Africa Journal of Physical Sciences 2 (1) (2015) 33-49

Geophysical investigations of Suyien Earthdam in Maralal, Samburu County, Kenya

KRHODA George Okoye[1,a*], AMIMO Meshack[2] and NYANDEGA Isaiah A.[1]

[1]Department of Geography and Environmental Studies, University of Nairobi, P.O. Box 30197-00100, Nairobi, Kenya.
[2.]Northern Water Service Board, P.O. Box, 495-7011 Garissa.

[a]george.krhoda@gmail.com*

ARTICLE INFO

Article History:
Available online 31 July 2014

Keywords:
water supply
geohydrology,
electrical resistivity
laggas

ABSTRACT

The Current economic and population growth has increased the water supply gap in Maralal, Samburu County. Water sources include boreholes, pans and the Suyien dam. Despite the high rainfall in the area, Suyien dam has never filled since its construction in March 2010. This study investigated the geological factors hindering the dam's impoundment of water. The aim was to determine the characteristics of the subsurface compromising this process. A desk survey of existing geological and hydrological reports as well as topographic and geological maps was undertaken. Analysis of laboratory tests, aerial photographs, electrical resistivity and trial pits was done. Results showed that the topography, dotted with several sinusoidal hills comprises Mozambiquan rocks, igneous intrusives, and Paleogene-Quaternary volcanics and sediments. Neo-Proterozoic and volcanic formations had surface joints and fractures implying secondary porosity and permeability. Hydrogeological information showed boreholes sited near rivers or laggas, yield about 1.4-2.5 m^3/hour and about 4 m^3/hour in volcanic rocks. Geophysical investigations showed subsurface rock sequences were fractured allowing groundwater leakage. Sediment deposition and vegetation growth at the dam's entrance also block water drainage into the dam. Suggested mitigation include, unblocking the dam's entrance to allow in surface runoff and the sealing of fractures with waterproof cement.

ISSN 2313-3317

1. Introduction

1.1 Water supply to Maralal Town

The present study in Maralal town, Samburu County, was prompted by the scarcity of water and the limited sources of water available for a growing population and economic fortune. The population of Maralal Town currently is estimated at 40,193 people and is set to increase at 5.8% per annum [1] with projected population of 53,282, 93,634 and 164,548 people for the years 2016, 2026 and 2036 respectively. There is an existing borehole at Nundoto (01^{0}02'45.9" N and 06^{0}40' 25.7" E, 1901m a.s.l) which contributes to Maralal water supply. There are two other boreholes located in a valley in Loikas Forest, Kirisia Division of Samburu District about 13 km North of Maralal Town. Further, Nundoto borehole with an average discharge of 4m^3/hr serves Elkorot community of about 400 people.

The combined yield for the current sources located at Nundoto Dam and the boreholes is 663 m^3/day against a demand of 4,500m^3/day rising to 13,451 m^3/day in year 2036. Water is pumped from Nundoto Dam (with a capacity of 230,000 m^3 and safe yield of 681 m^3/day) to a full conventional treatment plant (with capacity of about 836 m^3/day) through a 4 km UPVC Class E 6" rising main where it undergoes full treatment and stored in an 840 m^3 R.C [2]. The water is distributed through a 10 km network comprising 4" diameter UPVC and GI pipes to consumers.

The Suyien Dam, located on Loidongo stream, was constructed in March 2010 at an elevation of 2040m a.s.l and 300m upstream of a water pan. The catchment area of Suyien dam is 4.3 km2 with a slope of 8%. The design area of the reservoir is 22,800 m2. The maximum height of the dam is 9 m. The estimated annual runoff is 430,000 m3 while the design storage is 270,000 m3. The estimated evaporation loses is 41,040 m3. The dead storage is 107,500m3. The gross storage is 418,540 m3 with a crest width of 7m and a bottom width of 49.5 m. The embankment length is 100 m. There have been allegations that the use of porous soils, bad design of intake tower, inadequate catchment, that it was constructed on fault line and no grouting was done to seal it.

The county-wide water coverage is estimated at about 19.4% only. However, the majority of people in Maralal Town depend on existing Maralal Water Supply with an estimated coverage of 45.1%.This is supplemented by boreholes, traditional water sources and vendors concentrated in a 6km2 area against the town area of about 150 km2. Several options for water augmentation included construction of Suyien dam but the results have been very poor as a result of the dam not filling over the period. The present study investigates the geological factors hindering maximum impoundment of water into the Suyien dam. The present study will address causes of water losses from the dam and enhance water supply in Maralal town. The present study involved a desk survey of existing geological and hydrological reports, papers together with topographical and geological maps and aerial photographs of the area. After a field reconnaissance, electrical soundings were taken using terrameter, trial pit, and laboratory testing was carried out. The geophysical investigation was done in November 2012 to complement reports and interviews from expert water officers.

1.2 Climate

Samburu County falls within arid to semi arid region with annual mean rainfall of 200mm to 250mm. The relatively higher altitude of Maralal town raises the mean annual rainfall to 700 mm to 1000 mm which occurs in two rainy seasons and in 49 rainy days [3]. The long rains occur in March to May while the short rains occur from October to December. The rainfall distribution shows spatiotemporal variation with altitude and may be up to about 1500mm per annum. The lowest rainfall is observed in the eastern part of Maralal Town while the highest rainfall occurs at elevated areas such as Lpartuk Forest and in the forested highland area.

The mean temperatures range from 25^{o}C during the coldest month (June-July) and 35^{0}C during the hottest months of January to March. Mean annual temperatures are 30^{0} to 34^{0} C. High temperatures also raise evapotranspiration rates to range from 1800 mm to 3000 mm per annum. Over the hills, evapotranspiration rates of 1800mm per annum has been recorded [3].

2. Methods

The geology, soils, relief and surface and groundwater occurrence of/within the study area is based on literature review and groundtruthing. A total of 7 vertical electrical soundings (VES) were undertaken using an ABEM SAS 4000B Terrameter. The sites for VES were selected based on suitability of the terrain, accessibility and security considerations. Most of the dam area was dry at the time of measurements. The resistance, R, of a certain material is directly proportional to its length, L, and cross sectional area, A, expressed as:

$$R=\rho * (L/A). \quad (1)$$

where ρ is the specific resistivity, characteristic of the material and independent of its shape or size. With Ohm's Law:

$$R = V/I.$$
(2)

where V is the potential difference across the resistor and I is the electric current through the resistor. The specific resistivity was determined by the expression:

$$\rho = (A/L) * (V/I).$$
(3)

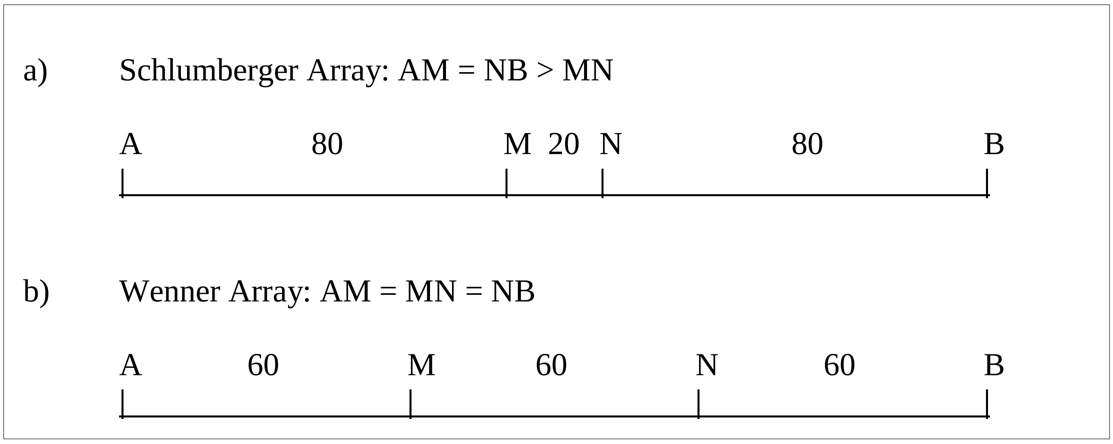

Figure 3: Schlumberger and Wenner Configurations for Resistivity Measurements (AB = current electrodes and MN = potential electrodes).

