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Determination of Shallow Groundwater Aquifer Geometry using Geo-Electrical Techniques in the Atankwidi Sub-Basin of the White Volta Basin, Ghana

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Abstract

This paper presents the research findings on the delineation of shallow groundwater aquifer geometry in Atankwidi sub-basin of the White Volta Basin. The potential use of shallow groundwater for small-scale dry season irrigation is a key issue for irrigation development in the arid zone of Ghana. Farmers within the Atankwidi sub-basin of the White Volta Basin are increasingly adopting groundwater as a source of irrigation water due to the unavailability of surface water during the dry season. There is therefore the need to determine the shallow groundwater aquifer geometry in order to ensure sustainability in the application and possible expansion of groundwater irrigation in the area. The geometry of aquifer system in the Atankwidi sub-basin has therefore been delineated using geophysical (VES and EM) techniques. The depth to water table in the sub-basin ranged from 0.4 - 7.8 m with a mean of 1.7 m whiles the depth to bedrock varied from 2 - 38.3 m with a mean depth of 8.4 m. The mean saturation thickness of the aquifer system is 6.3 m with a minimum and maximum thickness of 0.1 m and 35.0 m respectively. The estimated potential volume of groundwater storage of the aquifer system in the sub-basin is 370,777,191.2 m^3.

Keywords: Shallow Groundwater Irrigation; Aquifer geometry; Shallow well

1. Introduction

One irrigation development pathway, especially in the Upper Regions of Ghana, involves the utilisation of small reservoirs. However, the performance of many of these systems is reported to be affected adversely by management problems and the economic benefit relative to the investment is characteristically low and only benefits a limited number of farmers. The total potential of irrigable land in Ghana is put at 500,000 hectares with the current area developed for irrigation estimated at 11,000 hectares which represents only 0.02% of its irrigable land (Kunateh, 2008). Irrigation of some of these arable lands could not materialise due to the projected capital involvement in channeling surface water over long distances to the irrigable lands. Availability of groundwater is therefore a major asset that can greatly influence agricultural production.

The use of hand-dug wells, enables the utilisation of shallow groundwater for irrigated production of vegetables and cash crops during the dry season and, therefore, provides an alternative source of income for farmers and poor households. For instance, the large scale production of shallot and other vegetables using shallow groundwater in the Keta Strip has provided enormous income to the indigenous inhabitants (Kortatsi *et al*; 2000). In most cases, SGI has developed without any government or donor involvement. Since 1998, shallow groundwater irrigation using hand-dug shallow wells dug in alluvial beds have been spreading throughout the upper parts of the White Volta basin and are located mainly in inland valleys.

The rate at which shallow groundwater is being abstracted for irrigation in the Atankwidi sub-basin is increasing due to the increasing interest of the population in food production. This necessitates detailed identification of the aquifer system which is essential for sustainable development of groundwater resource in the area. Although, groundwater is increasingly being adopted by farmers within the Atankwidi sub-basin as a source of irrigation water, its sustainability in the near future can not be guaranteed since little is known about the geometry of the groundwater reservoir within the basin. The objective of this paper is therefore to determine the geometry of the shallow aquifer system in the basin to aid the sustainable management and development of this vital resource.

2. Study Area

2.1 Location and Size

The Atankwidi sub-basin is located between latitudes 10°49’47 N and 10°55’35 N and longitudinal 0°55’27 W and 0°59’27 W, a tributary of the White Volta located in the Upper East Region of Ghana between Navrongo and Bolgatanga (Kassena Nankana District) with its upper reach in Burkina Faso as shown in Figure 1. The sub-basin is located in one of the areas with the highest groundwater use per km² in the Volta River basin (Martin 2006). The sub-basin covers an area of about 275 km^2 of the White Volta basin.

