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Estimation of groundwater reserve in unconfined frequently exploited depth of aquifer using a combined surficial geophysical and laboratory techniques in The Niger Delta, South – South, Nigeria

[1]George, N.J., [2]Obianwu V.I. and [3]Obot, I.B

[1]Department of Science Technology, Akwa Ibom State Polytechnic, Akwa Ibom State, Nigeria
[2]Department of Physics, University of Calabar, Calabar, Nigeria
[3]Department of Chemistry, Faculty of Science, University of Uyo, Uyo, Nigeria

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ABSTRACT

Twenty-three profiles of vertical electrical soundings (VES) were obtained in the Niger Delta area of Nigeria, to estimate the usable capacity of groundwater reserve and the flow direction. The combination of the VES data, borehole data and laboratory analysis provided useful information on subsurface hydrogeologic conditions as well as quantitative description of the geometry of the exploitable aquifer in the study area. The resistivity and aquifer thickness were used to generate litho- and hydro-resistivity cross sections within the area. The static water levels measured in wells were also used to predict the flow direction while a surfer software programme helped a great deal in combining the porosity data from laboratory analysis and surface geoelectric data in estimating the natural groundwater reserve in the survey area.

Keywords: Vertical Electrical Sounding (VES), Schlumberger array, Niger Delta, Groundwater reserve, Aquifer total thickness and porosity.

INTRODUCTION

Although groundwater is a renewable resource, fear is being nursed about its imagined danger in case of inadequacy. The universality of its utility heightens the degree of fear as no other fluid can replace the uncountable roles played by water in the life of plants and animals. Groundwater is ubiquitous but sometimes its availability in economic quantity depends solely on the distribution of the subsurface geomaterials which are referred to as the aquifers. This implies that where groundwater is not potentially endowed enough, there may be either complete lack or inadequacy due to increasing industrial and domestic needs [1, 2]. The thickness and the distribution of water bearing geomaterials sometimes do not really predict the potential reserve since some of the delineated aquifer might be ideally non porous, dry and non prolific [3]. The determination of porosity of the saturated delineated geomaterials is the sure way of estimating the usable capacity of aquifers and the groundwater reserve in a given area [4]. This traditional technique measures the geometry of the aquifer and the portion of it that is saturated with groundwater which is now gradually replacing the surface water that is degraded in many ramifications.

This work was carried out to ward off the uncertainty in the availability of water in the study area. Before now, several hydrogeological studies in the area were all about estimation of ensemble of sand grains and the aquifer potential based on the surficial measurements of aquifer lithological attributes such as resistivity, thickness and depth of the aquifers [5 – 8]. This present work is practically conceived to quantitatively estimate the natural reserve of groundwater in the economically exploited depths of aquifer and this makes it unique and different from the previous geophysical studies in the area.
Successful exploration, exploitation and management of groundwater require a good knowledge of the spatial distribution of aquifer hydraulic parameters such as lithology, thickness, usable capacity and other hydraulic properties. Where such information are not available, geophysical surveys should be performed. Drilling and pumping tests are commonly used for evaluating aquifer characteristics. However, they are time and cost-consuming [9]. Electrical resistivity is widely considered as a useful parameter for hydrogeogical studies because the value is mainly controlled by lithological conditions of the aquifer. It also can be useful in correlating lithological facies between wells [10, 11]. Thus, the geoelectrical column and cross-sections deduced from the vertical electric sounding (VES) can provide an effective way to image the vertical and lateral variations of subsurface hydrolithology with a minimum need of observation wells. However, resistivity values are also sensitive to the porosity and water content of the aquifer as well as to the mineralization and salinity of groundwater [12 – 15]. Because of such complicated factors affecting the resistivity values, the lithology and water quality effects cannot be differentiated by the geoelectric resistivity survey alone [15]. For an affective use of geoelectric resistivity data to the hydrogeologic study, the correlation between the real data lithology logs and the field data is strongly recommended.

The main purpose of the present study is to provide information on the subsurface lithology and groundwater reserve for hydrogeologic interpretations using the integration of the geoelectric resistivity measurements, direct observation of lithology from borehole information and the laboratory measurements on the core samples obtained from the boreholes within the study area. A discussion on the relationship between th resistivity data obtained indirectly and the information obtained from the drilled hole is necessary in this work to evaluate the usefulness and limitation of the earth resistivity data in subsurface hydrogeologic investigations.

Geologic and hydrogeologic settings
The study area lies between longitudes $7^{o}45^{1}$ to $8^{o}10^{1}$E and latitudes $4^{o}30'$ to $5^{o}10'$N (Fig. 1). The geology of the area is Recent to Tertiary Sediments belonging to the Benin Formation. This formation is the youngest geologic unit in the Niger-Delta Sedimentary Basin. This formation comprises continental sand and gravel, deposited on the upper deltalic plain environment. The grain sizes range from coarse to fine sand in textures and are poorly sorted [16]. They are also thick and friable with minor intercalations of clay, silts and sandstones in the area mapped. The alternative sequence builds up multiple-aquifer systems with various thicknesses [17, 18]. Thus in the study area, the aquifer systems have been found to be a combination of ensemble of different grain sizes of sands.

The survey area sits on a relatively flat terrain and is drained actively by the Kwa Ibo River. It has humid tropical climate, characterized with two distinct seasons – the wet and dry seasons. Most of the coastal areas in the study area usually have salt-fresh water interface at certain depths. The aquifers are predominantly unconfined to semi-confined and this makes them to be water table aquifers. The static water levels in the area have minor variations and the results are minor hydraulic gradients observed in the area. The general recharge is from the surface flows and from the rivers which surround the study area [19].

MATERIALS AND METHODS

For this study, a total of 23 VES profiles were obtained in July 2010, using the OYO Mc OHM resistivity meter (Model 2115A) with the Schlumberger configuration (M-AB-N) Fig. 2. For each VES profile, the distance between potential electrodes MN was gradually increased in steps starting from 0.5m to 15m to obtain a measurable potential difference. The half current electrodes separation $\left(AB/2\right)$ was usually increased in steps starting from 1 to 300m or 400m depending on the accessibility.