The measuring setup consists of a resistivity instrument (usually placed in the middle of the array), connected to two current electrodes (AB), and two potential electrodes (MN) towards the center (Fig. 3). When carrying out a resistivity sounding, an electrical current (I) is passed into the ground through two metal pins, the copper electrodes.

The calculated apparent resistivity is plotted against current electrode half separation on a bi-logarithmic graph paper to constitute a sounding curve. The curve depicts a layered earth model composed of individual layers of specific thickness and resistivity. A computer-aided curve fitting procedure based on a mathematical convolution method [8] was used. In general, the number of possible solutions is reduced by mutual correlation of several sounding curves, knowledge of the local geology and drilling data. The layered earth model is a simplification of the many different layers that may be present.

A measure of subsurface variations in electrical conductivity is obtained in terms of the voltage drop (V) between a second pair of metal stakes. The ratio (V/I) provides a direct measurement of the ground resistance and the electrode spacing and the apparent resistivity (ρ_a) of the ground is calculated.

A standard Gewin Modeling software was selected for use for 1D VES graphs. The electrical resistivity data generated were analyzed using the Schlumberger configurations. The current electrode spreads of up to 250m against potential spreads of between 5m and 25m were employed to conduct the surveys. Copper electrodes were used for the potentials while steel iron electrodes were used for the currents since the terrameter had an induced polarization (IP) capability.

Geoelectrical sounding data were calculated and analyzed digitally by using IP2 WIN Software that has a capability to analyze induced polarization data with some electrode configuration like Wenner-Schlumberger, Wenner Alpha, Wenner Beta, etc. Using IP2 WIN entails some steps. The first step involves data input directly from field data (sounding data consist of AB/2, V, I, and K) or indirect field data (sounding data consist of AB/2 and (ρ_a). The second step is data error correction, the third step is adding data point, and the fourth and final step is cross section creation. Observations along the dam banks showed that there were thin layers of laterites at the top of weathered gneisses. The VES for each site was computed and are shown in Fig. 8 to 14.

Output of sounding data analyzed using IP2 WIN software includes resistivity layer, log resistivity graph, resistivity-depth table, and pseudo cross section.

The VES data generated was then modeled using Tomographic Imaging software, IP2WIN [9] determine the lateral and vertical extents of the fractures picked in the electrical resistivity curves during electro-soundings. Tomography involves relationships between different rock layers existing at different VES points in a straight line. VES were used to generate tomographic images (TI).

3. Results and discussion

3.1 Geology of the Samburu County

The undulating topography dotted with several sinusoidal hills reflect the general geology of Samburu County. The area stands at an average altitude of 2051m a.s.l. within a steep-dipping terrain punctuated with several ant hills and flood plains both on the south eastern and north western flanks. The County lies on the eastern shoulder of the Rift Valley and can be subdivided into two major geological divisions. The eastern side covered mainly by the Mozambiquan rocks interspersed with occasional igneous outliers which occupies roughly two thirds of the county. The western side constituting one-third of the county, on the other hand, is covered by basic lava of Paleogene-Neogene volcanics of the rift valley (Fig. 1).

The lithology may be classified into four major groups, namely, metamorphic rocks of the Neo-Proterozoic Mozambique Belt, igneous intrusives, Paleogene-Neogene volcanics and Quaternary volcanic and sediments. The sediment deposits were altered by tectonothermal events to form gneisses, schists, quartzites and marbles with large areas underlain by migmatites. These events were followed by successive stages of uplift and erosion, lasting until the Paleogene when lavas flooded Mozambiquan rocks, producing basalts in the early stages and phonolites and trachytes in later stages (Fig. 1). Recent deposits which consist of alluvium and colluvium, calcareous and lacustrine sediments, agglomeratic ash and residual soils have formed from weathering of the Mozambiquan rocks and the Paleogene volcanics with subsequent deposition on the lower regions and river valleys.

The igneous rocks are mainly granodiorites and granites but also include relatively small outcrops of pegmatites, quartz reefs, aplites and diorites. Only the major outcrops consists of foliated granites which often form inselbergs and hills, and granodiorites outcrop east of the Mathews

Range. Locally, underneath the volcanics, subvolcanic deposits of probably Lower Miocene age consisting of well rounded pebbles are fluvial erosion products of the Mozambiquan rocks.

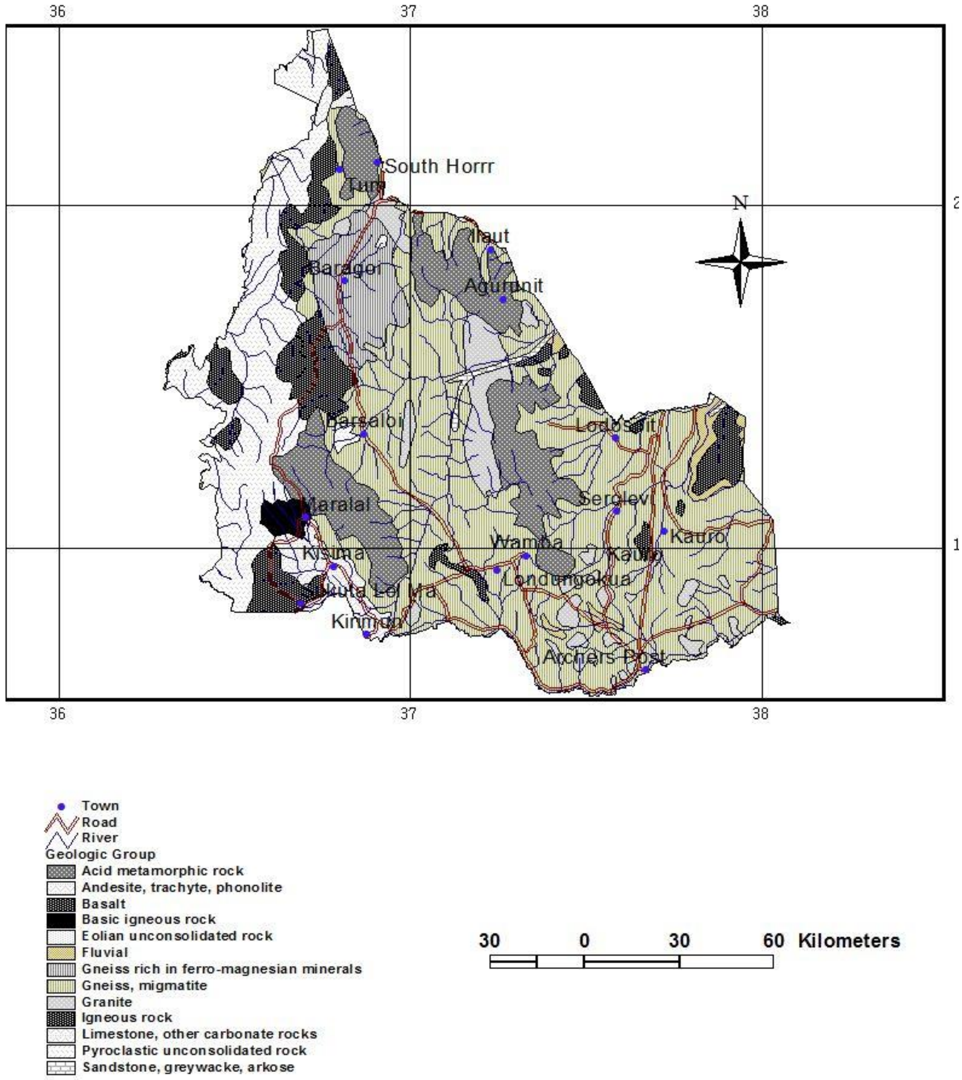

Figure 1: Lithology of Samburu County. The eastern part is covered mainly by gneisses and migmatites while younger volcanic and sedimentary successions cover the western part.