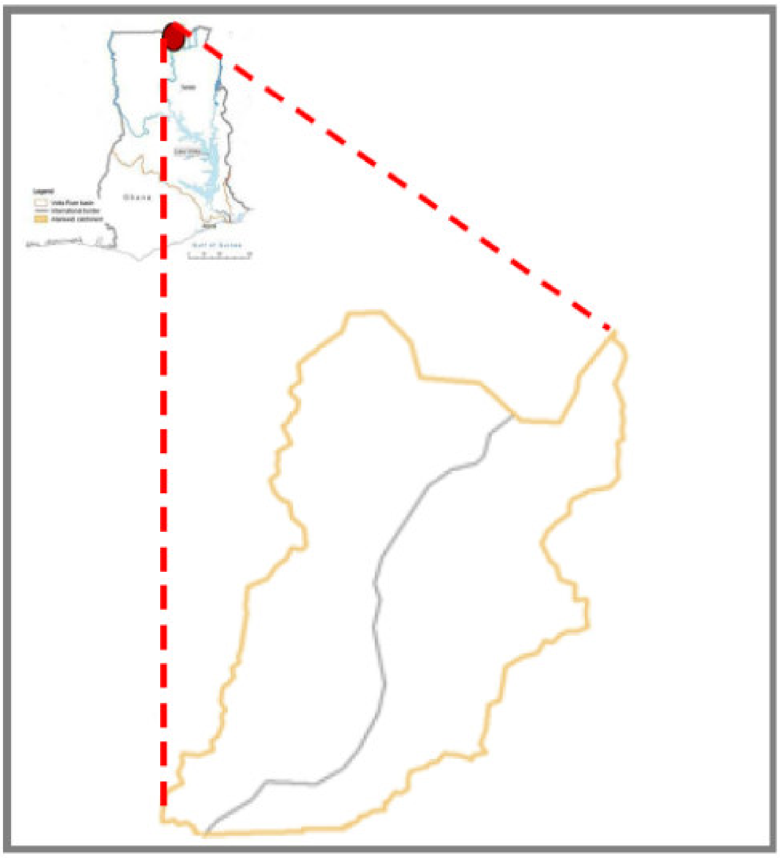


Figure 1. Map of the Atankwidi sub-basin

2.2 Climate and Vegetation

The study area falls within the Sudan-Savanna climate zone, which is characterised by high temperatures and a uni-modal rainfall distribution with a distinct rainy season lasting approximately from May to September. The mean annual rainfall in Navrongo is approximately 980mm. The spatio-temporal distributions of precipitation and evaporation have a large impact on the water regime including the groundwater variability. In the rainy season daily rainfall may exceed 50 mm, this falls in less than one hour. Monthly rainfall only exceeds potential evaporation in the three wettest months, July, August and September. The total potential evaporation is 2050 mm, which is twice the annual rainfall. The average annual temperature is 29 ^{o}C. The mean daily minimum temperature is 25 ^{o}C, coinciding with the peak of the rainy season, and rises to a maximum of 34 ^{o}C in April. Relative humidity is highest during the rainy season with 65 %. It drops quickly after the end of the rainy season in October, reaching a low of less than 10 % during the harmattan period in December and January (Martin, 2006).

2.3 Land Use

Open tree-savanna forms the natural vegetation in the Upper East Region. Trees show a large spacing and the area is largely covered with grass and shrubs. The most common economic trees are the sheanut, dawadawa, boabab and acacia. Common grasses include *Andropogen gayyanus* in the less eroded areas and *Hyperrhenia spp*., *Aristida spp*. and *Heteropogen spp.* in the severely eroded areas. Most of the area is used for small-scale agriculture. During the rainy season, almost 70 % of the area is covered with small plots of rainfed agriculture (Martin, 2006). Other parts of the area are used for livestock grazing and drinking. In the dry season, the amount of agriculture is substantially lower, approximately 1 % of the area (Unofficial report, GVP, 2007). The other parts of agricultural land remain as bare soil until the next rainy season starts. Land not used for agriculture is either sparse vegetation on shallow soils in stony areas or land used for the grazing of livestock, which is covered by grass, shrubs and trees.

2.4 Relief and Drainage

The relief of the sub-basin is generally flat, gently undulating with slopes ranging from 1% to 5% except in a few uplands where slopes are about 10%. According to Adu (1969), the relief of the UER is related to the geology, where a range of Birimian greenstone hills rising up to 457m above sea level dominate north of Bawku and Zebilla along the border with Burkina Faso and in the southwest along the White Volta River (WVR). The granite areas are generally of low, gently rolling relief ranging from 122 m to 260 m above sea level. The relief under Voltain rocks has similar characteristics to granites, with few escarpments rising above 518 m near the border with Togo in the east. The mean elevation for the area is 197 m above sea level (Liebe, 2002).

