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DIRECT CURRENT RESISTIVITY METHODS FOR GROUNDWATER PROSPECTING IN HARDROCK TERRAINS: A VIABLE APPROACH TO PROVIDING SUSTAINABLE POTABLE WATER

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ABSTRACT

Wide-spread application of direct current resistivity prospecting methods can result in providing sustainable potable water. Apparent resistivity (ρa) values between 100 and 200Ωm characterise water bearing zones in hardrock terrains. Prolific water boreholes were drilled at locations with such ρa horizontal profiling values at Awi campus of College of Education in Cross Rivers State of Nigeria. Sounding curves prepared from VES (vertical electrical sounding) data reveal the presence of water-bearing fractures. Longitudinal unit conductance (S) and transverse anisotropy (λ) can be estimated from VES data. Areas with high ground water yield are characterized by low λ and S values. Water-table topography was constructed from static water-level measurements taken in hand-dug wells, and were found to be similar to basement surface topography constructed from VES data acquired in Saukakahuta suburb in Minna, Nigeria. This demonstrates the potential of VES data for constructing groundwater flow pattern. Convergence zones identified from flow pattern, are sites for prolific water boreholes. VES data collected in Chanchaga suburb in Minna, reveals that the basement is deep in north-eastern and southern portions of Chanchaga. Spontaneous Potential (SP) values obtained in these areas ranges from 20 to 60mV. Deep basement combined with positive SP values often indicate high potential for optimum ground water yield. Induced polarization (IP) is not observed in clean sands devoid of clay.

Keywords: Horizontal profiling, Static-water level, Vertical electrical sounding, Water bearing fractures

INTRODUCTION

Hardrock terrains constitute greater than 20 per cent of world land surface [Davis and Dewiest, 1966]. Many Hardrock terrains exist in areas where surface water is either seasonal or non-existent. In hardrock terrains of countries with developing economy, people go through hard struggle to obtain potable water [Fig.1, 2 and 3].

FIG 1: African children in hard struggle for water. (Troften, 1973)

FIG 2 Mexican child employing a donkey to carry water(Troften, 1973)

FIG3: An Indian woman in tough search for water(Troften, 1973)

Water is the elixir of life, without which life is not possible [Fetter, 2001]. About 4 per cent of the earth's water is present in the subsurface as groundwater [Deming, 2002]. Groundwater constitutes a reliable source of water because it is renewable. It is exploitable via water wells. In hardrock terrains, groundwater occurrence is localised and unpredictable. Few tasks in hydrogeology are more difficult than locating drilling sites for water wells in igneous and metamorphic rocks [Davies and DeWiest, 1966]. Sites for drilling successful water wells can be cost effectively located by the applications of geophysical methods. The most widely used geophysical methods in hydrogeology are the electrical techniques [Keary and Brooks, 1988]. Of the several electrical geophysical methods, direct current resistivity has found the greatest application in hydrogeology [Zohdy et al, 1974]. Prospecting for water is essentially a geological problem [Bhattacharya and Patra, 1968] because groundwater occurrence is controlled by geology. The success of a geophysical survey depends upon an intelligent combination of physics and geology [Parasnis, 1986]. Successful exploitation of hardrock groundwater requires a proper understanding of its hydrogeological characteristics [Dan-Hassan and Olorunfemi, 1998], especially in areas of complex geology [Chandra et al, 2006].

GEOLOGICAL AND HYDROGEOLOGICAL SYNOPSIS OF HARDROCK TERRAINS

Common metamorphic rocks in hardrock terrains are migmatites, amphibolites, gneisses, quarzites, schists, slates, phyllites and dolomites. The igneous rocks include granites, rhyolites, gabbros, dolerites, syenites, diorites and basalts. A map showing hardrock areas in Nigeria and its immediate neighbourhood is as shown in Fig4.

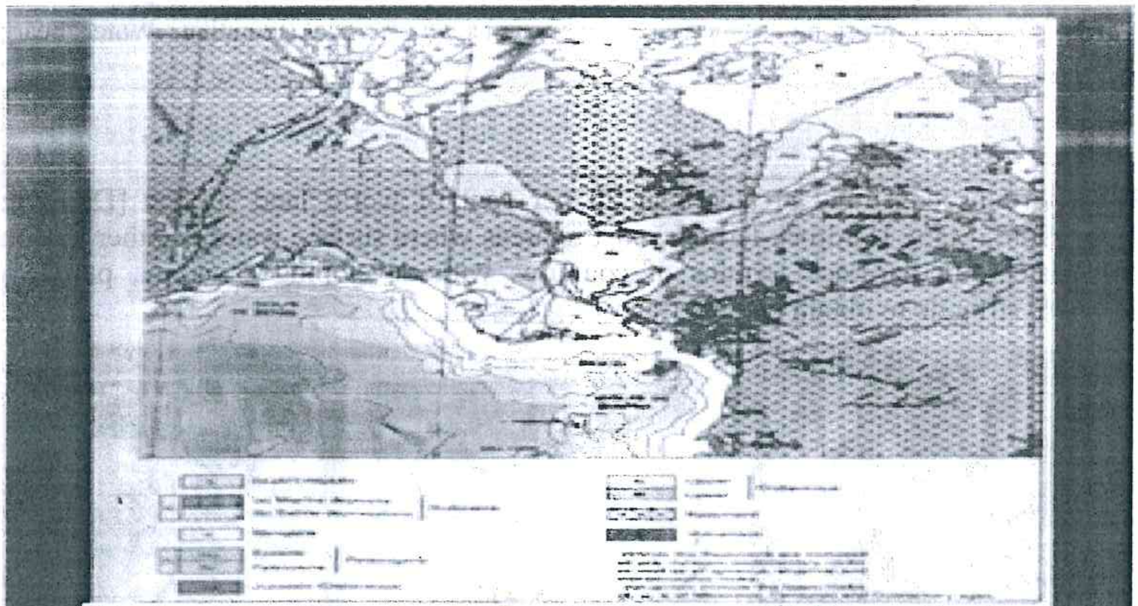

Fig4: simplified geological map of Nigeria & neighbourhood [Schlumberger,1985]

In-situ chemical weathering of hardrock results in a mantle of clastic material called regolith, which overlies fresh bedrock. The top portion of the regolith is soil while its lower portion is saprolite. A gradual transition exists between the saprolite and the bedrock. This transition is constituted by saprock [remnants of fresh bedrock set in altered matrix] and it is a few metres thick. In coarse grained massive crystalline rocks, the saprolite has a sharp boundary with the saprock while the boundary is transitional in finer grained or banded rocks [Clinton and Forster, 1995]. Beneath the saprock, the top of fresh bedrock is sometimes a few metres of fracture concentration [Fig. 5 and 6].