In the west, on the Rift Valley shoulder, the lower layers are more basaltic while the upper ones more phonolitic and trachytic. Volcanicity began in the area with the extrusion of an extensive series of basaltic pyroclasts and lavas, the Samburu basalts, followed by plateau phonolite and tuffs. Late Miocene to recent basalts and trachytes erupted over the western and northern extremities of the eastern shoulder. In the east, volcanicity began in the middle Miocene with the deposition of plateau phonolites and basalts [4]. The Mozambiquan rocks and volcanic species have surface joints and fractures, alluding to intense forces of fracturing, faulting, minor cracking, pneumatolysis and plate tectonics in the Precambrian orogeny and the Quaternary vulcanicity episodes.

The Quaternary sediments include alluvial infill and overspill to most water courses, calcareous deposits, Kunkar limestone, lacustrine deposits, agglomeritic ash, residual soil and colluvium passing laterally into talus at the bases of major hills. Sinuous and braided shallow channels related to sporadic flow after the last heavy rains are marked by medium grained sands with gravel bars which top the alluvium.

3.2 Relief Features

The relief of the county has a north-south ridge on the flanks of the Rift Valley running from Mount Nyiro Ndoto (2752 m.) through Baragoi, Maralal (2531 m.) and Suguta and another ridge on the east running from Aguru, Mathews Range and Wamba (2688 m.).The ridges form the major drainage divide (Fig. 2).

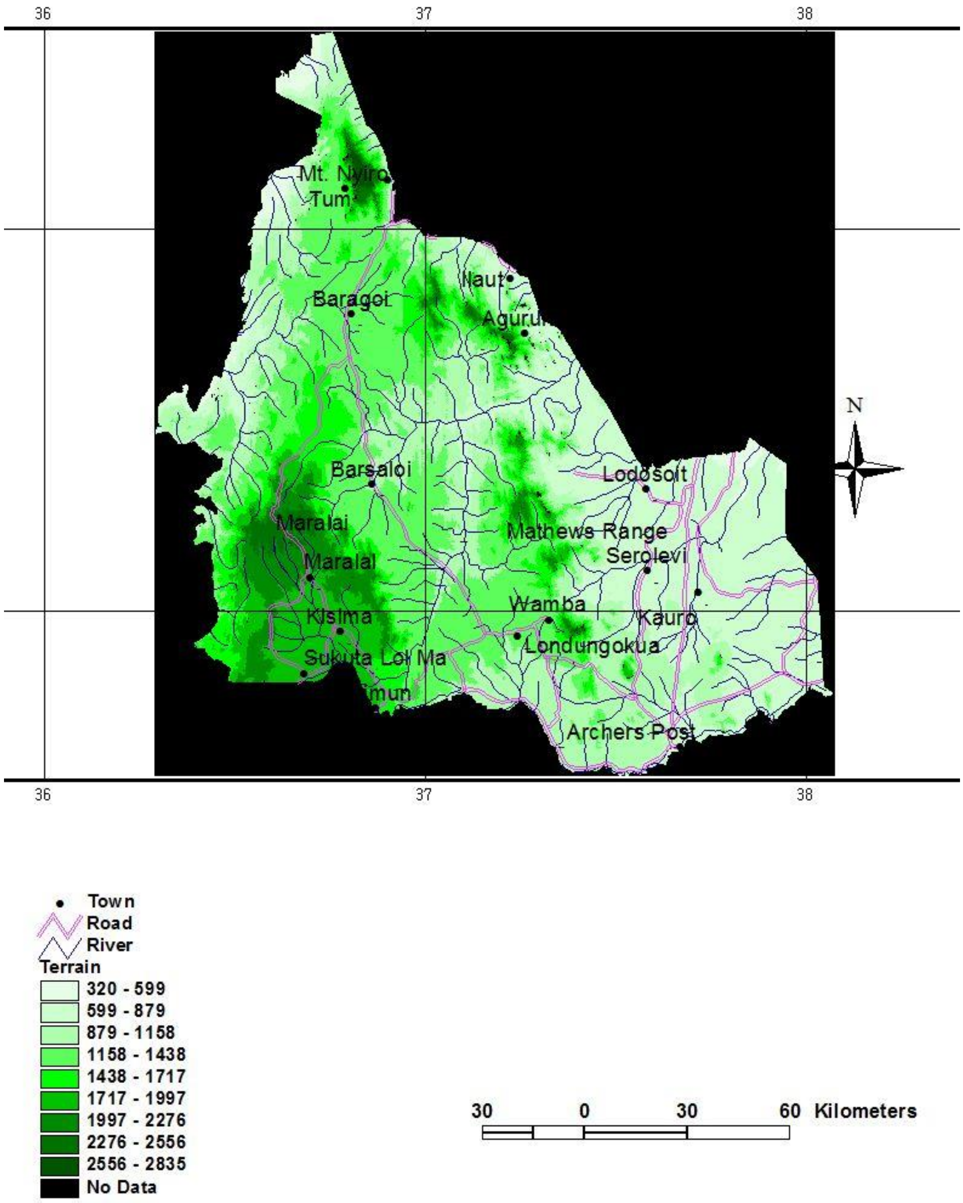

Figure 2: Major Relief Features of Samburu County. Note the drainage divide indicated by easterly and westerly flowing rivers. The central and western parts of the area are the highest (>1700m).

3.3 Soils

The soils vary with altitude and steepness of the terrain. Thick humus-rich topsoil occur over deeply weathered rock and are common at higher altitudes with forest cover. The mountains and hills are surrounded by long straight, sedimentary foot slopes, deep, well drained sandy loam soils in the upslope parts, merging towards sandy-clay textures downslope. Foot slopes are subject to widespread gully erosion, often of dramatic dimensions. This is due to the pastoralist's preference to establish *manyatta's* at the upslope side of foot slopes. Residual soils are rarely more than 2m thick and are mostly red-brown sandy loams with local variations related to underlying bed-rock. The area possesses soils with medium permeability, comprising of sands, gravels, clays and/or sandy loams. This low permeability enhances its ability to withstand soaking via capillarity effects. All colluvium is a crudely stratified, poorly sorted mixture of lithiclasts, sand, silt and clay which is thickest around peripheries of major hills. Calcareous deposits are found to occupy river valleys.

3.4 Surface and groundwater occurrence

Surface water is available in small quantities from River Ewaso Ngiro, the only major perennial river, at the southern border. High rainfall of about 700-1000 mm/year in the mountain ranges recharges springs in the lowlands. Most rivers in Samburu flow for short periods after rain. Dams and pans are common but their storage capacities have been reduced by siltation. The chemical quality of the surface water is generally good, however, bacterial contamination is common.