2.5 Geological setting

Three formations of the Birimian domain can be distinguished in the study area (Figure 2) from the geological map 1:125,000, sheets Navrongo (Van den Berg *et al.,* 1963) and Zuarungo (Murray and Mitchell, 1960). These are: Birimian metasediments; Granitoids (granodiorites, granite and gneiss) associated with the Birimian; Intrusive Bongo granite. Paleoproterozoic granitoids consisting of hornblende - biotite granodiorite, biotite granite and biotite gneiss make up the largest part of the study area and form the slightly undulating south-western part of the Atankwidi sub-basin. Birimian metasediments made up of phyllite, schist and quartzite are found in small patches among the granitoids.

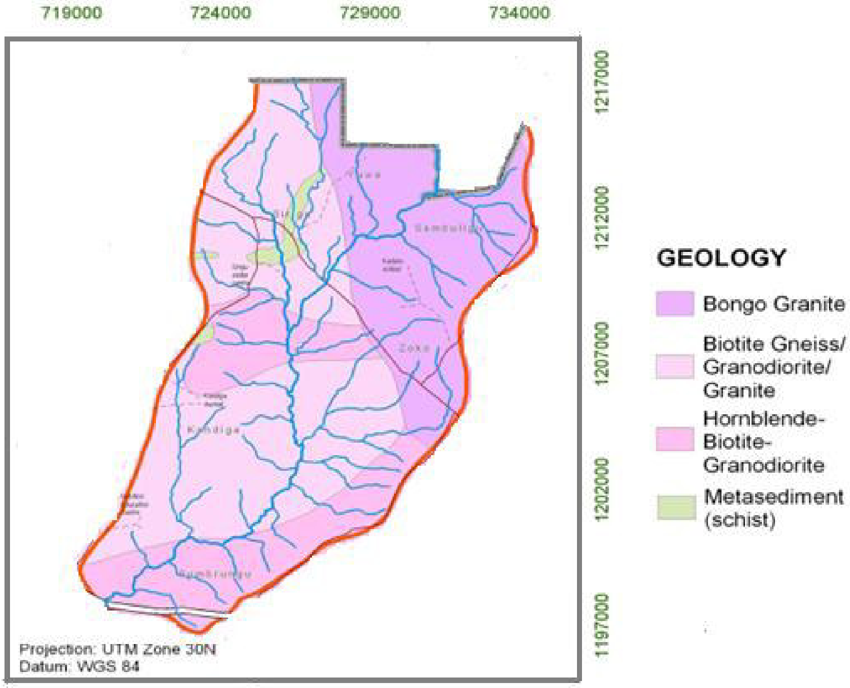


Figure 2. Geological and drainage map of the study area.

3. Research Methodology

This section presents the methodology used for the delineation of the aquifer and its geometrical configuration in the sub-basin. A field work for this study was conducted to first find out how the wells were dispersed in the sub-basin. As such, specific locations of wells were then taken with the help of GPS. The survey was also to ascertain the current status and extent of SGI and groundwater use generally in the area to aid data collection. Visits were therefore made to areas like Sirigu, Atankwire, Simburugu, Kaase and Akamo where farmers usually dig more shallow wells for dry season irrigation.

3.1 Geophysical Exploration

Resistivity techniques are well-established and widely used to solve a variety of geotechnical, geological and environmental subsurface detection problems (Ward, 1990). The primary purpose of the resistivity method is to measure the potential differences on the surface due to the current flow within the ground. Since the mechanisms which control the fluid flow and electric current and conduction are generally governed by the same physical parameters and lithological attributes, the hydraulic and electric conductivities are dependent on each other. Although there are other factors which govern the current flow and conduction into the soil (lithology, size, shape, mineralogy, packing and orientation of grains, shape and geometry of pores and pore channels, magnitudes of porosity, and permeability, compaction, consolidation and cementation and depth and water distribution) (Salem, 1999) are extremely variable. That is, the measured resistivity values are not absolute but relative, and therefore only relative conclusions about the area's hydraulic parameters can be made, and for this reason surface geophysical methods have been used for aquifer zone delineation and evaluation of the geophysical character of the aquifer zone in several locations in the world (Dhakate and Singh, 2005; Khalil, 2006).