Typical stratigraphic section in hard rock terrains

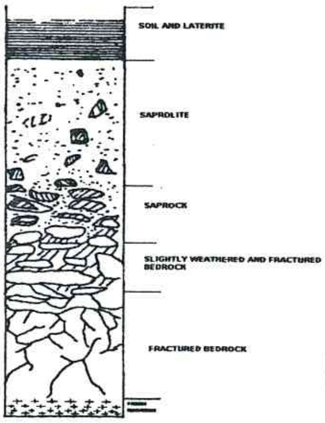

FIG 5:Subsurface cross section in hard rock terrain (Idowu and Ajayi,1998)

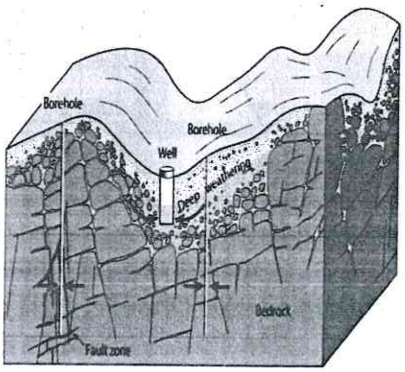

FIG 6: 3 D illustration of subsurface section in hard rock terrain (McDonald and Robins,2007)

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Sometimes a zone of decomposed veins lies within the fresh bedrock [Fig7].

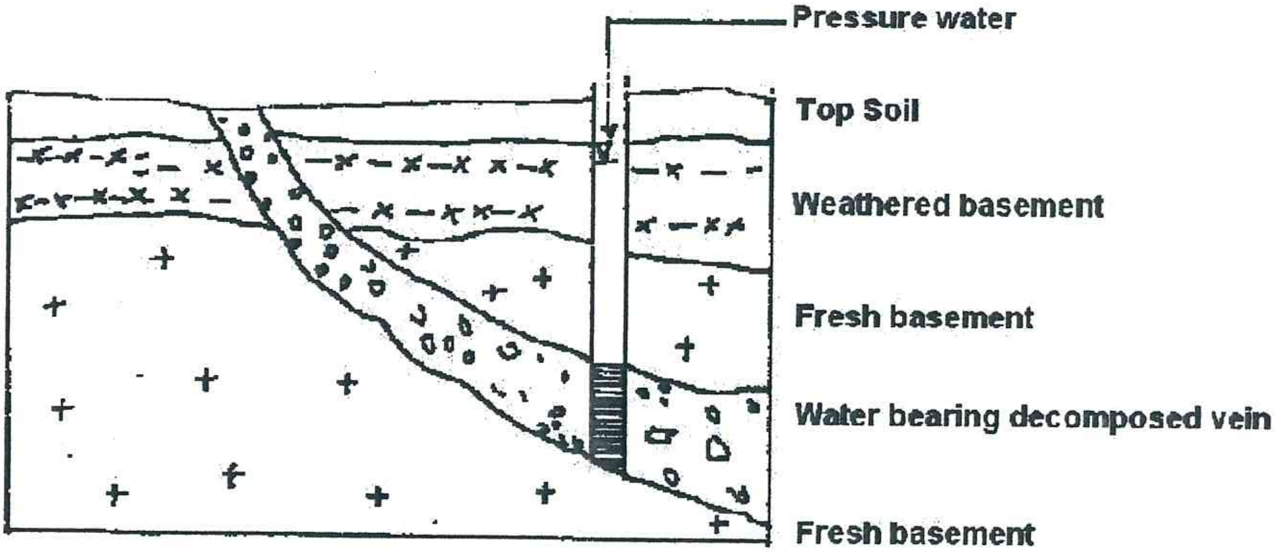

Fig 7:Decomposed vein aqiufer (Idowu and Ajayi, 1998)

The saprolite often constitutes weathered zone aquifer for groundwater. Lower and middle class households commonly exploit this aquifer via hand-dug wells. The hydraulic conductivity and hence groundwater yields of a saprolite depends on the relative proportions of quartz, feldspar and ferromagnesian minerals in the parent rock. Coarse grained granites weather into water-bearing regolith. This explains why the location of many villages and semi-urban towns are found on or near granite masses. Syenitic rocks with unstable minerals like feldspar predominating, do weather into clayey saprolites that behave as aquitards or aquicludes. The zone of decomposed veins within the fresh bedrock also constitutes bedrock aquifer. Basalts commonly displace river-channels in fluvio-volcanic series. As a result alluvium of gravels and sand are inter-bedded between fresh basalt above and weathered granites below [Fig. 8].

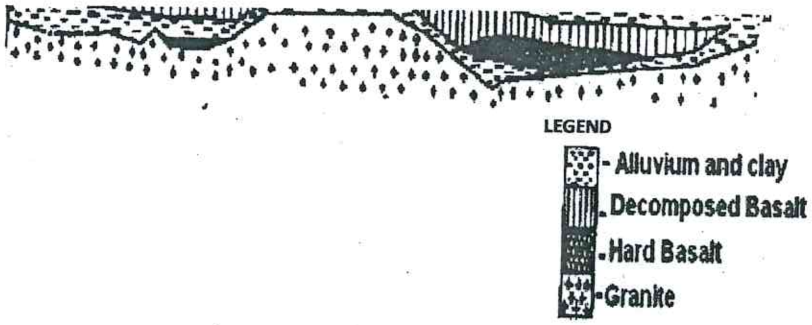

FIG 8:Aquifers in fluvio-volcanic series(Offodile, 1991)

This zone of alluvium and weathered granite constitute aquifer interval with excellent groundwater storativity and yield. Highest groundwater yield is common in hardrock terrains in areas where thick overburden overlies fracture zones [Oloruniwo and Olorunfemi, 1987; Olorunfemi and Fasuyi, 1993; Okereke et al, 1998]. These zones are often characterized by relatively low resistivity [Ali et al; 1993; Singh and Sinha, 2006).