The river channel that would discharge into the Suyien dam has been colonized by vegetation while the forested arm of the river blocks flow into the dam. The river channels and laggas (dry river valleys) are fracture-controlled as is manifested by sudden angular changes in the channel courses (Fig. 3). Major lineaments trending roughly north-south were observed from both the aerial photographs and LandSat imageries. A large Quaternary alluvial patch has formed south of Maralal town along the convergence of major laggas. These alluvial sediments are generally shallow and of limited extent to allow groundwater occurrence in significant quantities [5]. Additionally, groundwater fluctuates due to short recharge periods and prolonged droughts. Although groundwater quality in laggas sediments is usually good, it is perceptible to bacteriological contamination especially in unprotected dug wells with some indication of salinity (>500TDS) (Table 2).

The Mozambiquan rocks and the young volcanics are fairly fractured and hold groundwater in fractures, faults, as well as the contact zones between the volcanics and the metamorphic rocks or in the weathered zones. However, fractures and faults are of limited extent and therefore groundwater quantities are low. The groundwater in the upper sediments receives an annual rainfall recharge through direct infiltration while the deep-seated zones may be recharged via regional flow aided by the faulted channels [6]. In order to attain the maximum yield for optimum recharge of the groundwater, boreholes are sited near rivers or laggas where the yield is on average 1.4-2.5 m^3 /hr (Table 2).

Paleogene-Neogene volcanics occur generally over large relatively continuous areas and have relatively high infiltration capacity and hydraulically interconnected fissures. Lineaments within the volcanics are more easily discerned on the basaltic rocks, while the ones on the phonolites are covered by red and loamy soils formed from weathered rocks [6]. The recharge potential in this terrane is generally good with boreholes yielding on average 4 m^3 /hr. The water strike level is 80m (Table 2).

Table 1: Summary of the present yield from the boreholes.

	Borehole Name	Yield [m^3/day]
1.	L Partuk	1080
2.	Nontoto	90
3.	Shabaa	38.4
4.	Ledero	120
5.	Nundoto	96
6.	Loikas	60
7.	Kirisia	1092.6
8.	Total	**3,483.6**

Table 2: A summary of groundwater characteristics in Samburu County

Groundwater	Description	Tested Yield	Water Level		Quality
		Mean (m3/hr)	Struck (m)	Rest (m)	
Medium to High	Alluvial deposits along main laggas	0.5 - 3.0	0 - 2	0 - 2	Good
Medium	Contact zones intrusives	9	11	6	Fair
	Plateau phonolites	4	80	50	Good (TDS=500mg/l) though high fluoride
Low to medium	Pelitic basement	25	40	30	Variable but mostly bad (TDS=3000mg/l)
	Undivided basement				
	Granitic basement	1.4	24	16 (but 30% dry)	TDS=300 - 1800mg/l
	Magmatic basement				
Low	Western strip, volcanics	No data	Very deep	Deep	No data but probably acceptable
Very low	Mountain Ranges	Very low	Very low	Very deep	Good
	Inselbergs	Very low	Very low	Very deep	-
	Small plateau basalt areas	No data	Very low	Very deep	-

3.5 Vertical Electrical Soundings

The geological sequence and hydrogeology of the area were used to interpret the resistivity measurements (Figs.4-10). The crystalline rocks and volcanics are heavily fractured and lineaments could be detected on the surface. The laggas also follow fractures implying high water infiltration. Table 2 shows that groundwater in Mozambiquan rocks was reached after drilling between 24 m and 40 m while in Paleogene-Neogene rich aquifers were reached at 80 m. The areas of colluvium, alluvium and lacustrine sediments formed high groundwater at less than 2m. The types of rock formation in Table 3 have been based on field evidence along dam banks and eroded gullies, geological and geohydrological information.

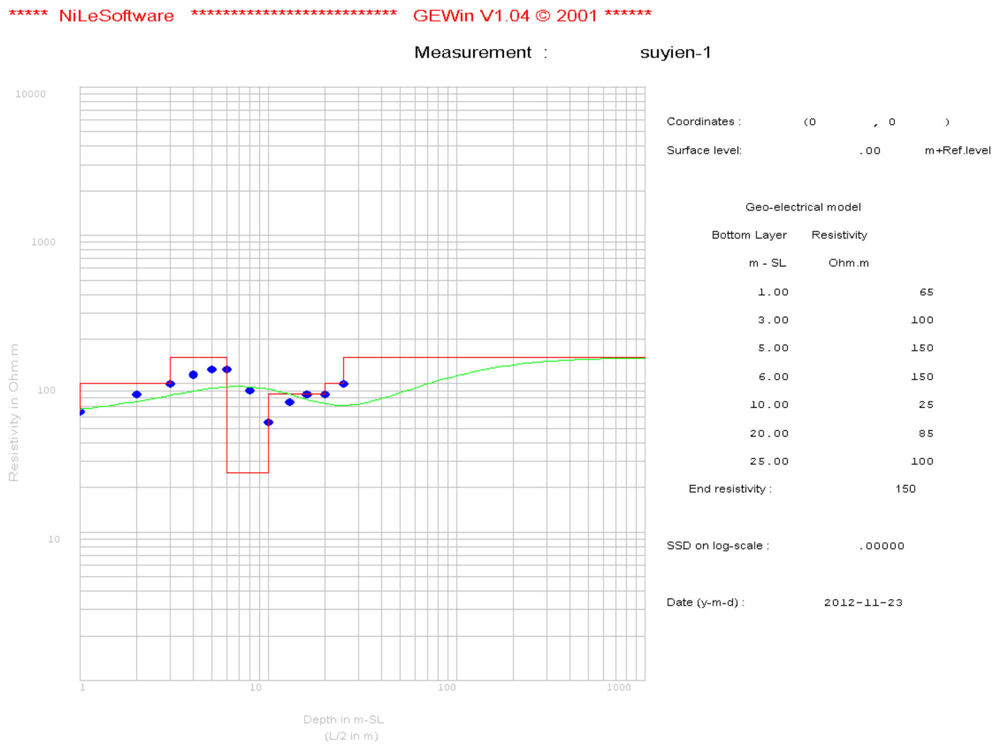

Figure 4: Vertical Electrical Soundings for Site 001/2012. The red and blue curves depict relation of AB/2 and the apparent resistivity with the blue curve showing resistivity variation. A comparison with computer generated curves and the goodness of fit is as shown.