The interpretation of the VES data was conducted using the Resist software which produces the resistivity model (resistivity, thickness and depth) fitting the aquifer field data with the least RMS-error between the observed and calculated resistivities. The iteration was performed until the fitting error between field data and theoretical model curve fell less than 10%. Because the resistivity of sediments depends on lithology, porosity, water content, clay content and salinity [12], it is important to correlate the VES results with the lithological and hydrological information obtained from adjacent boreholes [20]. Four boreholes B- 1, B – 2, B – 3 and B – 4 closed to the VES stations, VES-EK_1, VES-EK_8 VES-ONN_5 and VES-NS_6 respectively were used for the correlation Fig. 1

For the porosity, the core samples of aquifer of the twenty three boreholes drilled all over the study area by the Millennium Development Goals (MDGs) sponsored programme were obtained and processed for effective porosity measurements. The samples were cored using coring machine with sample corer of 750mm in diameter. The core samples were cut into cylindrical shape in order to calculate their volume.

To remove the original liquid and salt in the samples, they were washed with distilled water to clear them from clay and silt from coring operation [21]. Since prolonged soaking was unsatisfactory, the samples were put in a desicator and evacuated at a pressure of 0.3mbar for a period of 1hour according to [21]. At the end of this, deaerated distilled water was introduced into the desicator until the water completely covered the samples. They were soaked for 24hours to allow salts within them to diffuse into the surrounding solution. The clean samples were dried in a conventional temperature-controlled oven, utilizing a constant temperature of 105 degree Celsius for 16hours [22]. It was considered that reversible changes cannot take place at this point.

The dry core samples were cooled off in a desicator to ambient air temperature prior to being weighed. An electronic top pan balance of the least count error of 0.01g was used to weigh the sample. Before measurement of the wet weight of the samples, the diameter and length of the samples were taken and the average was found. For the saturation of the samples, vacuum pressure of 0.3mbar was used and the time of soaking of 16hours was used.

The effective porosity of each sample was calculated using the following relationship:

$$\Phi = \frac{(w_w - w_d)}{V} \times 100\% \tag{1}$$

where: Φ = effective porosity in %
w_d = dry weight in gm
w_w = wet weight in gm
v = volume in cm^3

The calculated effective porosities were converted to percentages as shown in Table 1. The results of the surficial geophysical measurements of resistivity, depth and thickness and the laboratory measurement of porosity were further analysed by using the surfer software to contour and image the quantities using the reference coordinates of easting and northing in metres. The contouring and imaging results in 2 and 3-dimensions were diagnostic of the useful information used in the estimation of groundwater reserve in the survey area.

Table 1: Table showing reference coordinates and calculation of effective porosity (ø) for aquiferous core samples of the different VES locations

VES Code	Dry weight (gm)	Wet weight (gm)	Wet weight – Dry weight	Volume Cm^3	Porosity %	Reference coordinate x(m)	Reference coordinate y(m)
EK_1	216.51	235.71	19.2	100.51	19.10	1285	14153
EK_2	224.31	241.84	17.53	-ditto-	17.44	1530	40402
EK_3	214.78	234.93	20.15	-ditto-	20.05	1620	17995
EK_4	212.50	230.61	18.11	-ditto-	18.02	3105	44803
EK_5	233.86	250.31	16.45	-ditto-	16.37	22039	12455
EK_6	203.86	233.56	29.68	-ditto-	29.51	22597	41084
EK_7	251.21	256.87	5.66	-ditto-	5.63	23960	14812
EK_8	247.34	250.11	2.77	-ditto-	2.75	22966	16018
ONN_1	248.87	253.74	4.87	-ditto-	4.84	0(reference)	0(reference)
ONN_2	232.41	239.72	7.31	-ditto-	7.27	2692	8970
ONN_3	241.07	249.22	8.15	-ditto-	8.10	1452	7908
ONN_4	234.63	244.19	9.56	-ditto-	9.51	1575	4088
ONN_5	202.09	229.73	27.64	-ditto-	27.48	3396	6724
ONN_6	205.10	241.31	36.21	-ditto-	36.00	22497	2446
ONN_7	199.88	239.59	39.71	-ditto-	39.48	22966	8344
ONN_8	185.17	225.48	40.31	-ditto-	40.08	28528	6423
NS_1	240.23	250.44	10.21	-ditto-	10.15	24060	15147
NS_2	165.28	203.43	38.15	-ditto-	37.93	30237	13973
NS_3	214.21	246.66	32.45	-ditto-	32.27	23502	15359
NS_4	212.79	252.11	39.32	-ditto-	39.09	29199	12131
NS_5	194.69	231.47	36.78	-ditto-	36.57	36861	12488
NS_6	198.79	238.89	40.21	-ditto-	39.98	27241	18196
NS_7	205.71	234.16	28.45	-ditto-	28.28	36459	22251

The geoelectric cross sections in the study area also give useful information that substantiate the spatial distribution of lithology and geometry of the materials that host the water.

RESULTS AND DISCUSSION

For effective interpretation that is devoid of error from the principle of suppression and equivalence on the inferred resisitivity data, correlations were performed between the borehole data and the interpreted data as shown on Figs 3- 6.

Based on the borehole lithology and geoelectrical column correlations, VES-ONN_4 and VES-EK_2 show similar litho-resistivity cross sections with the N-S trends. Again, the VES-NS_6 and VES-Ek_1 also show equivalent litho- and hydro-resistivity cross sections with the N-S trend as shown in the geoelectric cross sections in Figs 7 – 9. The static water levels have been identified to be from 12 – 25m as contained in the lithology log information and also as defined for the regions from survey by [2] in [6]. The geosections show three geoelectric layers for all the VES stations within the maximum current electrode separations. The layers from the top to the bottom are undifferentiated lateritic sand, fine sand and medium grained sand in Figs. 7 and 8 and lateritic sand, medium grained sand and fine sand in Fig. 9 respectively. The preferred aquifer in the region is a matter of choice between the fine sand and medium grained sand which is laterally distributed within the zones. Due to changes in facies, the resisitivity values vary between the different lithologic units and within the unit. The main groundwater table is identified at a depth of 17m by low resistivity ($251.4\Omega m$) VES-ONN_4, Fig. 7; 16m by resistivity ($525.7\Omega m$) VES – Ek_8, Fig. 8 and 10m by resistivity ($3372.5\Omega m$) VES – NS_1, Fig. 9 in lithohydrologic units of fine sand for VES-ONN_4 and VES-Ek_5 and medium grained sand in VES-EK_1 and VES-NS_1 respectively.