OVERVIEW OF THE THEORETICAL FRAMEWORK FOR DC- RESISTIVITY METHOD IN GROUNDWATER PROSPECTING

DC-resistivity method for groundwater prospection is hinged on Ohm's Law of electrical conduction, which states that the electric current (I) in a conducting wire is proportional to the potential difference (V) across the wire under constant physical conditions.

$V=IR$ ---eqn 1

For a given material, R (resistance) is proportional to its length (L) and inversely proportional to its cross-sectional area (A):

R — ---eqn 2

This gives $R =$ — ---eqn 3

ρ (called the resistivity of the material) is the proportionality constant and the physical quantity employed in hydrogeological interpretations.

Combining eqns 1 and 3 gives

— — ---eqn 4

which is equivalent to:

$E=\rho J$ ---eqn 5

in which E (or –) is electric potential gradient or electric field strength, and – is electric current density.

Eqn 5 is the field form of Ohm's Law employed for deriving formulae used in DC-resistivity prospecting.

The method commonly employs a four electrode configuration (Fig. 9) in which controlled electric current is supplied into the ground via current electrodes (A&B) and the resulting potential difference measured between potential electrodes(C&D)

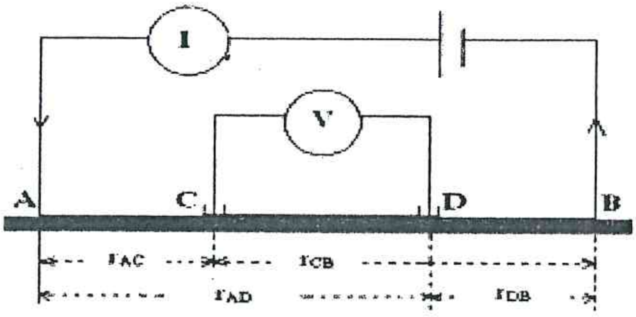

Fig. 9: Basic field electrode configuration system

ρ is obtained using (zohdy et al 1974):

ρ = –K ---eqn 6

where K is geometric factor whose value is determined by the electrode array used . K is obtained using (zohdy et al 1974):

$$\frac{1}{K}=\frac{1}{r_{AC}}-\frac{1}{r_{CB}}-\frac{1}{r_{AD}}+\frac{1}{r_{DB}}$$ ---eqn7

Modern resistivity meters (for example McOhm Resistivity Meter, ABEM SAS 4000, Campus Omega) evaluate – directly to give resistance R. Thus eqn 6 becomes:

ρ = 2πRk ---eqn8

Two basic routine procedures in DC resistivity prospecting are vertical electrical sounding(VES) and horizontal profiling (Kearey et al 2002; Telford et al, 1990; Parasnis, 1986; Keller and Frischknecht, 1970). Common field arrays are Dipole-Dipole Array, Schlumberger array and Wenner array. Horizontal profiling is commonly performed using Wenner array (Fig. 10).

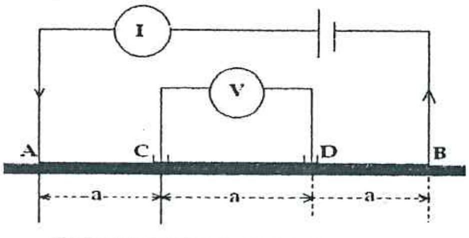

FIG 10: Wenner array

(Horizontal

With the above arrangement, the electrode spacing is constant (a) and ρ = 2π– .

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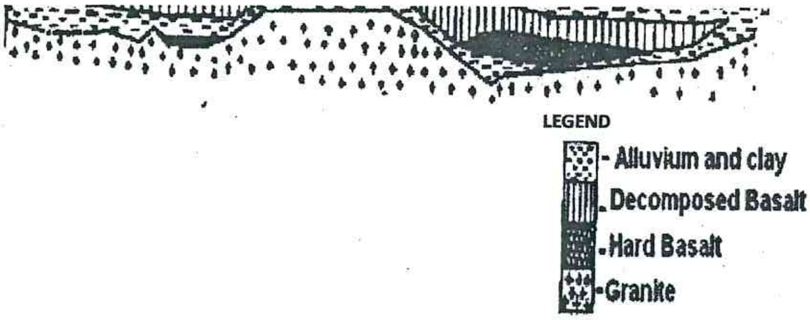

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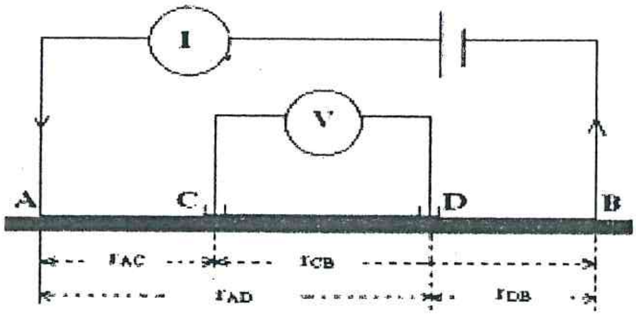

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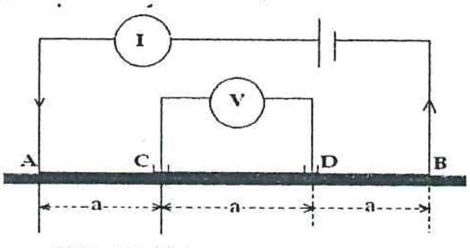

FIG 10: Wenner array

(Horizontal

With the above arrangement, the electrode spacing is constant (a) and ρ = 2π– .

Vertical electric sounding is commonly performed using Schlumberger array (Fig. 11).