3.2 Determination of Aquifer Geometry

In this study, a geophysical exploration using both electromagnetic (EM) and resistivity techniques was carried out in the study area by the Groundwater Division of the Water Research Institute of Ghana. The EM technique was used for the lateral profiling process for gridding of the study area using the Geonics M34-3 instrument. This was because the EM technique is known to be fast and precise in the horizontal direction. The resistivity technique was however used for the Vertical Electrical depth Sounding (VES) using the Abem Terrameter 1000 instrument.

VES measurements were planned so as to cover the whole study area and as such 428 VES measurements were carried out as shown in Figure 2.

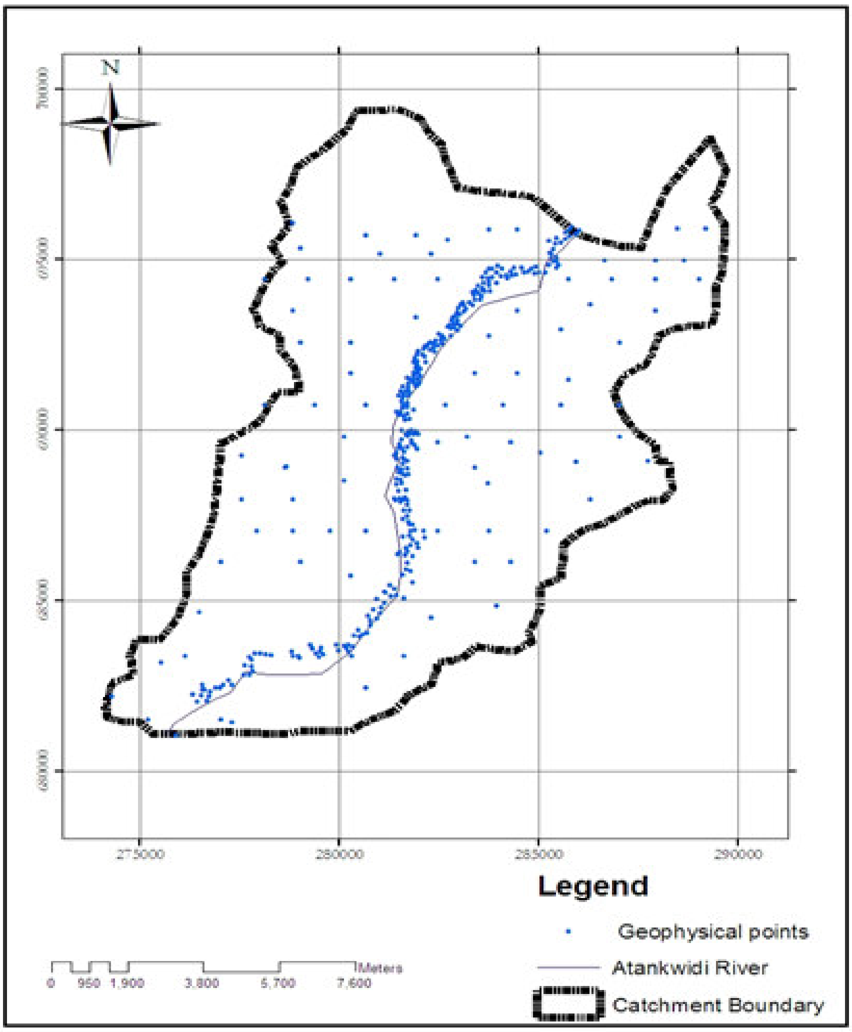


Figure 3. Map of VES locations in the study area

All resistivity soundings were inverted using the ResPlus software. The resistivity data were thereafter screened to remove outliers bringing the final results to 390 which were then analyzed to determine the aquifer configuration which included depths to water table and bedrock. The saturated thickness of aquifer in the area was then determined from the difference between the depth to the bedrock and the depth to water table

3.3 Estimation of Groundwater Storage

The total groundwater storage was determined from the relation;

$$\text{Groundwater storage} = A \times L \times n \qquad (1)$$

where, A = Average cross-sectional area of study area (m^2)
L = Longitudinal length across study area (m)
n = Porosity (%)

Five cross-sectional profiles as shown in Figure 4.4 were drawn across the catchment.