In cross section of Fig. 7, the fine sand overlies the medium grained sand in the northern part of the profile while the medium grained sand is more developed in the southern part of the zone. In geosection of Fig. 8, the fine sand is sandwiched with medium grained sand although this is seemed to be petered out at the deeper layer of the southern zone and shallow layer of the northern zone of the section. Fig. 9 shows a geoelectric section in which the medium grained sand is underlain by the convex shaped – fine sand. In all the three sections, the two aquiferous units (medium grained sand and fine sand) have 95% coverage of the entire column of the earth inferred. The orientations, the lithologic properties and the hydrogeological parameters favourably agree with the geology (correlation with lithology) and the previous work done within the vicinity by [1,2, 5, 7, 8]. The three sections were using data from profiles which were taken parallel to the flow direction according to [7]. The static water levels increase progressively from north to south (towards Atlantic Ocean) indicating apparently that the flow regime is toward the ocean. This is also gleaned from the available piezometric (water level) data which were used to prepare a two-dimensional contour map. The water levels increase from the south (discharge zone) towards the north (recharge zone) Fig. 10. This agrees with the nature of the terrain and affirms that discharge areas are topographically low while recharge areas are topographically high [24].

The lateral and vertical variations in the geoelectric columns which agreed well with lithology log indicate that VES profiles can be useful method to investigate the lateral and vertical variations of subsurface lithology as well as subsurface hydrology. The low resistivity values obtained in most of the layers are diagnostic of the thin layers of clay in lithoilogy logs which are suppressed in VES readings [25].

Estimation of groundwater reserve

From the inferred aquifer geometries, the total thickness of saturated layers was determined and the porosity estimated as explained in material and method. The inferred thickness data were used to compute the surface area and the volume as occupied in the subsurface, using surfer software. To the surface area of the three dimensional structure obtained from thickness data using surfer Fig.11, the total average thickness of all the aquifer was multiplied to have volume in (cm^3). The volume obtained directly from the software and the one obtained by multiplying aquifer average thickness to the surface area obtained from thickness data appeared almost the same and the average total volume between the two volumes were calculated. Using the surfer software, the thickness data were imaged to see the uniformity of the aquifer units Fig. 12. The result shows equilibrium distribution of the aquifer units with a reflection of minor variation in thickness at VES-ONN_4, ONN_5 and VES-ONN_8 where the image is darkest (Fig.12). The two dimensional image thickness distribution and the three-dimensional aquifer thickness elevation at their strategic locations shown in Figs. 11 and 12 are diagnostic of the saturated and potential groundwater reserve in the area. Mathematically, the usable volume capacity was evaluated using the equation 2: [4]

$$V = V_T \Phi \qquad (2)$$

Where V = usable volume (m^3)

V_T = total volume of the aquifer (9.2007×10^{10}) m^3 from software computation)

Φ = Average porosity of the unconfined aquifer which is 23%

However, to calculate the error in volume, the following relation was used.

$$\left(\frac{\Delta V}{V}\right) = \left(\frac{\Delta L}{L}\right) + \left(\frac{\Delta w}{w}\right) + \left(\frac{\Delta d}{d}\right) + \left(\frac{\Delta \Phi}{\Phi}\right) \qquad (3)$$

where ΔV is error in volume V; ΔL is error in length L; Δw is error in width w; Δd is error in depth d ($0.1m^3$) and $\Delta\Phi$ is error in porosity Φ (0.01%) . ΔL and Δw are almost negligible.

By substitution,

$$\Delta V = V(0 + 0 + 0.1 + 0.01) \qquad (4)$$

i.e $\Delta V = V(0.11)$ which is $1.01201 \times 10^{10} m^3$.

Therefore, the approximate volume of porous zone is 23% of the total aquifer volume. This implies that there exists $(9.2007 \pm 1.01201) \times 10^{10} m^3$ of water filling the pores of aquifer units in the study area.

CONCLUSION

The twenty-three VES profiles taken in the coastal region of Akwa Ibom State and the core samples of aquifer units obtained during drilling have proved to be significant in the estimation of natural groundwater reserve in the study area. The VES data analysis and the laboratory analysis of the core samples provided the aquifer total thickness and the porosity values which were used to estimate the usable capacity of about $(9.2007 \pm 1.01201) \times 10^{10} m^3$. Although this value is approximate and is open to further refinement, it provides a useful guideline which is significant in the groundwater management and exploitation in the area. The flow direction predicted using the water level elevation contour map in Fig. 10 is equally useful in the management of groundwater in the zone. Since this is a baseline study, it is recommended that groundwater geochemical and microbial analyses be carried out frequently to monitor the rate and kind of contaminations in the estimated groundwater usable capacity.