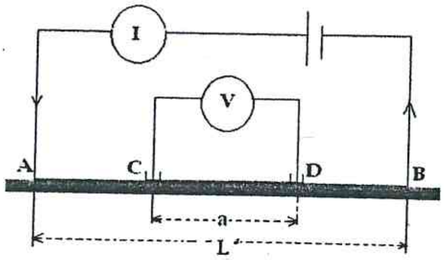

FIG11:Schlumberger array **(Vertical electrical sounding)**

With Schlumberger array, $$\rho_a = \frac{\pi}{4}\frac{V}{I}\frac{\left(L^2 - a^2\right)}{a}$$

GROUNDWATER PROSPECTION APPLICATIONS IN HARD-ROCK TERRAINS

Direct Current (DC) resistivity data are used to locate sites where water well will produce optimum yield of groundwater. The application is anchored on the calibration of resistivity data in terms of geoelectric layers, hydrogeologic units and aquifer characteristics. In hardrock terrains, the generally observed distinct geoelectric layers with their respective thickness are given in Table 1.

Table1: Thickness of geologic layers in Hard Rock Areas (Rao, 1987)

Layer No	Particular	Thickness (m)
1	Soil	1-2
2	Weathered layer (saprolite)	10-20
3	Semi-weathered/fractured hardrock (saprock)	10-30
4	Fresh bedrock	up to infinity

Tables 2 and 3 are respectively the calibration of regolith resistivity and saprock resistivity in terms of aquifer characteristics, as modified by Olayinka et al (1997), after Wright (1992).

Table2 : Calibration of regolith resistivity in terms of **aquifer** potential(Wright,1992:Olayinka et al,1997)

Regolith resistivity (Ohm-m)	Aquifer potential
<20	Clay with limited potential
20-100	Optimum weathering and groundwater potential
100-150	Medium conditions and potential
150-300	Limited weathering and poor potential

Table 3 : Aquifer potential as a function of bedrock **resistivity** (Wright,1992:Olayinka etal,1997)

Fractured Bedrock resistivity (Ohm-m)	Aquifer Potential
<750	High fractured permeability as a result of weathering: high aquifer potential
750-1500	Reduced influence of weathering: medium aquifer potential
1500-3000	Fairly low effect of weathering: low aquifer potential
>3000	Little or no weathering of bedrock: negligible potential

Places where the subsurface contains thick units of water-bearing weathered and fractured rocks, show typically low apparent resistivity values in contrast to places with dry subsurface. In basement complex in eastern Uganda, the majority of successful boreholes had within water-bearing zones, minimum apparent resistivity values of less than 200 and 100Ωm, from the observed resistivity profiling anomalies and VES respectively (Wright, 1992).Horizontal profiling detects lateral variations in apparent resistivity values, and thus constitutes an efficient procedure for delineating places with high groundwater yielding potential. Horizontal profiling is a stratigraphic hydrogeophysical prospecting technique because it locates groundwater bearing subsurface by distinguishing the physical property imparted by the presence of water, which is low resistivity. Minasian(1979) reports that groundwater bearing lava are shown as local low apparent resistivity zones in electrical profiling.Fig 12 is a horizontal apparent resistivity profile with the location of a successful borehole, Ako(BH1)(Okereke et al, 1998).

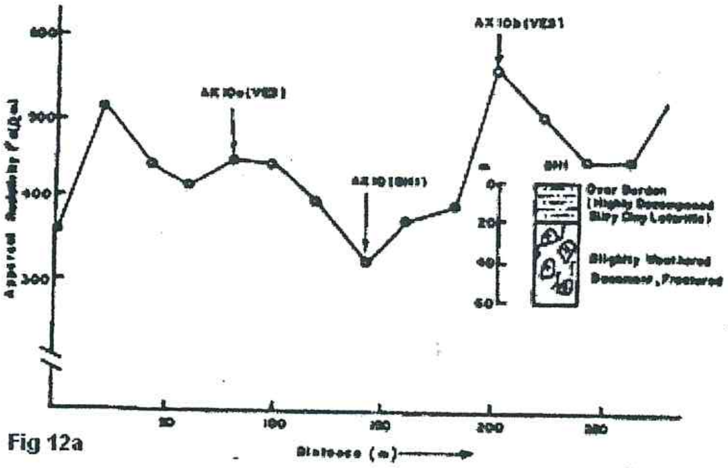

Fig 12a

Productive borehole(BH1) on the resistivity profile on COE campus, Awi, Cross River state, SE Nigeria (Okereke et al 2000)

1998

Ako10 (BH1) was cited by only profiling within the campus of College of Education, Awi in Cross River State of Nigeria. BH1 revealed 20m thick overburden underlain with lower 40m thick semi B weathered/fractured bedrock

(Okereke et al, 1998). Inspection of sounding curves reveals the presence of fractures. In Fig 12b, the undulating nature of the sounding curve between electrode spacing of 10 metres and 100 metres reveal the presence of fracture within this interval and this is verified by the lithological log.

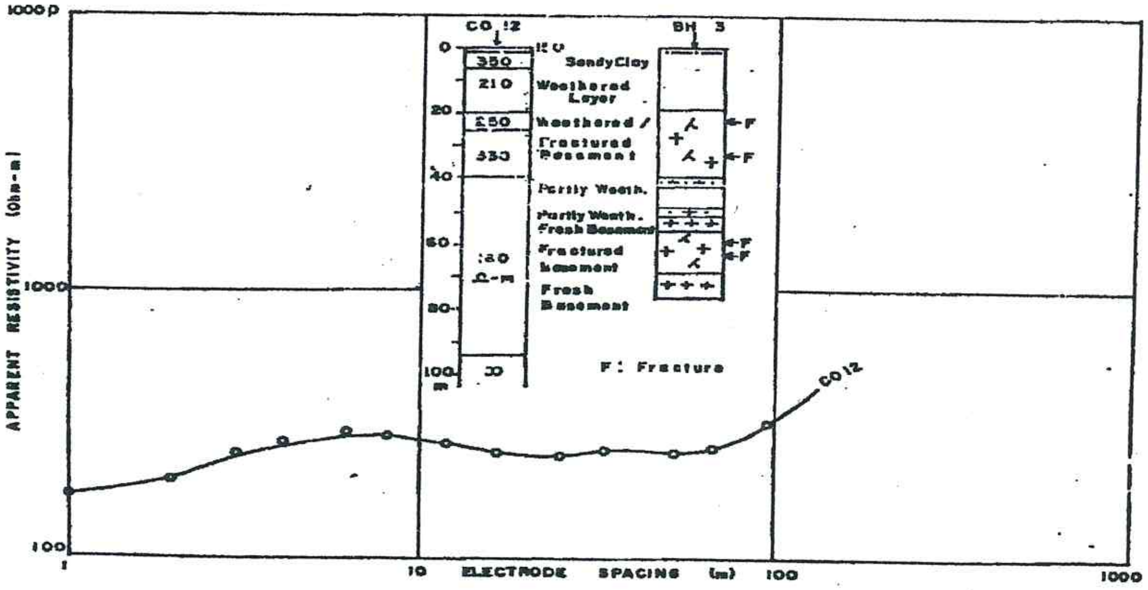

FIG 12b: KH-type Schlumberger sounding curve and interpreted geoelectric section with the borehole section in part of Akure metropolis (Olorunfemi et al 1999)