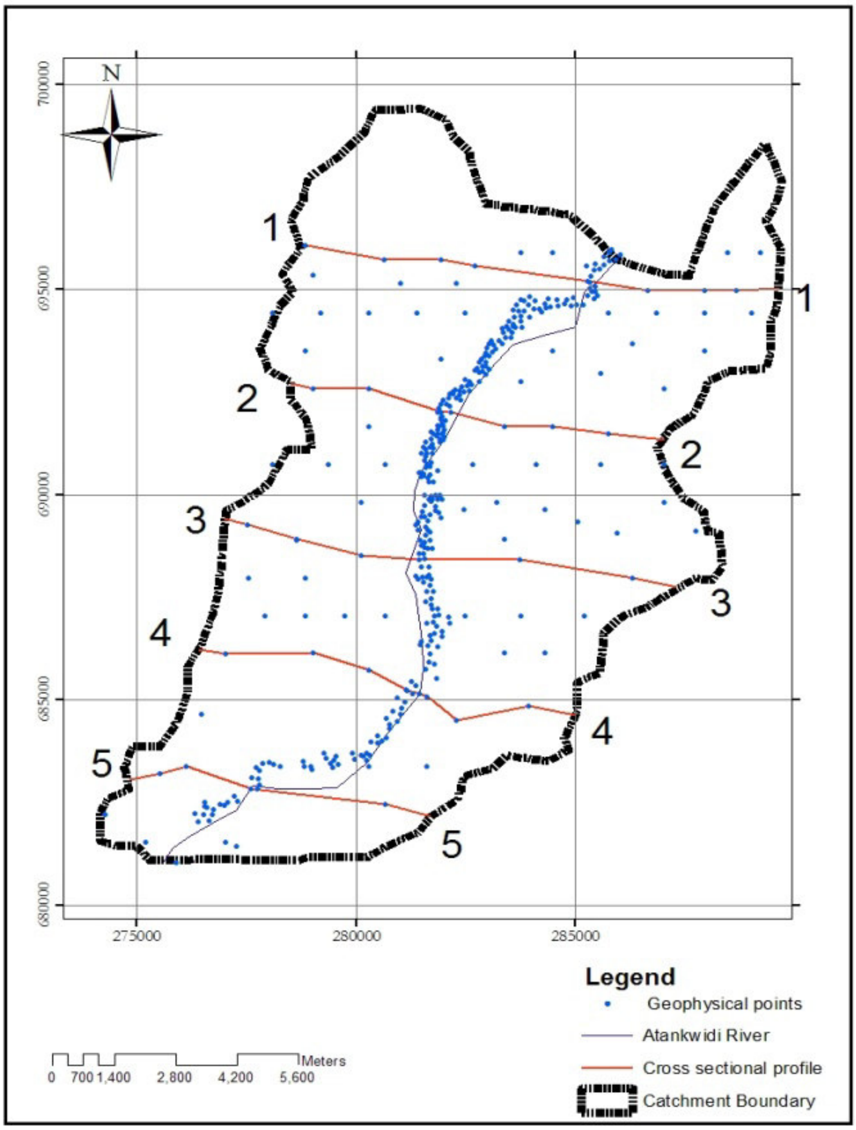


Figure 4: Map showing cross-sectional profile lines.