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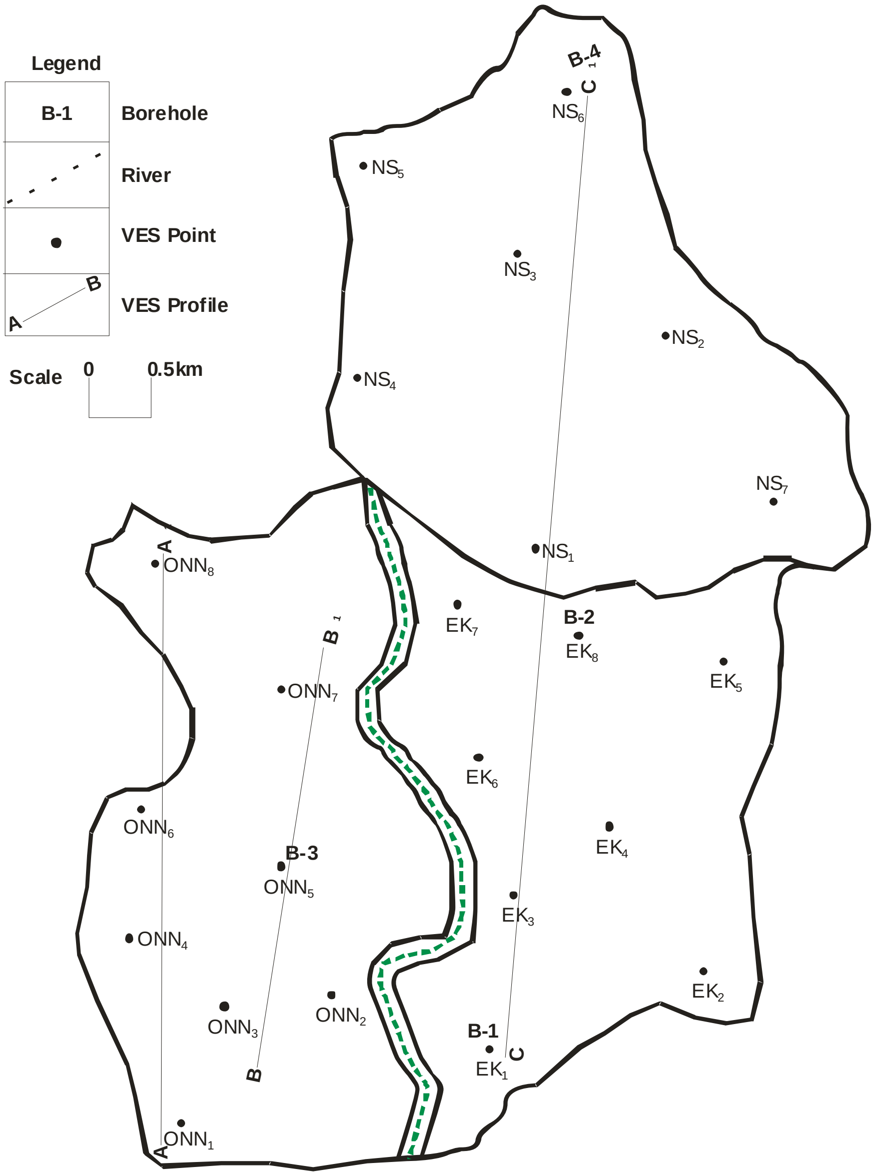
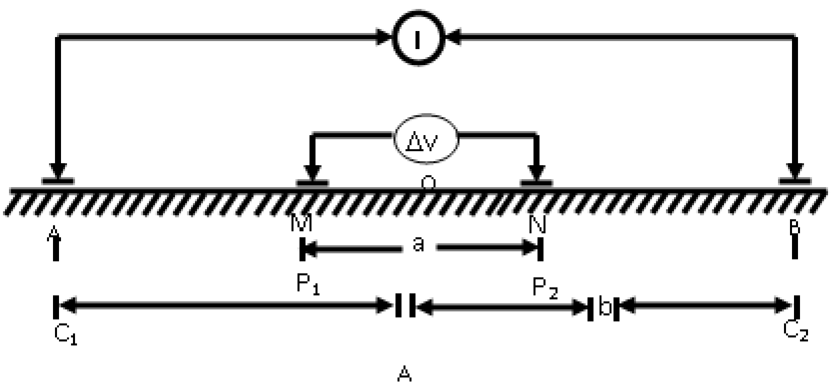


FIG. 1: Map Showing the profile and the borehole location in the study area.

Fig. 2: Sketch diagram of Schlumberger array used in resistivity data acquisition



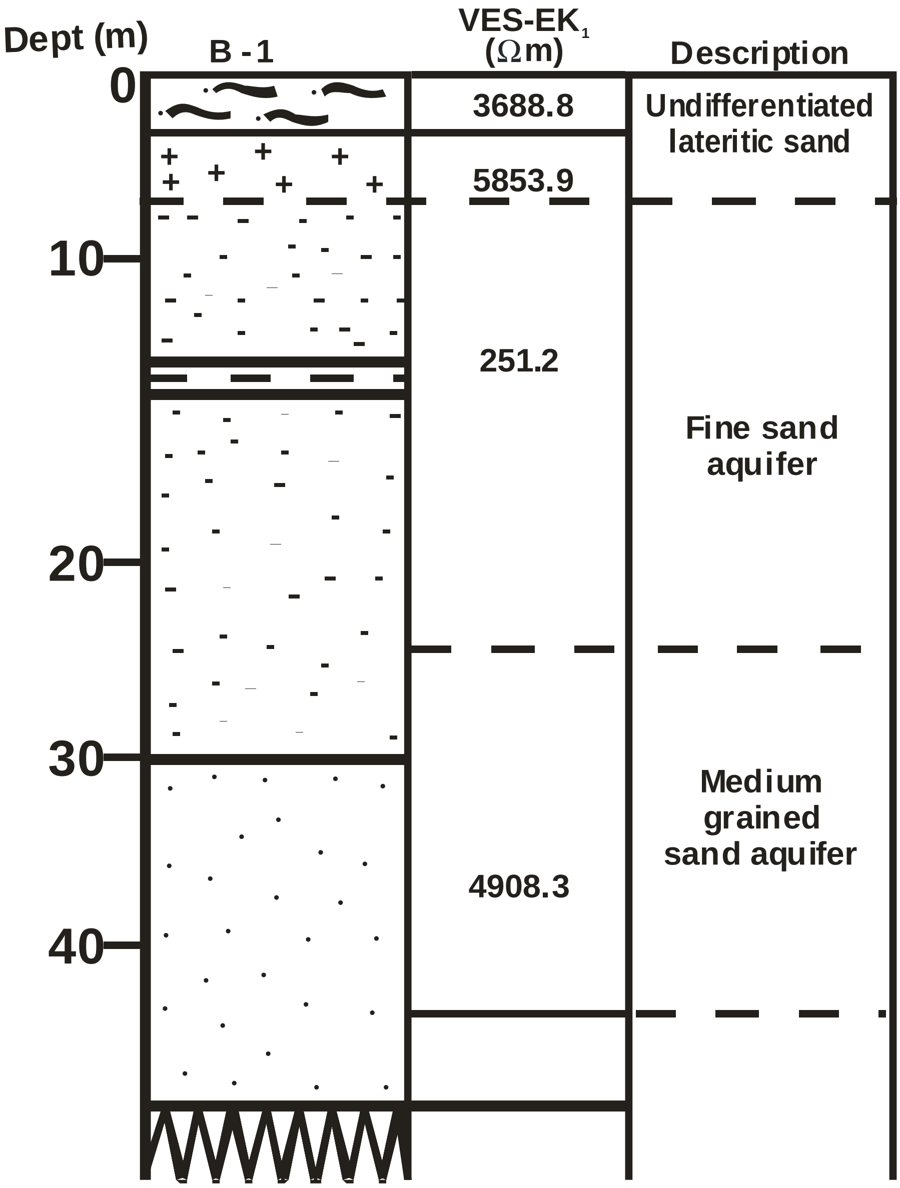


Fig. 3: Representative coordination of VES-EK$_1$ with lithology log of the nearby borehole (B – 1)