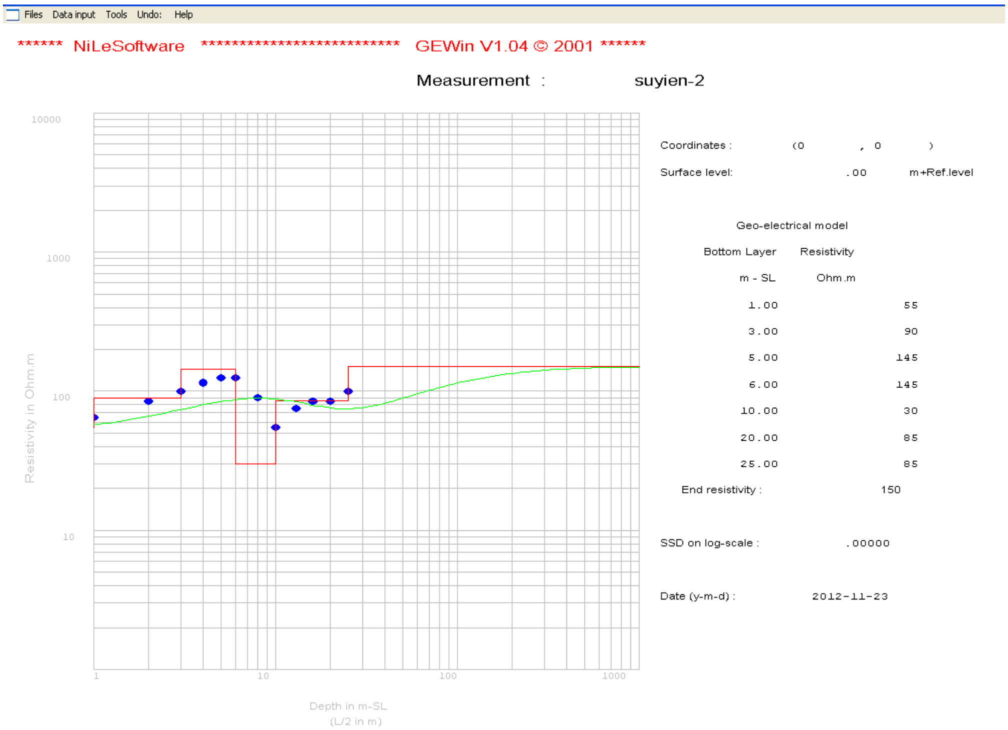

Figure 5: Vertical Electrical Soundings Site 2 002/2012

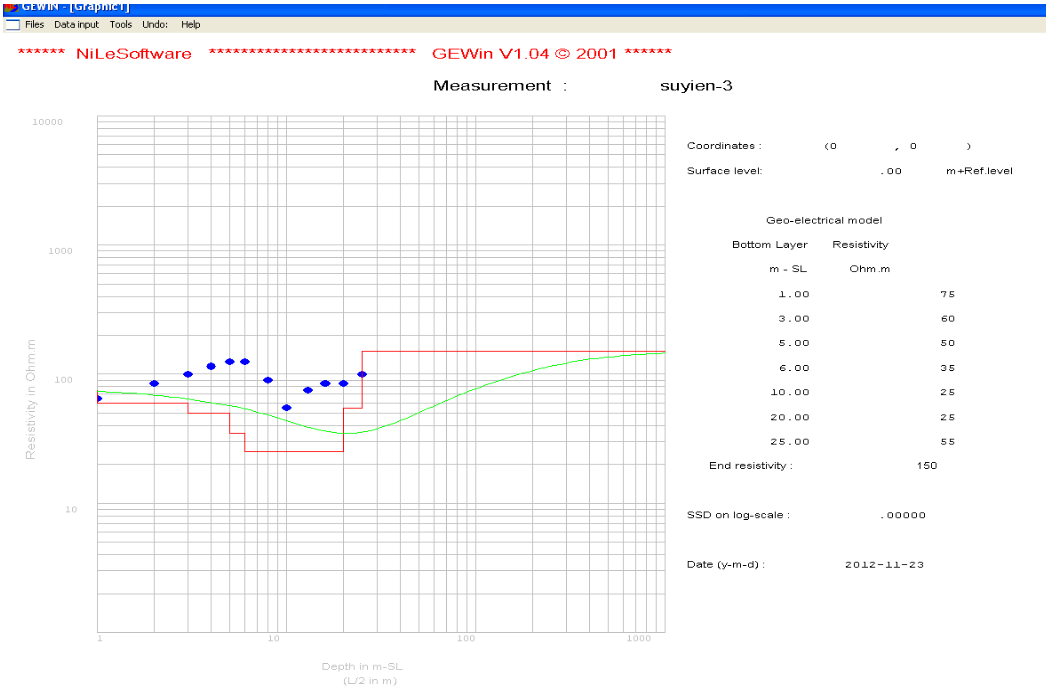

Figure 6: Vertical Electrical Soundings Site 003/2012

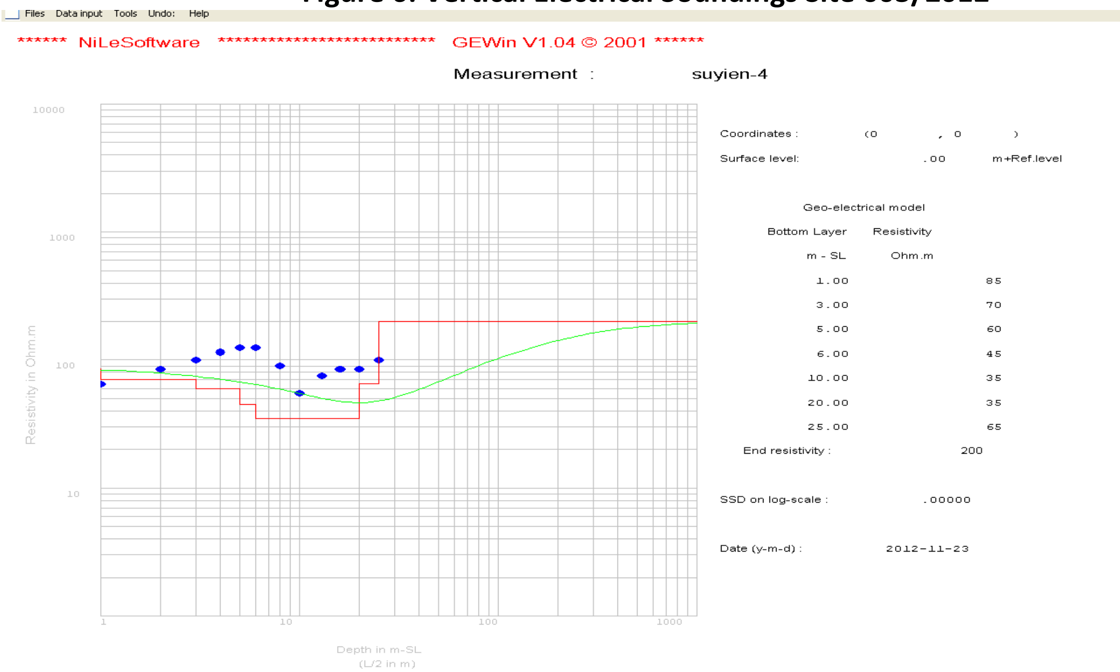

Figure 7: Vertical Electrical Soundings Site 004/2012

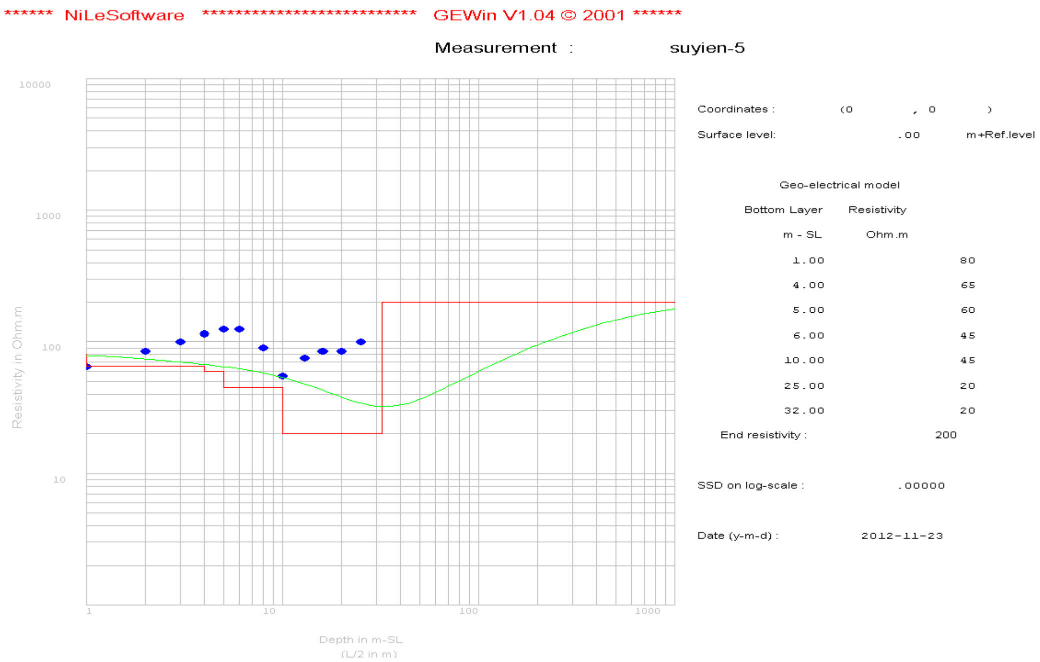

Figure 8: Vertical Electrical Soundings Site 005/2012

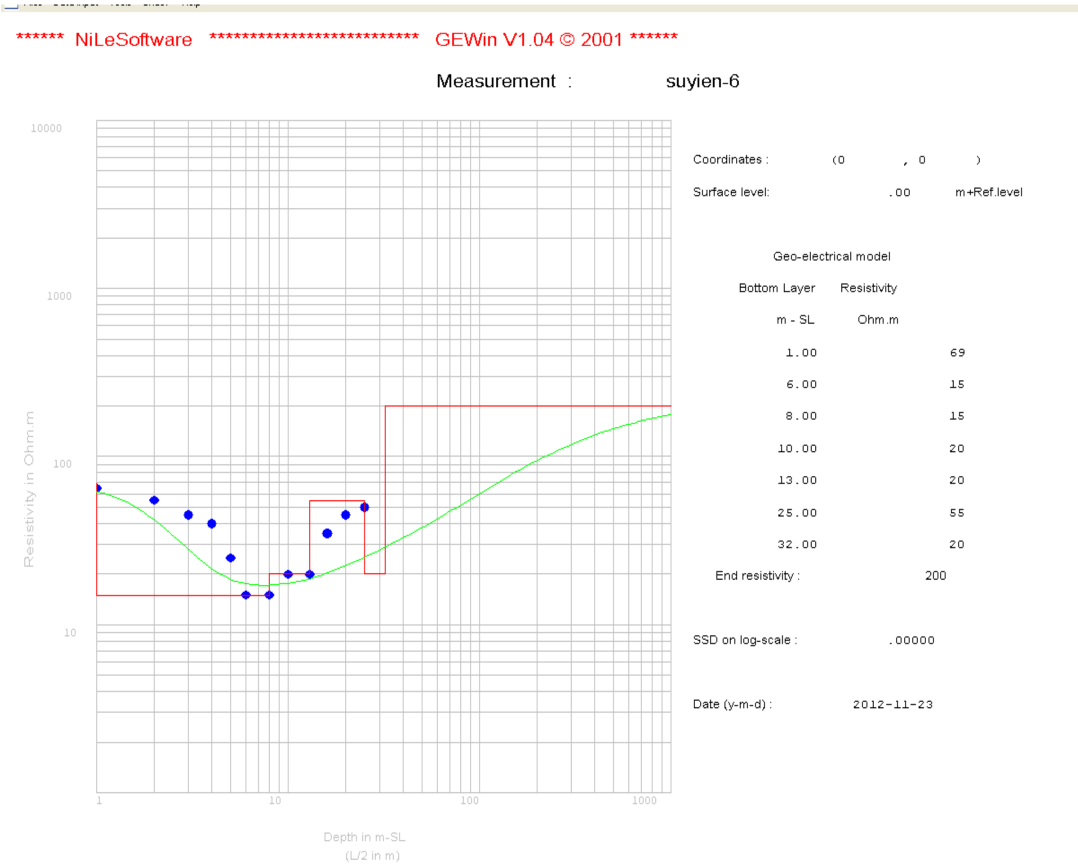

Figure 9: Vertical Electrical Soundings Site 006/2012