VES data are used for generating geoelectric sections. A geoelectric section is a composite of geoelectric layers, which are each characterised by two basic parameters: ρ_i and h_i . Other parameters derivable from ρ_i and h_i are longitudinal unit conductance (S), transverse unit resistance (T), longitudinal resistivity (ρ_L), transverse resistivity (ρ_t) and anisotropy (λ).

For n layers,

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n}$$

$$T = \sum_{i=1}^{n} h_i \ \rho_i = h_1 \ \rho_1 + h_2 \ \rho_2 + \cdots + h_n \rho_n$$

$$\rho_l = \frac{H}{S}, \ where\ H = \sum_{i=1}^{n} h_i$$

$$\rho_t = \frac{T}{H}$$

$$\lambda = \sqrt{\frac{\rho_t}{T_l}} = \frac{\sqrt{TS}}{H}$$

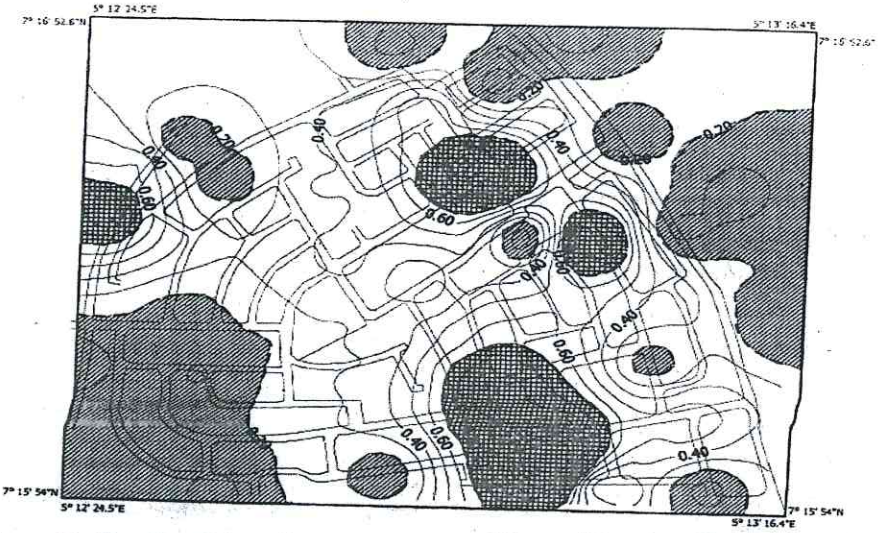

Fig 13: Longitudinal unit conductance map of Ijapo Housing Estate in Akure (Oladapo et al, 2004)

The eastern, southwestern and northern portions of the estate show a longitudinal unit conductance (S) <0.20[indicated by single stripes]. Oladapo et al (2004) reports that hydraulic conductivity and transmissivity values are excellent in these potions of the housing estate. The southern portion and isolated parts of the central portion show S > 0.60[indicated by cross-stripes]. The hydraulic conductivity and transmissivity values are low in these areas. In hydrogeologic investigations, T has been demonstrated to be functionally analogous to hydraulic transmissivity (Kalinski et al,1993; Kosinski and Kelly,1981; Sr Niwas and Singhai,1981; Kelly and Reiter,1984; Mazac et al,1985). High groundwater yield is associated with high transmissivity and hydraulic **Fig 14: Groundwater yield and hydraulic conductivity and transmissivity in parts of Kaduna (Dan Hassan and Olorunfemi, 1999)**

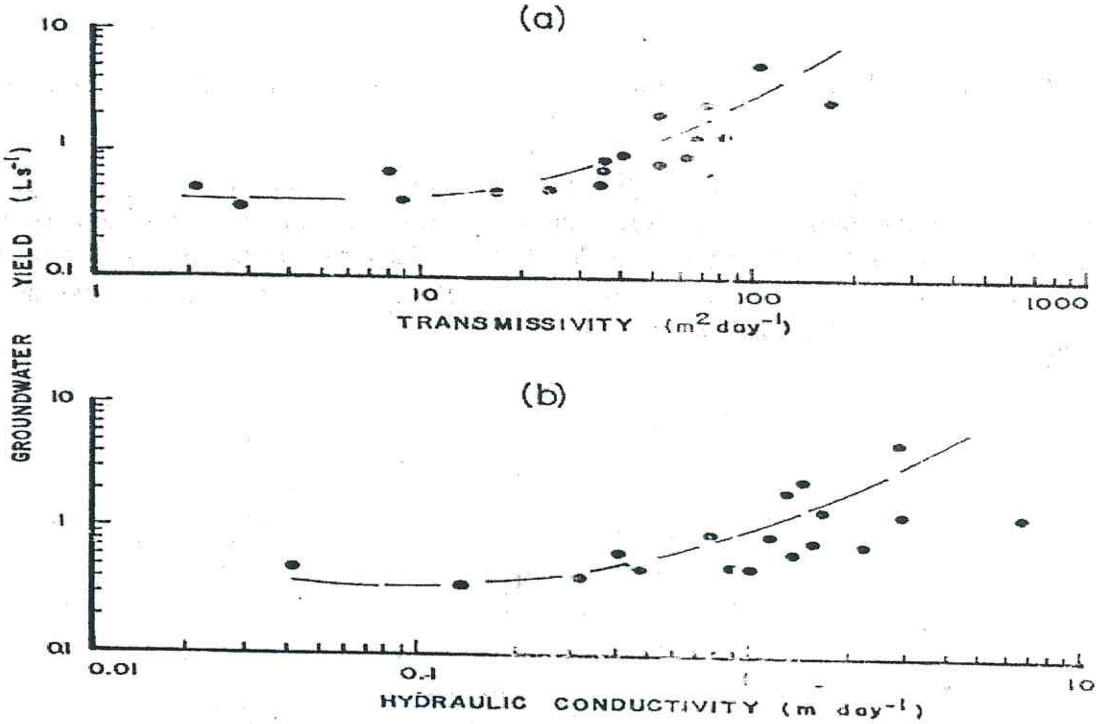

Fig 14: Groundwater yield and hydraulic conductivity and transmissivity in parts of Kaduna (Dan Hassan and Olorunfemi, 1999)