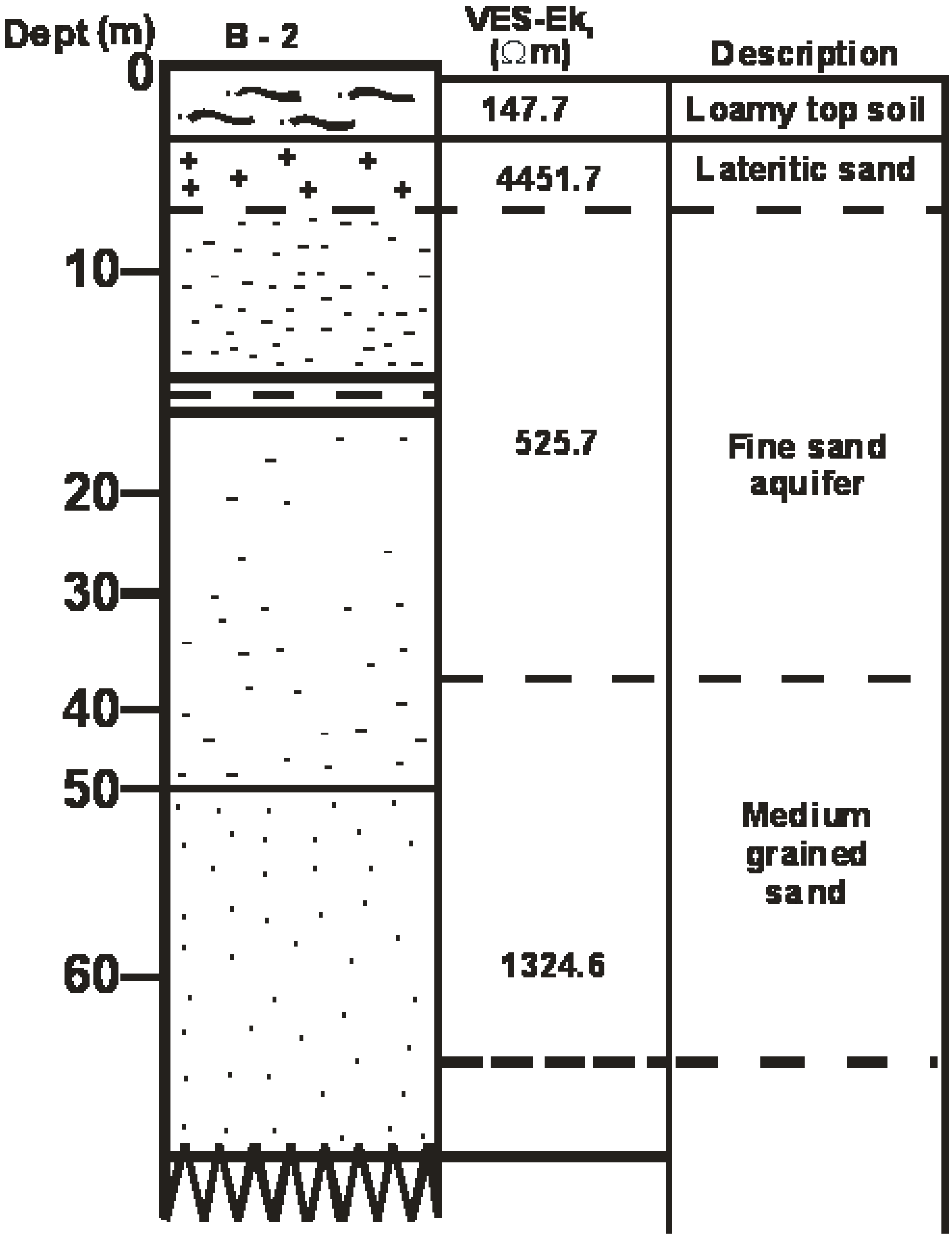


Fig. 4: Representative coordination of VES-EK$_8$ with lithology log of the nearby borehole (B – 2)

