Evaluation of soil corrosivity and aquifer protective capacity using geoelectrical investigation in Bwari basement complex area, Abuja

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Bwari is one of the six municipal area councils of the Federal Capital Territory (FCT), Abuja with its attendant growing population and infrastructural developments. Groundwater is the main source of water supply in the area, and urbanization and industrialization are the predominant contributors of contaminants to the hydrological systems. In order to guarantee a continuous supply of potable water, there is a need to investigate the vulnerability of the aquifers to contaminants emanating from domestic and industrial wastes. A total of 20 vertical electrical soundings using Schlumberger electrode array with a maximum half current electrodes separation of 300 m was employed. The results show that the area is characterized by 3–6 geoelectric subsurface layers. The measured overburden thickness ranges from 1.0 to 24.3 m, with a mean value of 7.4 m. The resistivity and longitudinal conductance of the overburden units range from 18 to 11,908 Ωm and 0.047 to 0.875 mhos, respectively. Areas considered as high corrosivity are the central parts with $\rho < 180 \Omega\text{m}$. The characteristic longitudinal unit conductance was used to classify the area into zones of good (0.7–4.49 mhos), moderate (0.2–0.69 mhos), weak (0.1–0.19 mhos), and poor (<0.1) aquifer protective capacity. Zones characterized by materials of moderate to good protective capacity serve as sealing potential for the underlying hydrogeological system in the area. This study is aimed at delineating zones that are very prone to groundwater contamination from surface contaminants and subsurface soils that are corrosive to utility pipes buried underground. Hence the findings of this work will constitute part of the tools for groundwater development and management and structural/infrastructural development planning of the area.

1. Introduction

Groundwaters entails water existing beneath the earth surface and sustainable amount of groundwater is contained in geologic formation or part of geologic formation called aquifers. Prospecting for viable aquifers for groundwater supply has over the years been done or carried out using various means ranging from physical observations to surface- and subsurface-geophysical techniques (Todd and Mays

2005). Geophysical techniques detect differences of physical properties such as density, magnetism, elasticity, and electrical resistivity within the earth crust (Todd and Mays 2005). Geoelectrical methods (principally vertical electrical sounding) have been preferred in groundwater and environmental studies when compared to other geophysical survey techniques, since these methods provide portability of equipment, rapid measurement of electrical resistivity, and lesser ambiguity in interpretations of

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results when compared to other methods and also these methods do not have any destructive effect on the environment (Todd and Mays 2005). The electrical resistivity techniques involve sending direct currents into the soil/rock via electrodes (current electrodes) and measuring the resulting potential difference via potential electrodes. Different standard electrode arrangements or arrays have been developed; however, Werner and Schlumberger arrays are the most widely used. The measured current and potential difference is used in estimating the apparent resistivity of soils and rock over unspecified depths or positions. The resistivity of soils and rocks depends largely on rock properties such as porosity, permeability, ionic content of the pore fluids, and clay mineralization and these vary with space and time. It is this variation in the rock resistivity (anomalies) as a function of the rock properties that is being targeted in electrical resistivity surveys to give a picture of the subsurface geologic materials and structures (Wightman *et al.* 2003; Oseji 2010).

Geophysical techniques have also been developed for groundwater contamination studies like mapping the extent of migration of contaminant plumes in aquifers and soils (Kelly 1976; Benson *et al.* 1997; Arristodemou and Thomas-Betts 2000; Adepelumi *et al.* 2001; Naudet *et al.* 2004) and in recent years, have been used to delineate areas that may be susceptible to contamination should any occur (Braga *et al.* 2006; Mogaji *et al.* 2007; Abiola *et al.* 2009; Atakpo and Ayolabi 2009). Because of the growing population of Abuja, more wastes, which are potential groundwater contaminants are being generated by the increasing population. So, in this regard, our main aim was to map or locate the zones that were non-corrosive to bury utilities/pipes and also to delineate areas that have good protection for the underlying aquiferous units.