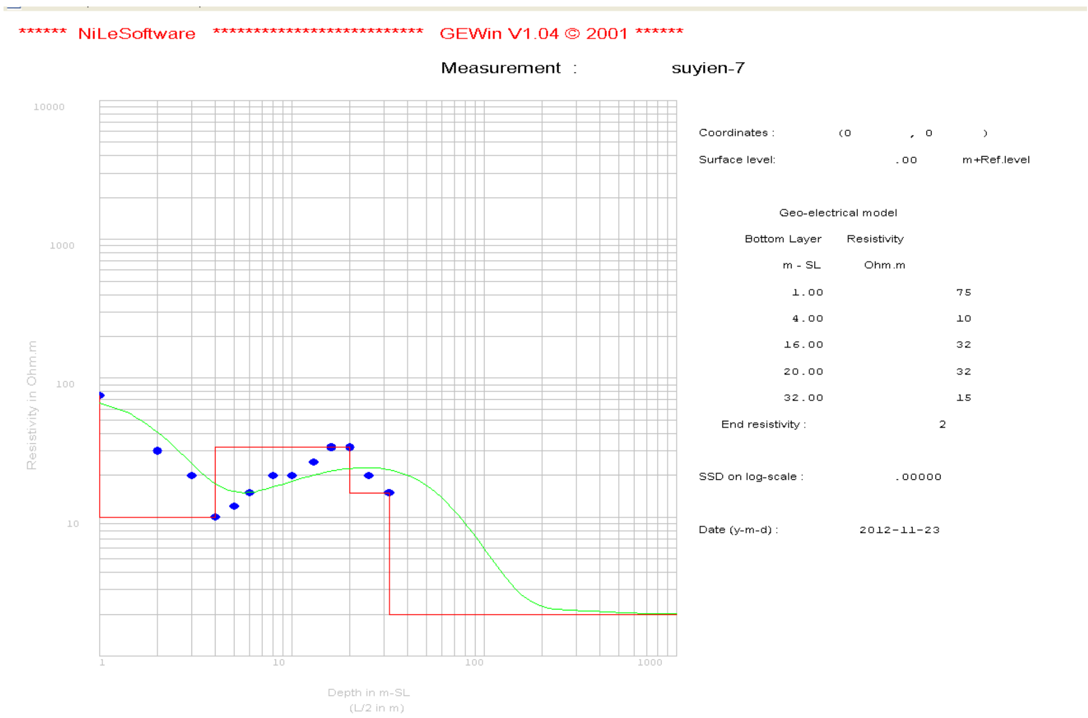

Figure 10: Vertical Electrical Soundings Site 007/2012

Table 3 shows the resistivity measurements for all the seven sites considered. The expected geological formation is dependent on whether the resistivity curve is rising or falling and may not be represented adequately by the absolute resistivity value. The rising limb of the resistivity curve points to fresh gneisses while the falling limb of the resistivity curve points to fractured or weathered geological formation.