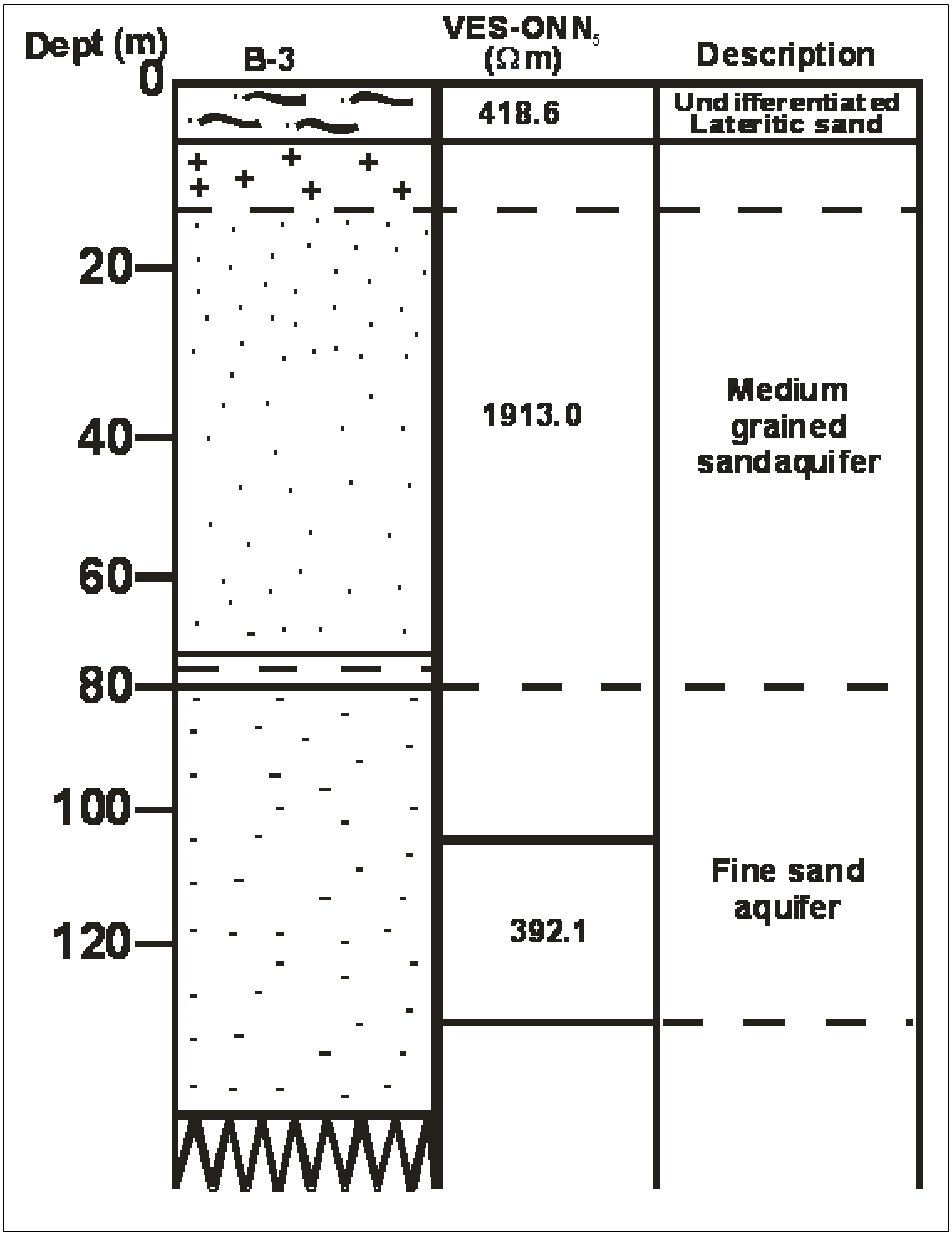
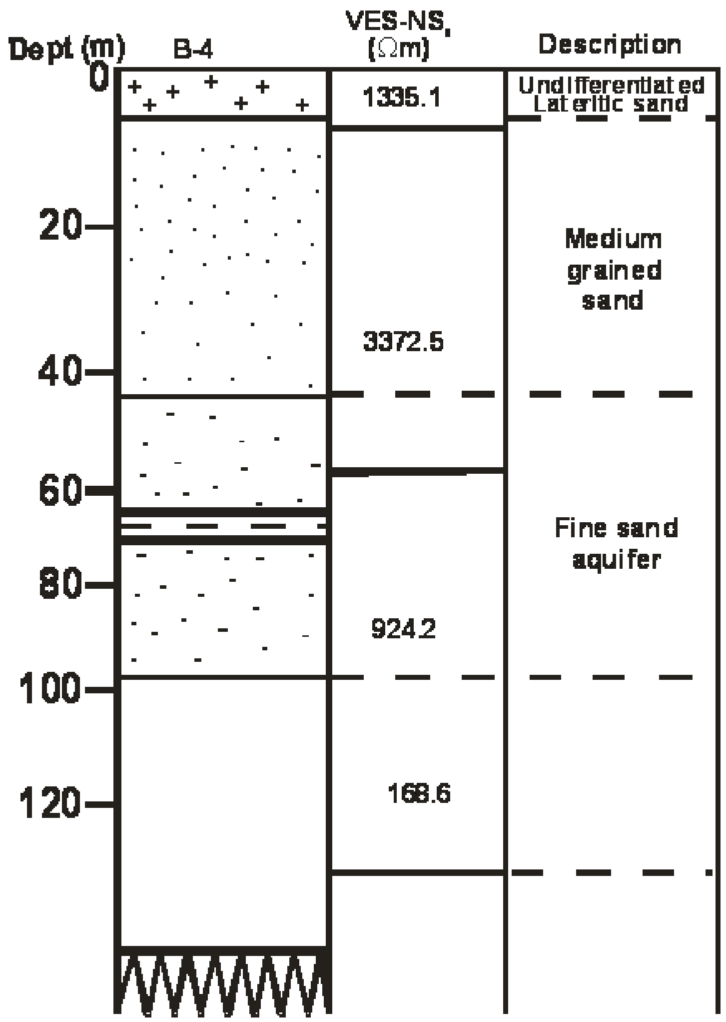
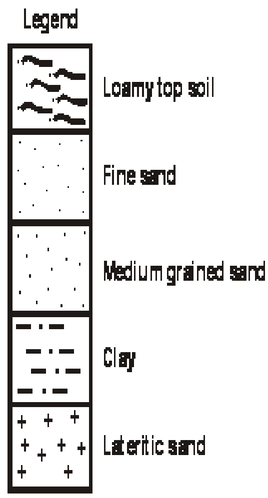


Fig. 5: Representative coordination of VES-ONN$_5$ with lithology log of the nearby borehole (B – 3)





General description of lithology in Figs. 3 - 6

Fig. 6: Representative coordination of VES-NS$_6$ with lithology log of the nearby borehole (B – 4)

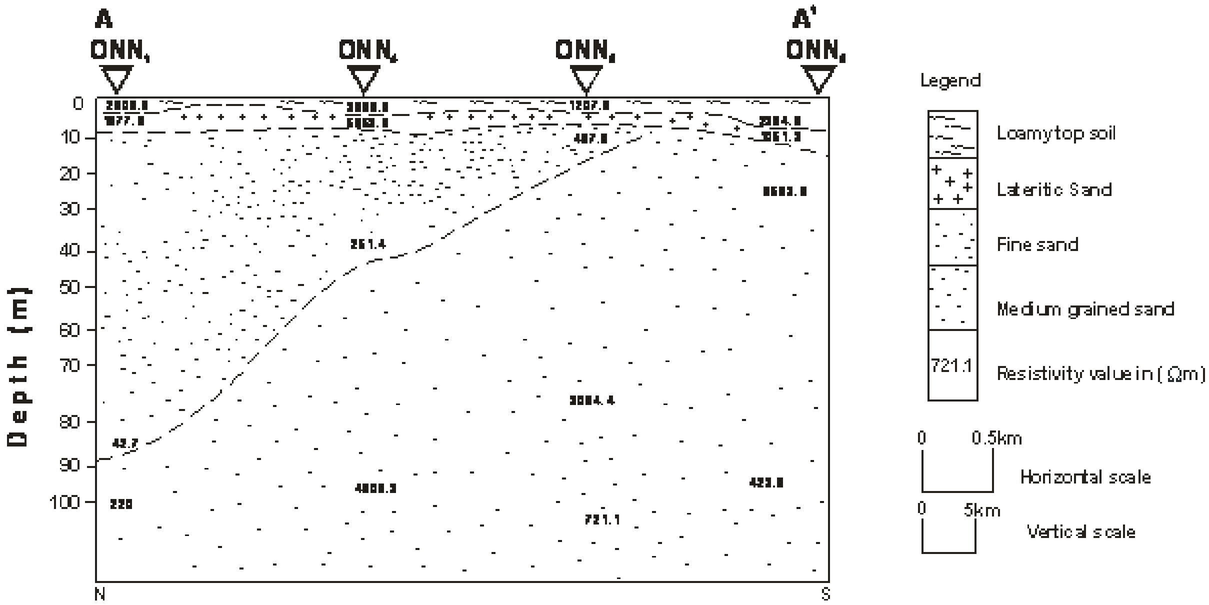


FIG 7: Equivalent geoelectric section along AA' in the coastal region of Akwa Ibom State