Using the Simpsons rule, the respective areas of the saturation zones of the five cross-sections were determined and hence the average area (A). The Simpsons rule is given by:

$$A = \frac{1}{3} \times \begin{pmatrix}\text{width of}\\ \text{interval}\end{pmatrix} \times \left[\begin{pmatrix}\text{first + last}\\ \text{ordinate}\end{pmatrix} + 4\begin{pmatrix}\text{sum of even}\\ \text{ordinates}\end{pmatrix} + 2\begin{pmatrix}\text{sum of remaining}\\ \text{odd ordinates}\end{pmatrix}\right] \qquad (2)$$

The porosity was adopted from Barnie (2010). For the longitudinal length across the study area, the longitudinal length between the topmost and down most ends of the study area and approximately perpendicular to the cross-sectional profiles was taken as shown in the Figure 5. The total groundwater storage was thereafter computed with the known parameters using equation stated above.

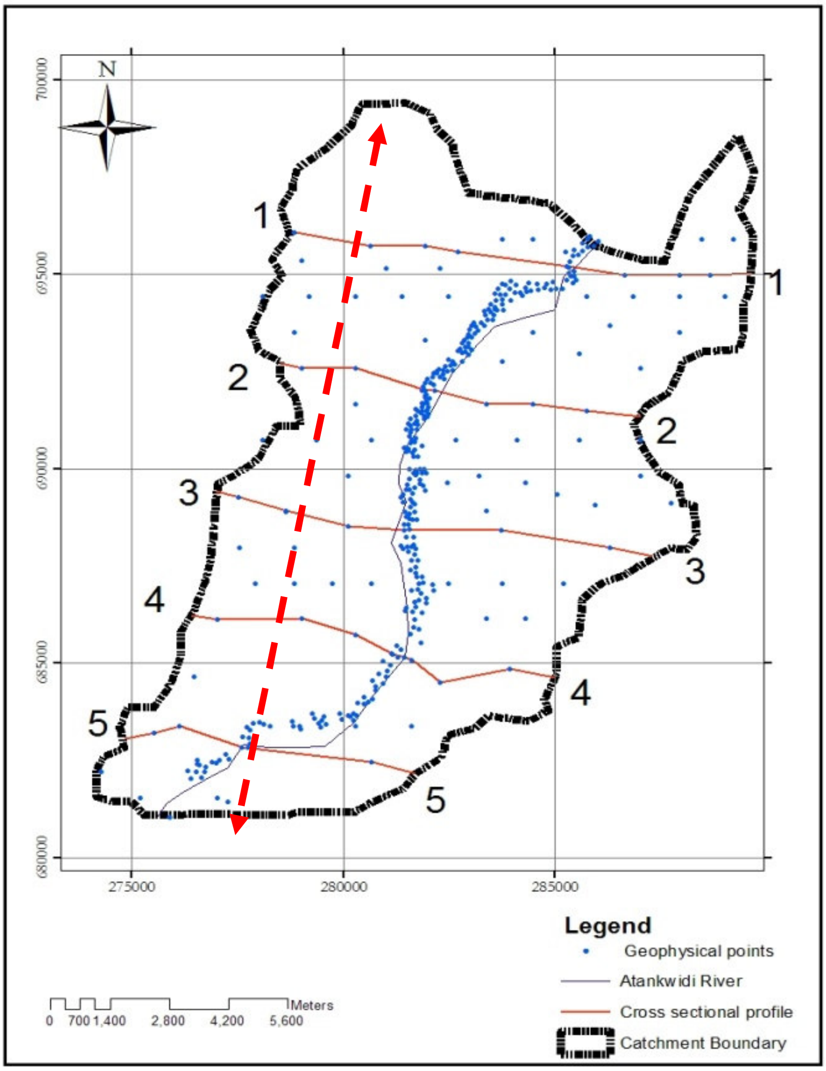


Figure 5: Longitudinal length across the study area

4. Results and discussion

The results of some (Anateem, Atababa, Kandiga junction and Kologo) of the processed VES measurements from the ResPlus software are shown below. That is, the shallow aquifer geometry (depth to water table, depth to bedrock and saturation thickness) has been dealt with.