Coefficient of electrical anisotropy (λ) is indicative of clay content in regolith. Low λ implies low clay in regolith, and this connotes high hydraulic conductivity and transmissivity and hence high groundwater yielding potential. Low λ areas in Fig. 15 approximately coincide with areas of higl hydraulic conductivity and transmissivit in Fig. 13 of Ijàpo Housing Estate, anc vice-versa.

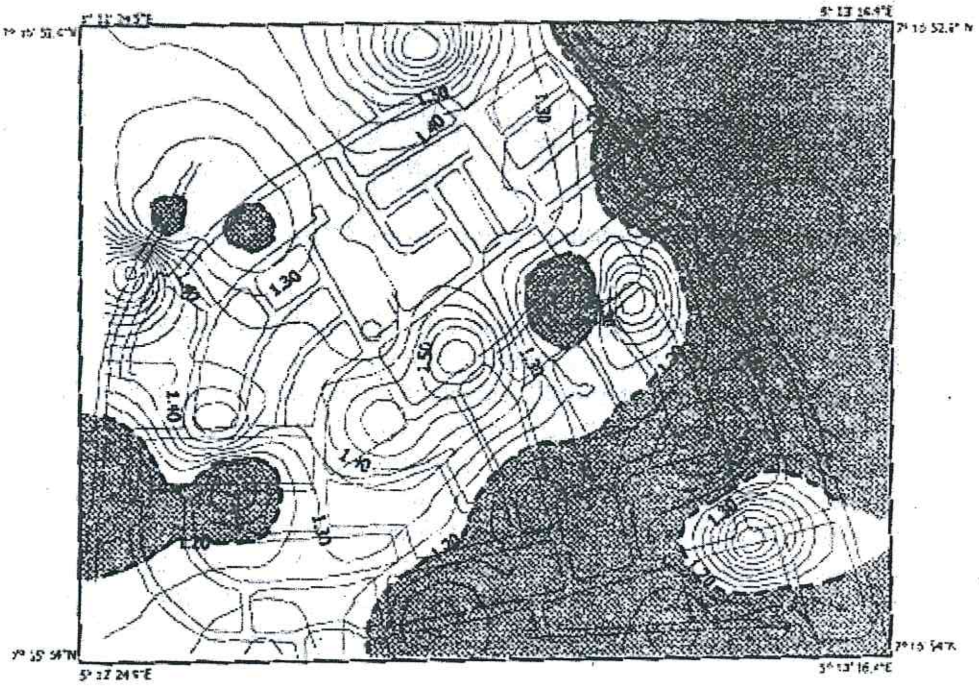

Fig 15: Electrical anisotropy map for Ijapo Housing Estate in Akure (Oladapo et al, 2004)

Pseudo resistivity sections can be plotted from VES data collected at different locations along a traverse. The pseudo-resistivity sections give an indication of true formation resistivity with depth. Thus low resistivity zones are graphically presented. Fig16 is Schlumberger pseudo resistivity section in parts of premises of Bahago Secondary School, Minna.

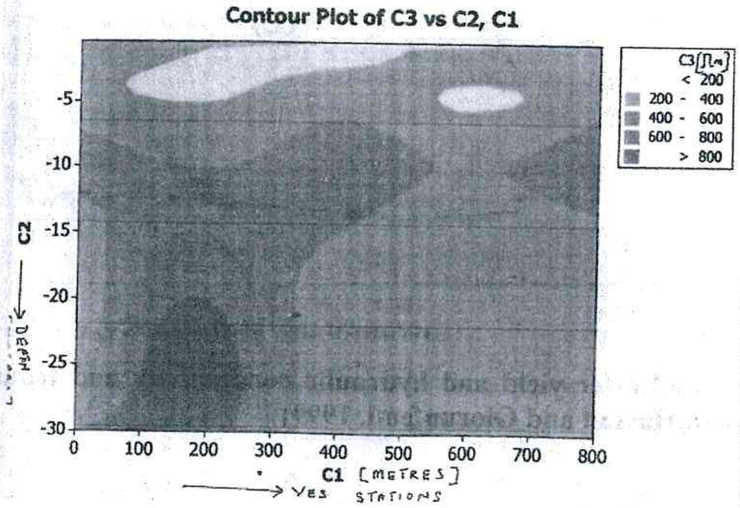

Fig16: Pseudo resistivity section from part of Bahago Secondary School premises, Minna (Autl

Between 400m and 800m on the traverse is low resistivity zone, suggesting high groundwater yielding potential. Between 100m and 300m along the traverse is <200Ωm resistivity values at <5m depths, indicating that hand-dug wells will tap groundwater in overburden. VES data collected from a grid of stations can be used to plot a contour map of depth to top of bedrock. Topographic lows and highs are delineated on bedrock depth contour map. Since water flow downhill, topographically low zones constitute converging centres for groundwater while topographic highs are diverging zones. Dan-Hassan and Olorunfemi (1999) reports that boreholes located within basement topographic lows in Kaduna gave relatively high yield (0.4-0.5LS^{-1}) while those located within topographic high gave low yield (0-0.5LS^{-S}). Their basement topography map for the part of Kaduna is shown as Fig. 17.