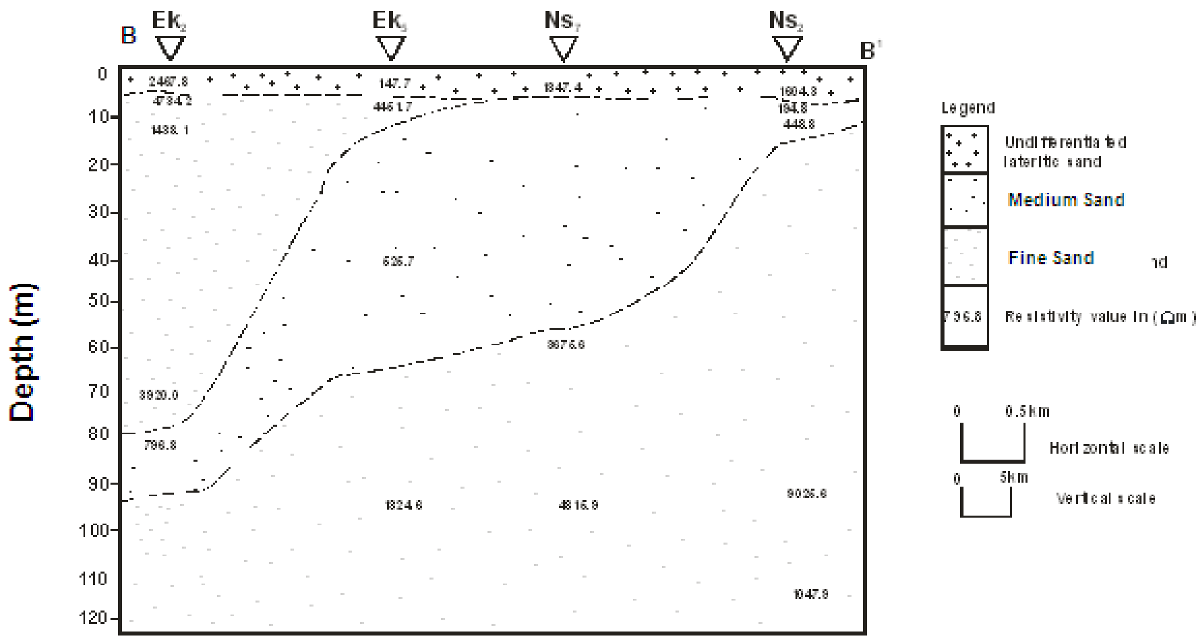


FIG. 8: Equivalent geoelectric section along BB[1] in the coastal region of Akwa Ibom State

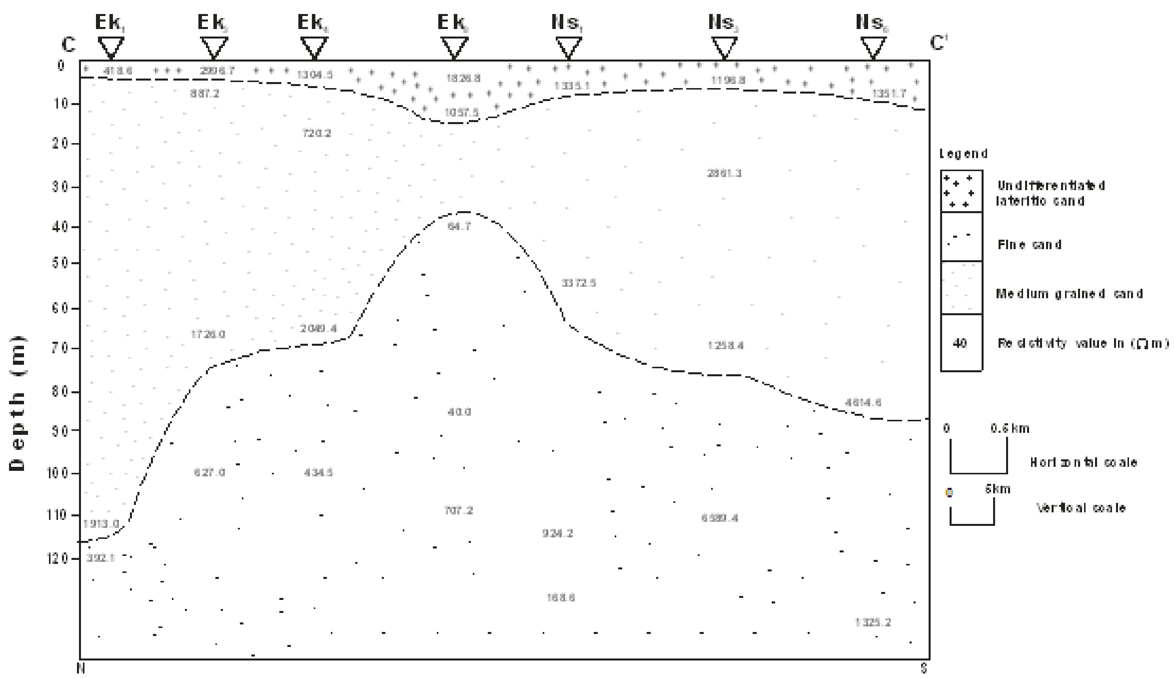


FIG. 9: Equivalent geoelectric section along CC[1] in the coastal region of Akwa Ibom State