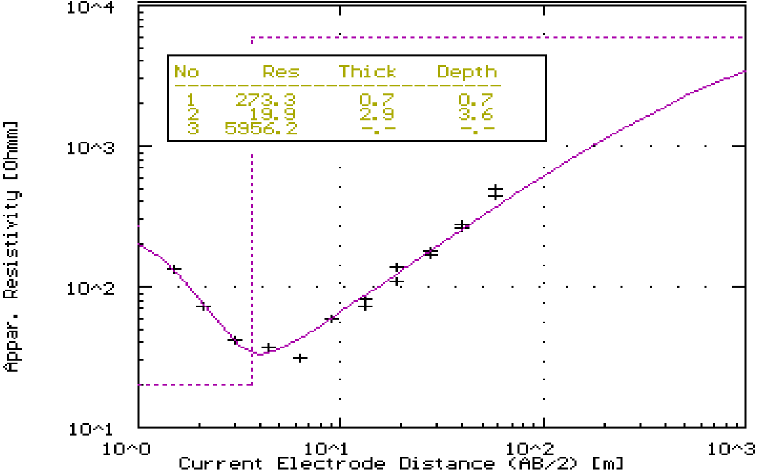
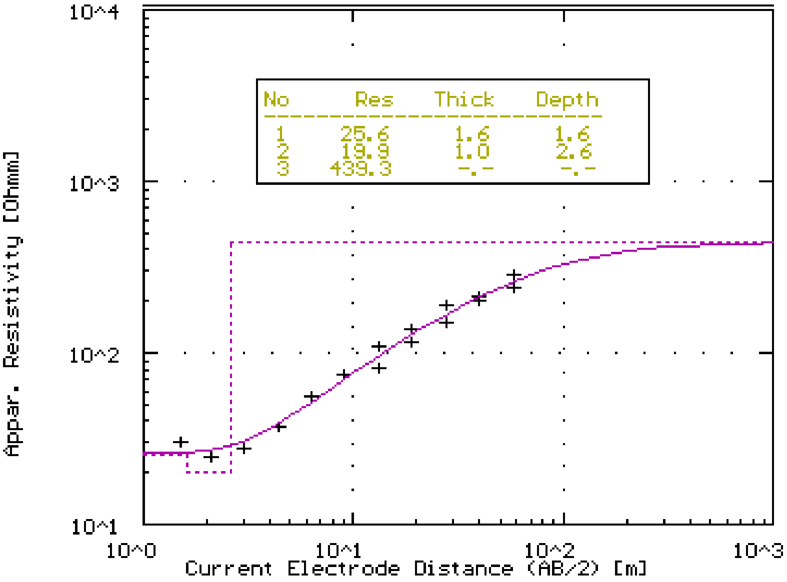
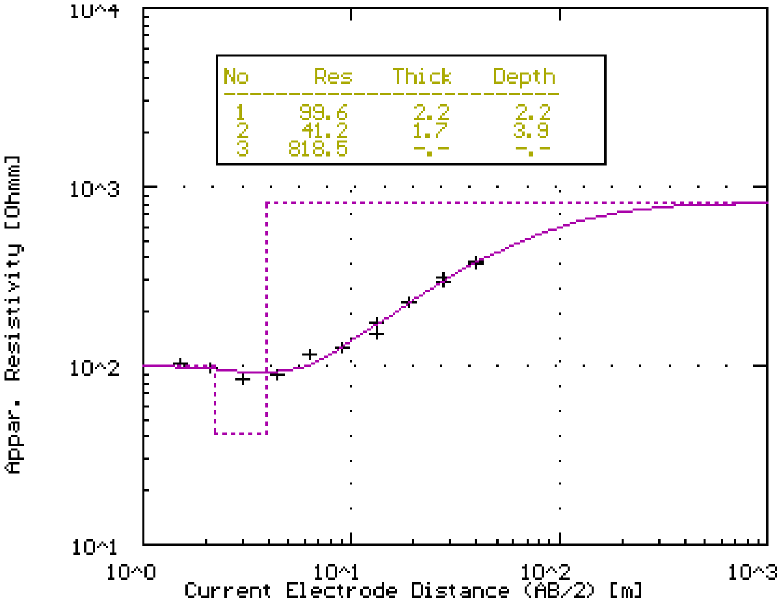