2. Geology of the study area

The study area is located between latitudes 9°15'27" and 9°17'51"N and longitudes 7°19' 39" and 7°24'9"E as shown in figure 1. It covers an approximate area of about 40 km². The area is underlain by migmatite-gneiss complex and granitoids (FSN 1978; Rahaman 1989). The rock types observed as outcrops are granites and migmatitic gneiss. The granites range in texture from medium to coarse grained, and are grey-coloured, massive and homogenous. Migmatite gneiss in the area is characterized by medium to upper amphibolites-facies. The geological map of Abuja, which shows the various rock types underlying the area is presented in figure 2. Hydrogeologically, the area can

be divided into two units namely: the aquiferous zone within the weathered overburden overlying the fresh basement rocks and the aquiferous zone within the intense fracture joint system in the partially weathered basement.

3. Materials and methods

In this research work, electrical resistivity survey was used, 20 vertical electrical soundings (VES) were carried out, and the Allied Omega tetramer and its accessories were used. The conventional Schlumberger array pattern, with half electrode spacing (AB/2) varying from 1 m to a maximum of 150 m, was adopted. The apparent resistivity was computed using the equation:

$$\rho_a = \pi \left(\frac{a^2}{b} - \frac{b}{4} \right) \frac{\Delta V}{I}, \quad (1)$$

where ρ_a is apparent resistivity, π is $\frac{22}{7}$, $G = \pi(a^2/b - b/4)$ is geometrical factor, and $\Delta V/I = R$ is the resistance.

The apparent resistivity values obtained from equation (1) were plotted on bi-log graph against the half current electrode separation spacing. From these plots, qualitative deductions, such as the resistivity of the first or top layer, the depth of each layer, and the curve signatures or types were made. The initial quantitative interpretations were made using partial curve matching technique, in which the field curves produced or generated were matched segment by segment with the appropriate master curves and auxiliary curves.

The resistivities and thicknesses of the various layers were improved upon by employing an automatic iterative computer program following the main ideas of Zohdy and Martin (1993). The WIN-RESIST computer software was employed for carrying out the iteration and inversion processes. The iteration process was conducted for each sounding station until the root mean square (RMS) error of lower than 5% was obtained.

The total longitudinal conductance (S_T) of the overburden unit at each vertical electrical sounding station was obtained from the mathematical relation (Zohdy *et al.* 1974):

$$S_T = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (2)$$

where S_T = total longitudinal conductance of the overburden, ρ_i = layer resistivity, h_i = layer thickness, and n = number of layers and were used to characterize the aquifer protective capacity of the area.

Figure 1. Google map of Bwari area, showing the VES points and borehole locations with the map of Nigeria and Abuja as insets.

Figure 2. Geological map of Abuja (adapted from Dikedi 2012).

4. Results and discussion

4.1 Geoelectric sections

The summary of the results of the 20 vertical electrical soundings is presented in table 1. From the table, the resistivities of the first to fifth layers

range from 44 to 1177 Ωm , 18 to 11,908 Ωm , 32 to 13,242 Ωm , 16 to 92,805 Ωm and 234 to 5338 Ωm , respectively. The thicknesses of the top layer to the bottom layer vary from 1.0–6.6 m, 0.2–52.2 m, 1.0–63.7 m and 6.2–25.6 m, respectively. The longitudinal conductance of the overburden units estimated from the resistivities and

Table 1. *Layers' resistivity, thicknesses, curve types and longitudinal conductance.*