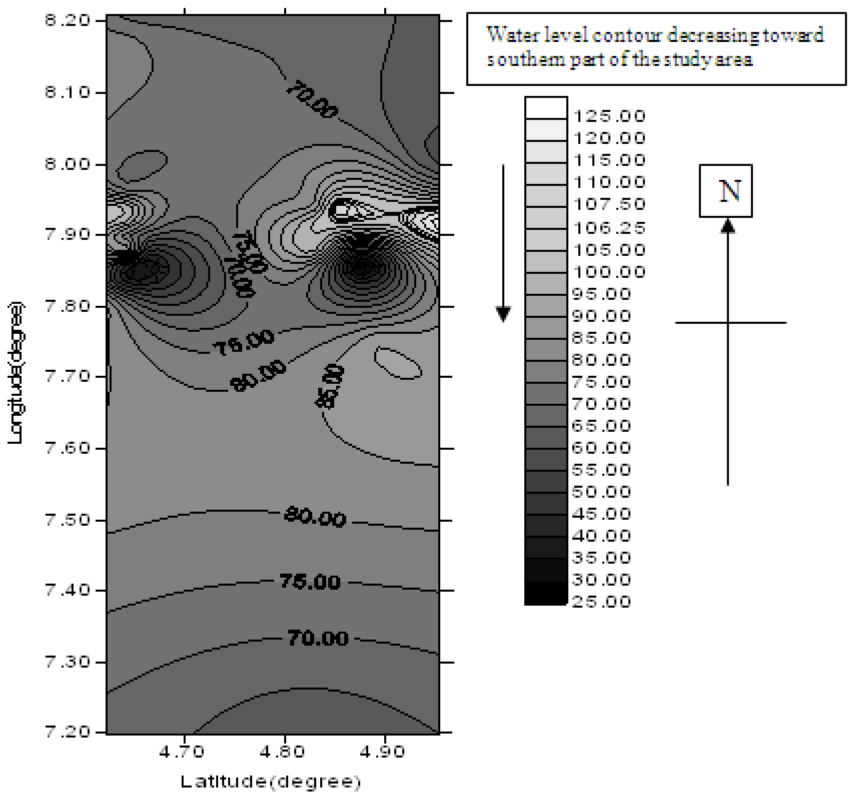


Fig.10: Contour map of water level decreasing from north to south of the study area

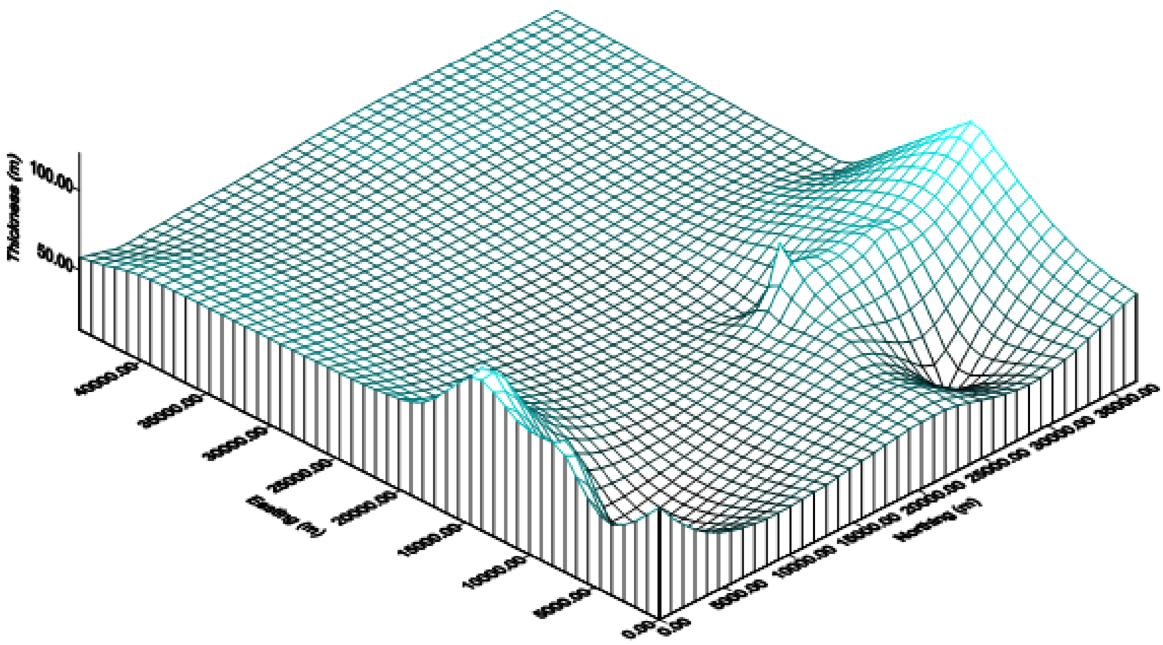


Fig.11: 3-Dimentional total thickness map showing thickness distribution in the study area

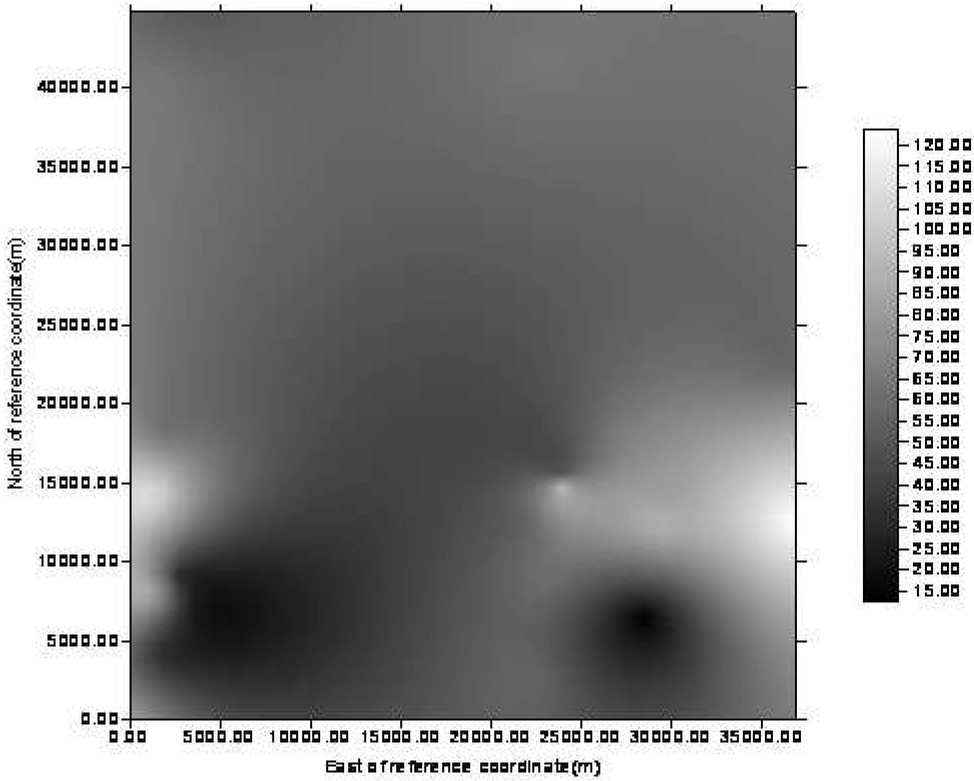


Fig.12: 2-Dimentional image of usable aquifer thickness distribution