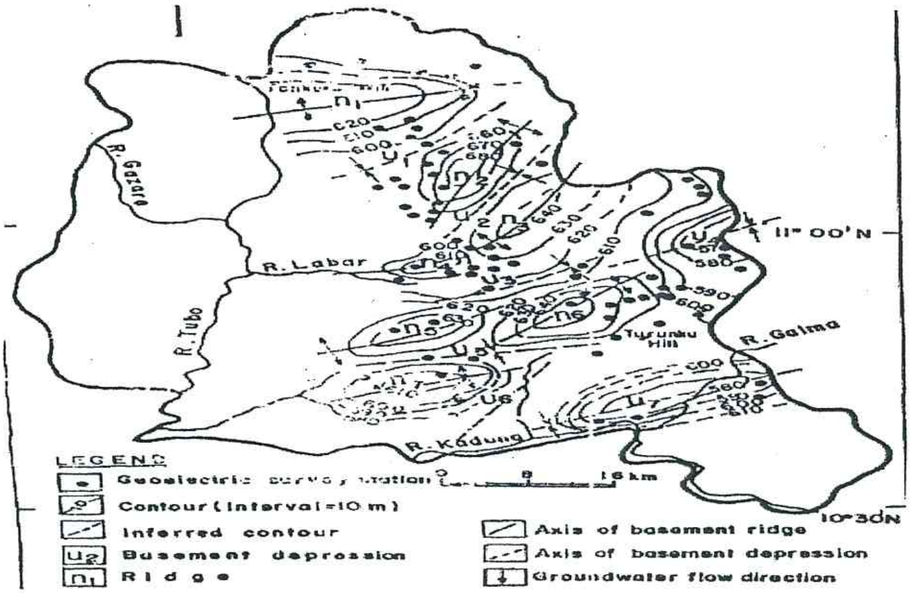

Fig 17: Basement topography map for the part of Kaduna (Dan-Hassan and Olorunfemi, 1999)

The water table elevation (static water level) map for Soka kauta area of Minna (Fig.18) indicates that groundwater flows southwestward (convergence zone) from northwest and northeast.

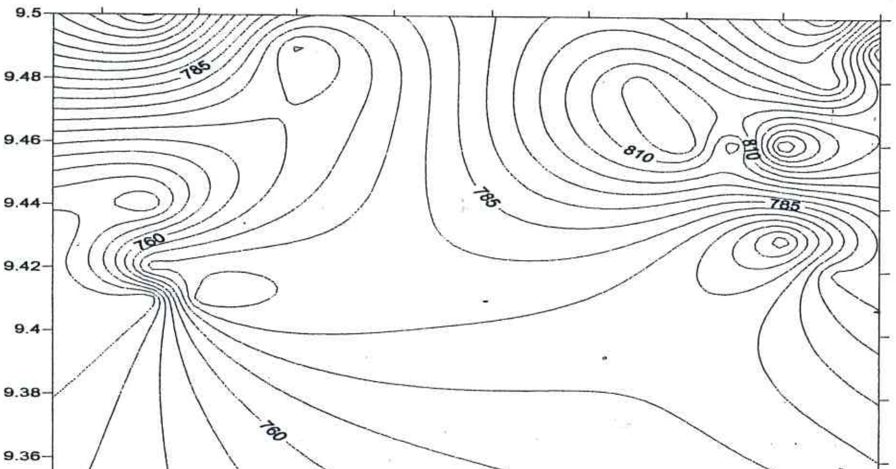

Fig 18: Water table elevation (static water level map for parts of Soka kahuta in Minna (Author)

Fig. 19 representing subsurface basement topographic map in the same parts of Soka kahuta indicates that depth to top of fresh basement increases southeastward.

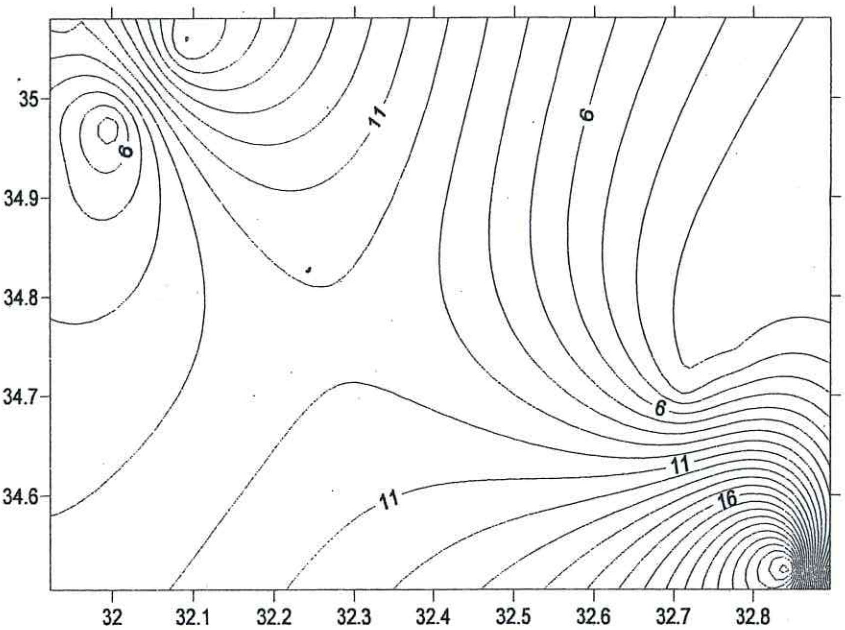

Fig 19: Subsurface basement topographic map for parts of Soka kauta in Minna (Author)

Similarity in water table topography with basement surface topography demonstrates the potential of VES data for identifying groundwater flow pattern and hence groundwater convergence zones. This approach to groundwater prospection by delineating locations of groundwater convergence is structural hydrogeophysical prospection method.

Limitations of Direct Current Resistivity Method for Groundwater Prospection in Hardrock Terrains

The applicability of dc resistivity surveys to groundwater prospecting hinges on the fundamental principle that water saturated rocks have lower resistivity than unsaturated dry rocks. Water bearing portions of saprolite and fracture zones commonly show low resistivities. Dry clayey saprolite and clayey fracture zones also give low resistivity values. The presence of electronically conductive minerals (notably graphite, pyrrhotite, pyrite,chalcopyrite, galena and magnetite) in hardrocks gives them resistivity variation patterns that mimic the pattern observed in zones with high groundwater yielding potential. The similarity in diagnostic resistivity anomalies between high groundwater yielding potential zones and mineralized subsurface creates ambiguity in interpreting dc resistivity data in terms of hydrogeologic units and aquifer characteristics. The level of ambiguity is minimized when resistivity data are compared with self potential (SP) and induced polarization (IP) data from the same areas. Resistivity anomalies due to mineralised subsurface are accompanied with negative SP anomalies of the order of a few hundred to several hundred millivolt.