VES# station	Layer resistivity (ohms)						Layer thickness (m) ⁺					Curve type	Longitudinal conductance (mhos)
	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	h_1	h_2	h_3	h_4	h_5		
1	442	5078	1982	62	234	21063	2.6	0.4	5.4	15.9	48.6	AKHA	0.472036
2	44	2184	35	1668			2.1	0.8	25.5			KH	0.768650
3	349	18	3357				2.9	6.3				H	0.354468
4	214	62	1226				5.6	52.2				H	0.874761
5	1177	155	7040				6.6	37.5				H	0.246919
6	479	1047	1560	10618			1.3	6.5	18.6			AA	0.128304
7	251	1066	2107	134	5338		1.6	1.3	4.0	25.6		AKH	0.199958
8	344	274	5117	54677			1.1	11.9	1.0			HA	0.046919
9	336	43	909				1.1	5.8				H	0.137220
10	207	64	5941				1.0	9.3				H	0.148342
11	110	59	3257	16	1232		1.5	1.5	1.0	6.2		HKH	0.421985
12	455	482	111	6391			4.8	3.9	30.5			KH	0.293415
13	438	11908	575	25454			1.5	0.7	63.7			KH	0.114288
14	1109	357	6830	92805			1.4	22.6	1.9			HA	0.064846
15	278	588	75	7075			1.6	1.4	54.9			KH	0.736265
16	387	562	97	413			2.2	0.8	11.0			KH	0.120052
17	212	314	77	17627			1.7	0.6	6.2			KH	0.090997
18	95	101	13242				3.5	4.1				H	0.077594
19	495	772	305	1391			3.5	0.9	15.9			KH	0.059770
20	496	942	207	756			6.1	0.2	26.5			KH	0.140345

#VES = vertical electrical sounding, * ρ_1 = first layer resistivity, ρ_2 = second layer resistivity, ρ_3 = third layer resistivity, ρ_4 = fourth layer resistivity, ρ_5 = fifth layer resistivity, ρ_6 = sixth layer resistivity, ⁺ h_1 = first layer thickness, h_2 = second layer thickness, h_3 = third layer thickness, h_4 = fourth layer thickness, h_5 = fifth layer thickness, m = meters.

thicknesses of the overburden units range from 0.0469 to 0.875 mhos. Eight transverses connecting the 20 VES points were covered and their subsurface geoelectric sections are presented in figure 3. The lithology of each layer was inferred by comparing inverted resistivity with typical electrical resistivity of earth materials bearing in mind the surficial geology within the vicinity of the sounding station. VES at stations 2, 5 and 14 were carried out in the vicinity of existing boreholes. The lithology of the various layers in the boreholes was determined from washed core samples that were taken at specific intervals of depth. The inferred lithologies and thicknesses of the various layers from the subsurface geoelectric sections of these VES stations were compared with the lithologic logs of the boreholes located very close to them and it was revealed that they are very well correlated (figure 4). At VES 5, the VES reveals three subsurface geoelectric layers which correspond to the number of the subsurface layers described by the lithologic logs. Also, the inferred lithologies and thicknesses of the various subsurface layers from the VES correspond essentially with the lithologies and thicknesses of the various subsurface layers defined by the lithologic logs (figure 4). At VES 2, the geoelectric section reveals the same number of subsurface layers as the lithologic log. The thicknesses of the subsurface layers described by

the VES varied slightly from those of the lithologic log (figure 4) while at VES 14, four subsurface layers were defined by the VES and three layers by the lithologic log (figure 4). The 4th subsurface layer of the geoelectric section was inferred to be fresh basement rock which was not described by the lithologic log. According to Zhody *et al.* (1974), the 3rd layer of the lithologic log is characterized by two distinct resistivity values and these two units within the layer having different resistivities are seen as two distinct layers by the VES. The uncertainties involved in the estimates of resistivity and depth of the subsurface lithological layers include the problem of approximate equivalence between two multilayer sections attributed to the principle of suppression which causes errors in depth of contact estimation known as pseudoanisotropy. Due to monotonic change in resistivity, where there is either an increase or decrease monotonically in the resistivity of the subsurface layers, the sounding curves of a 3-layer model (A and Q) and 4-layer model (AA and QQ), may resemble curves of a simple 2-layer model.

From figure 3, the geoelectric subsurface section ranges from 3 to 6 layers with the 4-layer as the dominant type. The 3-layer geoelectric section is characterized by H curve type (figure 5) and is generally made up of top loose soil, laterite/clay, and fresh basement rock from top to bottom with

Figure 3. 1-D geoelectrical models for VES 1-20.