Table 3: Resistivity measurements along specific sites in the dam

Resistivity Curve No.	Formation Depth Interval (m)	Resistivity (ohm.m)	Expected Geological Formation
001	0-1	65	Top soils/loams
	1-3	100	Laterites
	3-5	150	Weathered/fractured gneisses/laterites
	5-6	150	Weathered gneisses
	6-10	25	Fractured gneisses/highly weathered gneisses
	10-20	85	Weathered gneisses
	20-25	100	Weathered gneisses/ weathered gneisses
	Over 25.0	infinity	Weathered gneisses/slightly weathered gneisses
002	0-1	85	Top soils/loams
	1-3	90	Laterites
	3-5	145	Weathered/fractured gneisses/laterites
	5-6	145	Weathered gneisses
	6-10	30	Fractured gneisses/highly weathered gneisses
	10-20	65	Weathered gneisses
	20-25	85	Weathered gneisses
	Over 25.0	infinity	Weathered gneisses/slightly weathered gneisses
003	0-1	75	Top soils/loams
	1-3	60	Laterites
	3-5	50	Weathered/fractured Gneisses/laterites
	5-6	35	Weathered gneisses

	6-10	25	Fractured gneisses/highly weathered gneisses
	10-20	25	Weathered gneisses
	20-25	55	Weathered gneisses/ weathered gneisses
	Over 25.0	infinity	Weathered gneisses/slightly weathered Gneisses
004	0-1	85	Top soils/loams
	1-3	70	Laterites
	3-5	60	Weathered/fractured gneisses/laterites
	5-6	45	Weathered gneisses
	6-10	35	Fractured gneisses/highly weathered gneisses
	10-20	35	Weathered gneisses
	20-25	65	Weathered gneisses/ weathered gneisses
	Over 20.0	infinity	Weathered gneisses/slightly weathered gneisses
005	0-1	80	Top soils/loams
	1-3	65	Laterites
	3-5	60	Weathered/fractured gneisses/laterites
	5-6	45	Weathered gneisses
	6-10	45	Fractured gneisses/highly weathered gneisses
	10-20	20	Weathered gneisses
	20-25	20	Weathered gneisses/ weathered gneisses
	Over 20.0	Infinity	Weathered gneisses/slightly weathered gneisses
006	0-1	69	Top soils/loams
	1-6	15	Laterites
	6-8	15	Weathered/fractured gneisses/laterites
	8-10	20	Weathered gneisses
	10-13	20	Fractured gneisses/highly weathered gneisses
	13-25	55	Weathered gneisses
	25-32	20	Weathered gneisses/ weathered gneisses
	Over 32	infinity	Weathered gneisses/slightly weathered gneisses
007	0-1	75	Top soils/loams
	1-4	10	Laterites
	4-16	32	Weathered/fractured gneisses/laterites
	16-20	32	Weathered gneisses
	20-32	15	Fractured gneisses/highly weathered Gneisses
	Over 32.0	infinity	Fresh gneisses/ weathered gneisses
			Weathered gneisses/slightly weathered gneisses

3.6 Tomographic Imaging of Stratigraphic Units

The TIs provide a 2D (depth-horizontal) comprehensive picture than 1D probes and are shown for sites marked TMGR-01 to TMGR-07. The structures at the floor of the dam demonstrate water seepage from dam floor (Fig. 11).

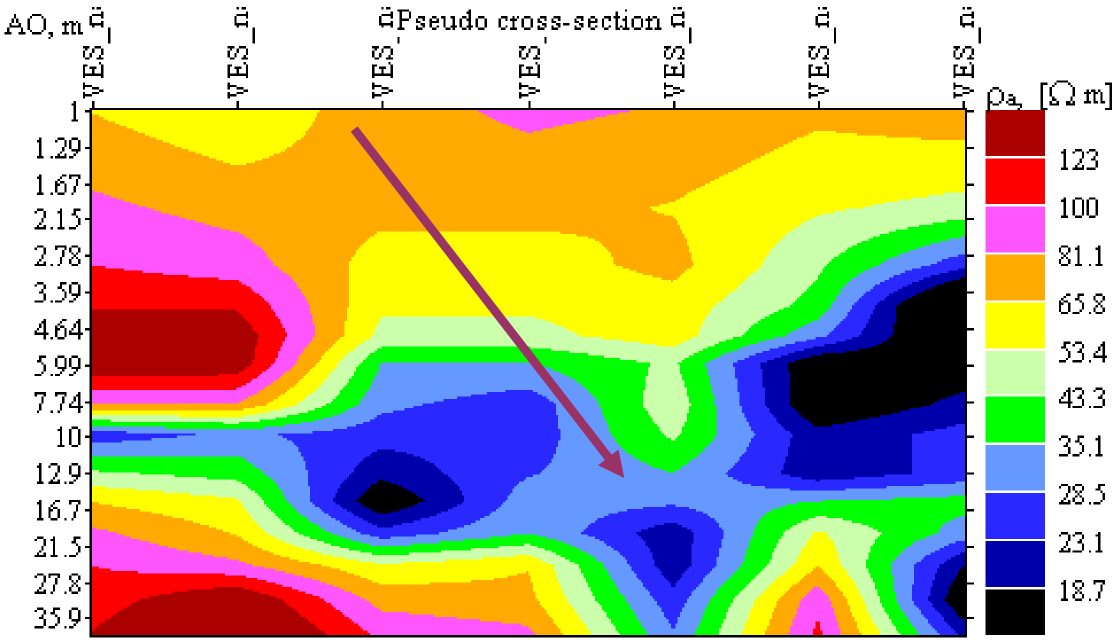

Figure 11: Tomographic image of the bottom of the Suyien dam Site TMGR-01

Tomography (2D) distinguishes all sub-layers of rocks such as wet sands, dry sands, clayey sands etc, which 1D resistivity curve lumps together as one layer. Where VES may have given 3 layers, tomographic image may give 5 or more layers. The tomographic image provides for weathered gneisses, slightly weathered gneisses, and highly weathered gneisses, while VES may refer to all of these gneisses as weathered gneisses. The color coding and color scale in a tomographic model facilitates interpretation of the layers.

Colorful layers are a representation of resistivity value distribution from seven interpolated VES data. From the above tomographic profile (Fig. 11), it is readily noted that there is a fractured/weathered zone comprising the brownish laterites at the floor of the dam which channels the water to the bluish cross section comprising weathered/fractured zone. The water consequently seeps away from a depth of 3 m at site TMGR- 7 to the depth of 35.9m bgl at site TMGR**-** 5. Under the circumstances, there needs to be a water proofing material on the dam floor without further delay.

At zone VES TMGR-3 site in (Fig. 12) the brownish zone showing a fracture occurs in varying depths. The fractured zone begins from 0.1m to 3.0m of depth, meaning that the fracture has a thickness of 2.9m. Extending to 7.74 m as the arrow points out. High resistivity values indicates that water seeps through the fractured zone.