SP anomalies of +20 to +40mv are characteristically obtained over pegmatites and quartz veins (Parasnis, 1986). Thus, resistivity anomalies accompanied by positive SP values indicate groundwater filled pegmatite bodies. Comparing Fig. 20 (contoured depth to fresh basement surface obtained from digitized VES curves for parts of Chanchanga area in Minna) and Fig. 21 (contoured SP values at 20m electrode spacing for the same parts of Chanchanga) reveals that northwestern, northeastern and southern portions of the surveyed area are choice zones for water well drilling. These are areas with positive SP values.

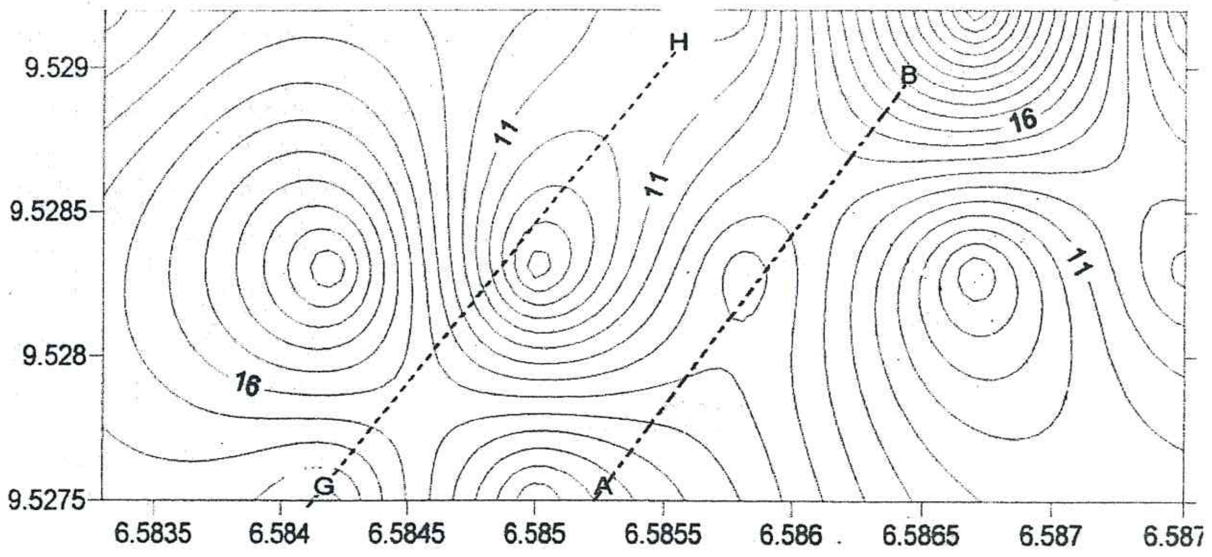

Fig 20: Contour map of depth to fresh bedrock in parts of Chanchanga, Niger State, Nigeria (Author)

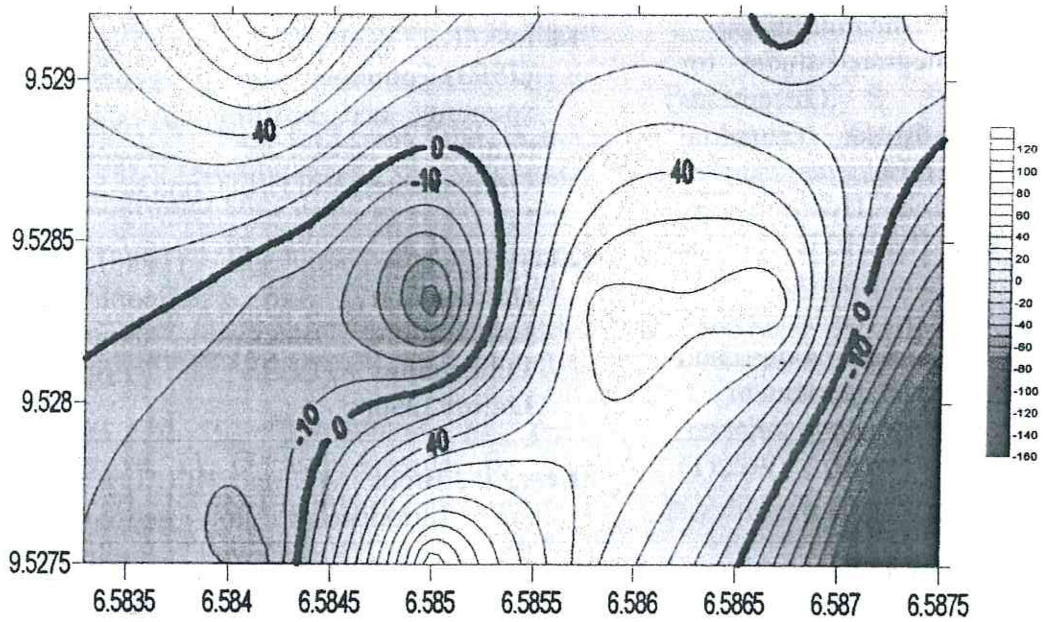

Fig 21: Spontaneous potential map at electrode spacing of 20 meters in parts of Chanchanga, Niger State, Nigeria (Author)

Induced polarization is not observed on clean quartz sand or similar media devoid of clay (Parasnis, 1986). For a particular fluid concentration, the polarisation decreases with increasing rock porosity. Thus zones with high potential for optimum groundwater yield are characterised combined low resistivity, positive or background SP values, and very low or nil IP values. Modern resistivity meters like SAS 4000 combine resistance, SP and IP measuring modes. McOhm and Omega-campus resistivity meters combine resistance and SP measuring modes.

CONCLUSION

Though direct current resistivity method has proved useful for groundwater prospecting in hardrock terrains, wells drilled solely on the basis of resistivity contrast have sometimes failed to produce water. Similar resistivity anomaly pattern is produced by dry chlorite schists, dry graphitic schists and dry igneous and metamorphic rocks with conductive mineral impregnations. Drilling dry wells is avoidable through complementary interpretation of integrated resistivity, self potential and induced polarization data.

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