Figure 4. Correlation between geoelectric section and lithological log.

Figure 5. Typical H curve type.

variable thicknesses and resistivities. The 4-layer geoelectric section is characterized by KH, HA, and AA curve types (figures 6–8). The 5-layer geoelectric section is characterized by AKH and HKH curve types (figures 9 and 10). Curve types depict the relationships between lithological layers'

resistivity (table 2). The occurrence of different curve types from place to place within an area shows high variability in the nature of the subsurface geological materials (Zohdy *et al.* 1974). The overburden thickness ranged from 1.0 to 24.3 m with a mean of 7.4 m; thickest and thinnest

Figure 6. Typical KH curve type.

Figure 7. Typical AA curve type.

Figure 8. Typical HA curve type.

Figure 9. Typical AKH curve type.

Figure 10. Typical HKH curve type.

Table 2. Classification of curve types.

Curve type	Layer's resistivity relationship
H	$\rho_1 > \rho_2 < \rho_3$
HA	$\rho_1 > \rho_2 < \rho_3 < \rho_4$
KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$
AA	$\rho_1 < \rho_2 < \rho_3 < \rho_4$
HKH	$\rho_1 > \rho_2 < \rho_3 > \rho_4 < \rho_5$
AKH	$\rho_1 < \rho_2 < \rho_3 > \rho_4 < \rho_5$
AKHA	$\rho_1 < \rho_2 < \rho_3 > \rho_4 < \rho_5 < \rho_6$

Note: ρ – resistivity.

overburden is observed around places such as Zuma and Bwari, respectively (figure 11).

4.2 Evaluation of soil corrosivity

Civil engineering construction works generally include laying of metallic pipes. Buried pipes are

susceptible to corrosion and subsequent failure if the host soil medium is corrosive and aggressive (Akintorinwa and Abiola 2011). Topsoil constitutes the layer within which normal civil engineering foundations and utility pipes are buried. The thickness of this layer ranges from 1.0 to 6.6 m while the resistivity ranges from 44 to 1177 Ωm in the present study. The topsoil (first layer) resistivity values obtained from the interpretations of the VES results were utilized in evaluating the corrosivity of the subsoils. Very high resistivity values ($>1000 \Omega\text{m}$) and low resistivity values ($<40 \Omega\text{m}$) are observed at the northeastern and central zones, respectively. Topsoil resistivity values were classified in terms of soil corrosion based on (Baekmann and Schwenk 1975; Agunloye 1984; Oladapo et al. 2004) soil resistivity classification model (table 3). Topsoil resistivity values range from 44 to 1177 Ωm , with a mean value of 415.41 Ωm and the topsoil corrosivity

Figure 11. Overburden isopach map of Bwari basement area.

Table 3. Classification of soil resistivity in terms of corrosivity (based on Baeckmann and Schenwenk 1975; Agunloye 1984; Oladapo *et al.* 2004).

Soil resistivity (Ωm)	Soil corrosivity
< 10	Very strongly corrosive (VSC)
10–60	Moderately corrosive (MC)
60–180	Slightly corrosive (SC)
> 180	Practically noncorrosive (PNC)

varied from ‘practically noncorrosive’ to ‘moderately corrosive’.

Part of the central area is considered to be of high corrosivity ($\rho \leq 180 \Omega\text{m}$) while the remaining areas are of low corrosivity ($\rho \leq 180 \Omega\text{m}$; figure 12). Over 60% of the study area has relatively high topsoil resistivity values with low tendency for corrosivity. Only the sections around the central area where ‘moderately’ and ‘slightly’ corrosive topsoil are observed will metallic pipes/utility buried in them be susceptible to corrosion.