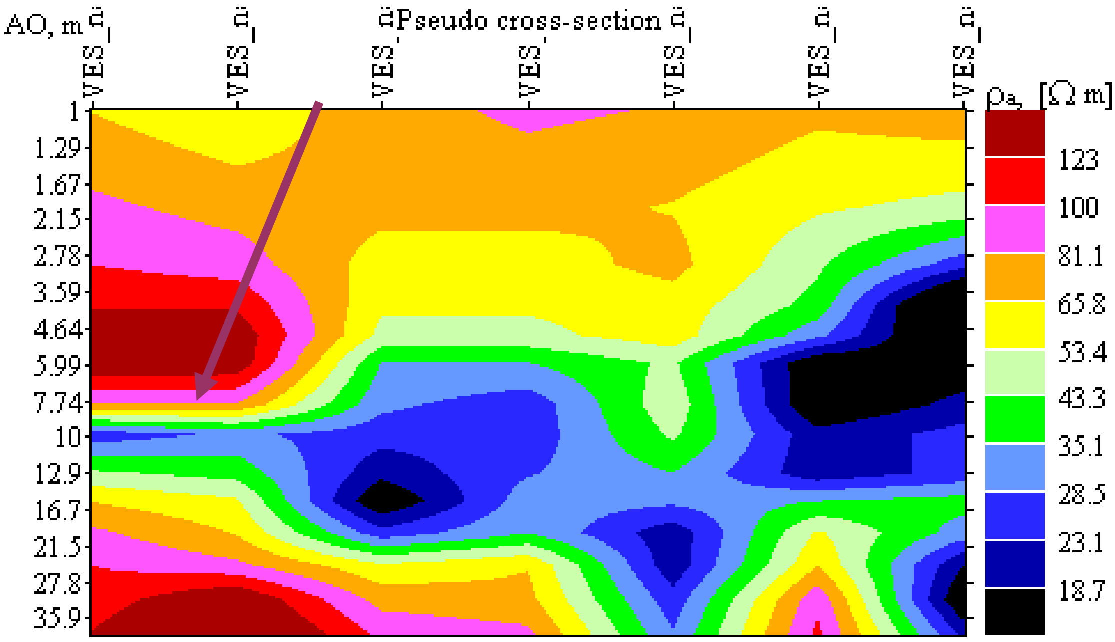

Figure 12: Tomographic image of the bottom of the Suyien dam Site TMGR-03

At zone VES TMGR- 5 sites (Fig.13), the fractured zone begins from 0.1 m to 3.9m, meaning that the seepage fracture at this point on the dam floor has a thickness of 3.8m bgl.

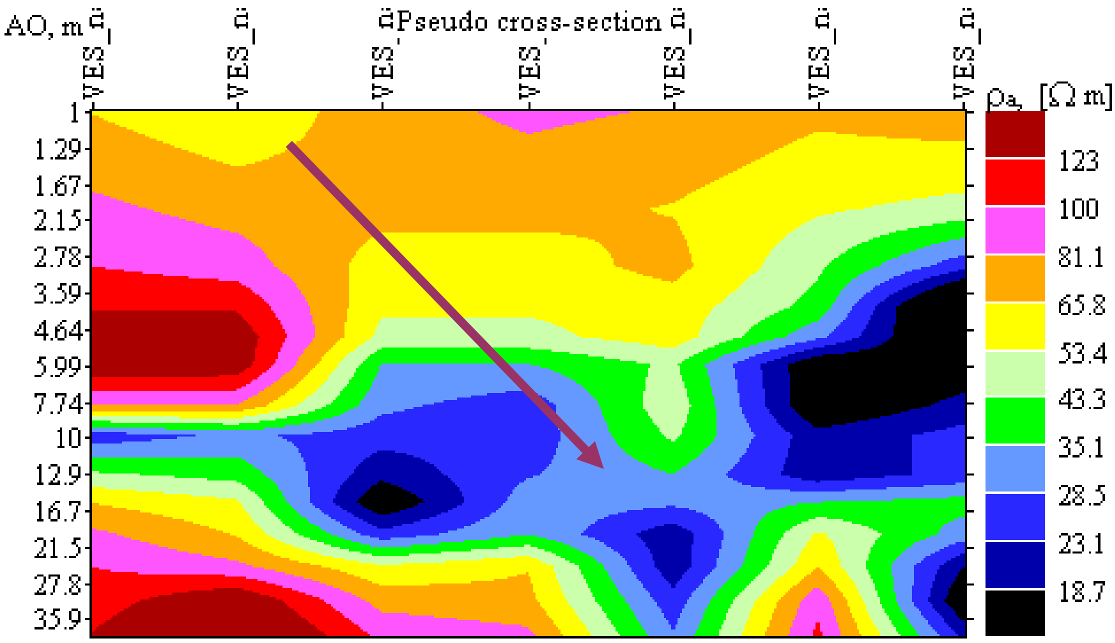

Figure 13: Tomographic image at Site- TMGR-05

The bluish zone, occurring in varying depths, and which isprobably weathered gneisses, is where the seeping water flows into. At zone VES TMGR-7 site (Fig.14), the 'reservoir' zone occurs in two distinct portions, namely from depths 3 to 13m below ground level (bgl) and as from 21 to 35m bgl, giving the respective seepage 'reservoir' thicknesses at these two points on the dam floor as 10m and 14m bgl. However, at zone VES TMGR- 7 spot, the thickness of the laterites is 0.1 to 1.2m bgl.

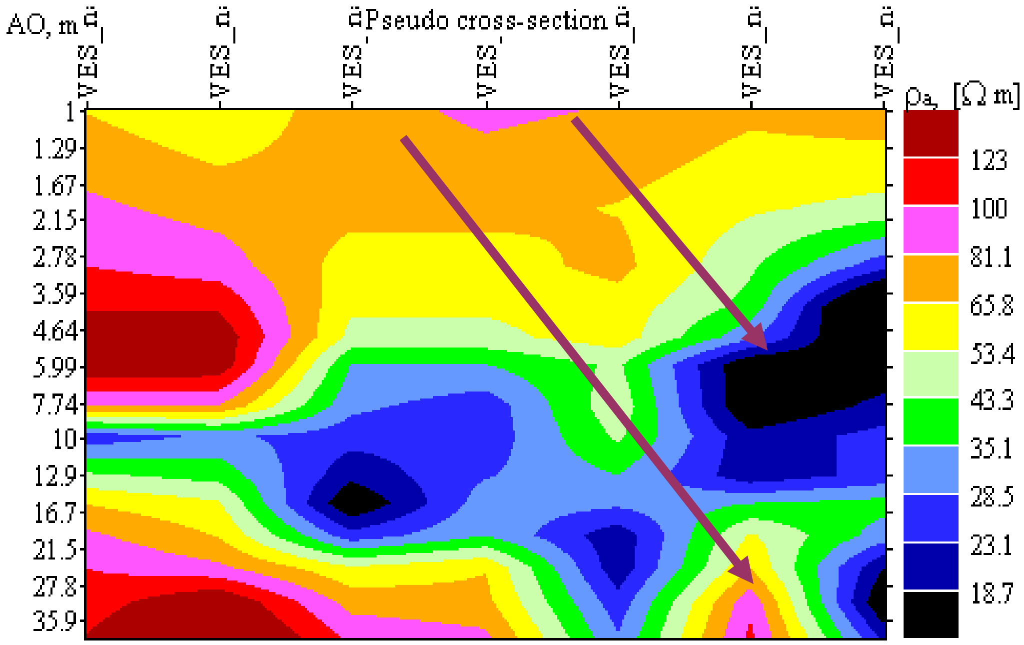

Figure 14: Tomographic image at Site TMGR-07

4. Conclusions

The area of superficial deposits and weathered surface is limited to the 50 m on either side of the dam thus limiting groundwater recharge to the dam. Field observations reveal two critical areas within the catchment. One area contains community wells where surface water seeps into the wells and changes to subsurface flow while in the second area, water infiltrates underground due to porous nature of sandy soils covering these areas. The sandy/clayey species are mainly the alluvial sandstones texture, derived from river sediments transported from the hills downwards by flash floods. The heavily forested portion is domed, with the left wing draining westwards, whilst the right wing drains eastwards. These flows should be routed towards the dam to ensure maximum recharge is tapped to fill the dam.

The lagga through which runoff and superficial groundwater recharge reaches the dam has vegetative growth that have limited flow conveyance. There is a westwards loss and an eastwards loss of water meant to flow straight into the dam channel way. Therefore, very minimal recharge flows into the dam zone. Some trenching could be done to re-route the flow away from the heavily colonized stream channel portion.

A fissure was identified at the center bottom of the dam which possibly allows water to seep through. Remediation measures such as water proof cement to seal off the dam floor cracks is recommended.

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