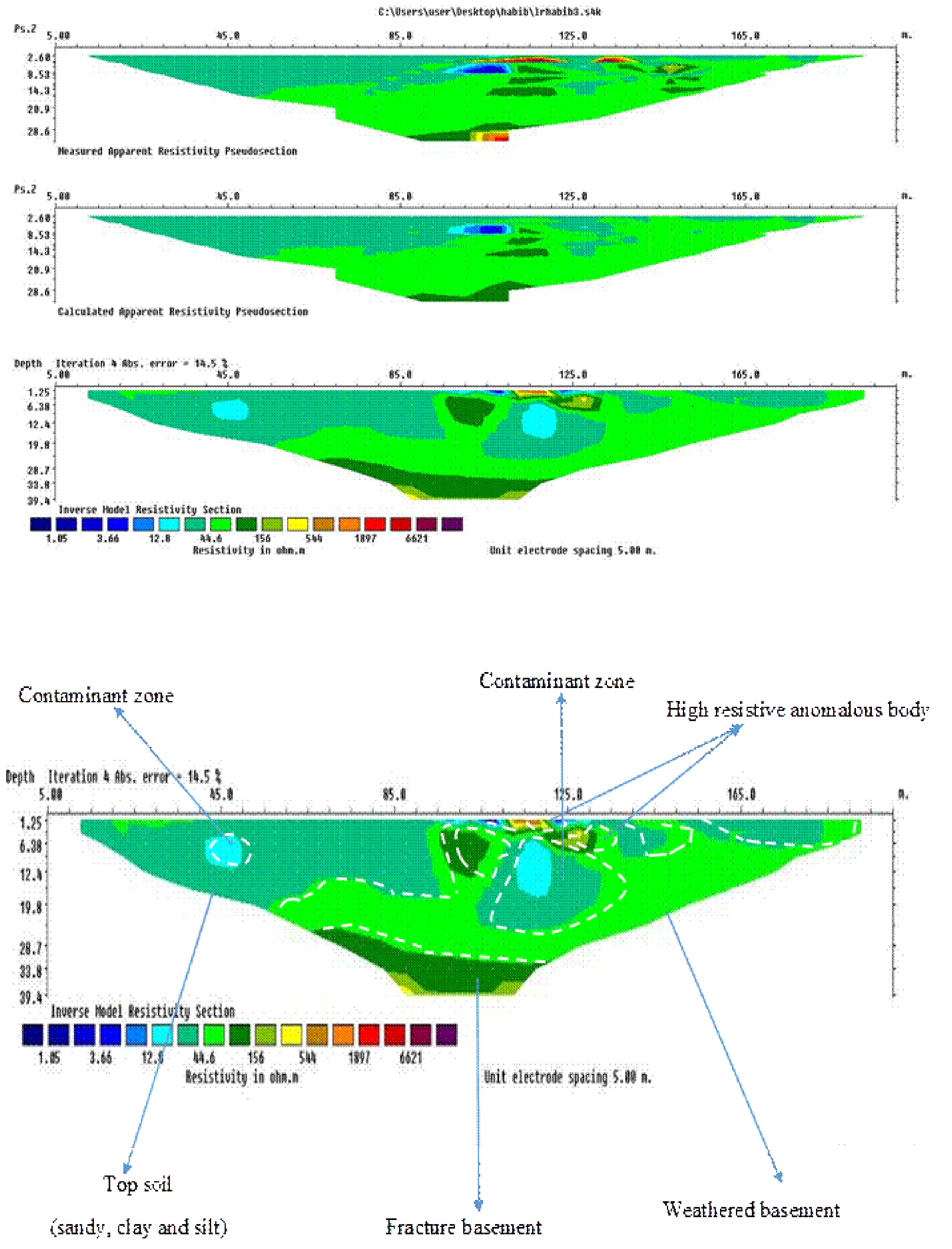


Fig. 3: Profile LunDam03

Fig. 3: Profile LunDa03

4.0 Conclusion

Two-dimensional electrical resistivity imaging was carried out to determine the path of contaminants plume zones and the pathway for the contamination transport. The subsurface resistivity of the layers indicates that the fractured basement is underlying the weathered basement. Thus the groundwater of the study area can be contaminated through the fracture. The low resistivity zones which are suspected to be high conductivity areas are the areas of the contaminant plumes. The fracture beneath the weathered basement can serve as the pathway for contamination transport. Thus, the groundwater in the study area is prone to be contaminated through the fractures.

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Compliance with Ethical Standards Declarations

The authors declare that they have no conflict of interest.

Data availability

All data used in this study will be readily available to the public.

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data Public.

Competing interests

The authors declared no conflict of interest.

Funding

There is no source of external funding

Authors' contributions

Mahmood Umar – Research Concept, design and writing the paper
Bala Baiarabe – Data acquisition
Zubairu Ahmed – Software contribution
Abdullahi Mohammed Wanzan – Data analysis
Musa Sa'adu – Data acquisition