4.3 Evaluation of aquifer protective capacity

Aquifer protective capacity (APC) is the ability of the overburden unit to retard and filter percolating ground surface polluting fluid into the aquiferous unit. The second order geoelectric parameter, longitudinal conductance (Dar Zarrouk parameter) was evaluated from the primary/first order parameters (thickness and resistivity) of the geoelectric subsurface layers which were used in the classification of the APC of the area. Highly impervious materials such as clay and shale usually

have high longitudinal conductance values (resulting from their low resistivity values) while pervious materials such as sand and gravels have low longitudinal conductance values (resulting from their high resistivity values). While high longitudinal conductance value corresponds to excellent and good APC, low longitudinal conductance values are associated with poor and weak APC.

Based on longitudinal conductance values, overburden units can be classified into excellent, very good, good, moderate, weak and poor aquifer protective capacity. Overburden units with longitudinal conductance value >10 mhos give an excellent APC, and longitudinal conductance values ranging from 5 to 10 mhos give rise to very good APC. Longitudinal conductance values in the range of 0.7–4.9 mhos and 0.2–0.69 give rise to good and moderate APC ratings, respectively. Weak and poor APC ratings are defined by longitudinal conductance in the range of 0.1–0.19 and <0.1 , respectively.

Figure 13 presents the spatial distribution of the longitudinal conductance of the overburden units of the study area, with highest and lowest values around places such as Bwari and Zuma respectively. In order to categorize the aquifer protective capacity of the area, aquifer protective capacity rating model (after Henriot 1976; Oladapo *et al.* 2004; table 4) was employed. Four aquifer protective capacity zones, weak 0.1–0.19, poor < 0.1 , moderate 0.2–0.69 and good 0.7–4.49 were delineated. The good and medium aquifer protective capacity zones coincide with zones of appreciable overburden thicknesses with clayey column and low resistivity while the weak and poor zones coincide with zones of shallow or thin overburden and high

Figure 12. Soil corrosivity map of Bwari basement area.

Figure 13. Spatial distribution of longitudinal conductance of the overburden units.

Table 4. Longitudinal conductance/aquifer protective capacity rating.

Longitudinal conductance (mhos)	Aquifer protective capacity rating
> 10	Excellent
5–10	Very good
0.7–4.49	Good
0.2–0.69	Moderate
0.1–0.19	Weak
< 0.1	Poor

Source: Henriet (1976) and Oladpo *et al.* (2004).

electrical resistivity. The aquifer protective capacity map of the study area (figure 14) revealed that about 60% of the area covered by poor and weak

aquifer protective capacity zones are vulnerable to surface contamination sources (leakage from underground petroleum storage tanks, infiltration of leachates from decomposing of open refuse dumps and diffuse pollution from agricultural activities) in the area. The good and moderate aquifer protective capacity zones which constitute 40% of the area have higher attenuation property on contaminated fluids so that in the face of contamination such zones are apparently safe.

5. Conclusions

Surface geoelectrical investigation has been applied to environmental study of Bwari basement complex

Figure 14. Aquifer protective capacity map of Bwari basement area.

area. The results revealed the efficiency of electrical resistivity surveys in delineating different zones of soil corrosivity of the topsoil units and the aquifer protective capacity of the overburden units.

The northern, southern, western and eastern parts of the study area with high resistivity ($\rho > 180 \Omega\text{m}$) topsoil are precisely noncorrosive. While a section of the central part of the study area contains corrosive topsoil with low resistivity ($\rho < 180 \Omega\text{m}$); metallic utilities/pipes, etc., required for reticulation works buried within the superficial layer in the area are susceptible to corrosion suggesting a significant contribution of clayey matrix in the layer.

Four distinct aquifer protective capacity zones were defined, namely poor, weak, moderate and good. The rating was based on longitudinal conductance values. Vertical electrical sounding stations, whose computed longitudinal conductance values range from 0.7 to 4.9 mhos, 0.2 to 0.69 mhos, 0.1 to 0.19 mhos and <0.1 mhos are respectively classified as good, moderate, weak and poor aquifer protective capacity zones. Poor and weak aquifer protective capacity zones are very vulnerable to contamination, while areas of moderate and good aquifer protective capacity zones are less vulnerable to contamination.

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