Figure 6. VES curve at point 337 at Anateem



No	Res	Thick	Depth
1	25.6	1.6	1.6
2	19.9	1.0	2.6
3	439.3	-.-	-.-

Figure 7. VES curve at point 340 at Atababa



No	Res	Thick	Depth
1	99.6	2.2	2.2
2	41.2	1.7	3.9
3	818.5	-.-	-.-

Figure 8. VES curve at point 342 at Kandiga junction

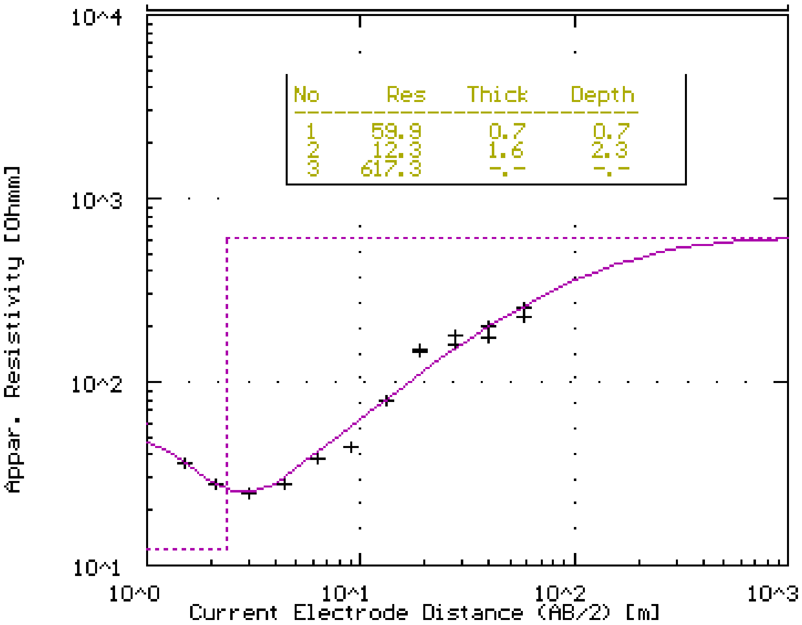


Figure 9. VES curve at point 346 at Kologo

4.1 Depth to Water table of Regional Aquifer system

The summary of depths to water table or aquifer top is shown in the Table 1.

Table 1: Summary of depth to water table of Atankwidi sub-basin

Range of depths, m	**Vertical Electrical depth Sounding (VES) points**	**Percentage**
0 – 1	129	32.3
1 – 2	173	45.0
2 – 3	51	13.1
3 – 4	18	4.6
4 – 5	7	2.0
5 – 6	6	1.5
6 – 7	2	0.5
7 – 8	4	1.0
TOTAL	**390**	**100**

These depths range from 0.4 - 7.8 m with the mean depth, median and standard deviation are 1.7, 1.4, and 1.3 m respectively. The area from the table above can be seen to generally have a shallow water table or depth to the aquifer top. That is, about 90 % of the values obtained fell within 0 – 3 m. This justifies the reason behind the depths of most hand dug wells in the area used for irrigation ranging between 3 – 5 m.

4.2 Depth to Bedrock

The Atankwidi sub-basin generally has depths to bedrock ranging from 2.0 - 38.3 m with a mean value of 8.4 m. The median and the standard deviation values are 7.3 m and 5.5 m respectively. The summary of the various depths to the bedrock in the study area is presented in the Table 2.

Table 2: Summary of depths to bedrock of aquifers the Atankwidi sub-basin

Range of depths, m	**Vertical Electrical depth Sounding (VES) points**	**Percentage**
0 – 5	99	25.4
5 – 10	193	49.5
10 – 15	62	16.0
15 – 20	21	5.4
20 – 25	7	1.8
25 – 30	3	0.8
30 – 35	3	0.8
35 – 40	1	0.3
TOTAL	**390**	**100**

4.3 Saturated thickness of Aquifer

The saturated thickness of aquifers in the area ranges from 0.1 – 35 m with a mean, median and standard deviation of 6.3, 5.6 and 7.4 m respectively. The summary is given in the Table 5.3. It can be realized from the table that more than 80 % of the VES points showed a saturated thickness of 0.1 – 10 m with only 1 % showing thickness of between 30 – 35 m.

Table 3: Summary of saturated thickness of aquifer in Atankwidi sub-basin

Range of thickness, m	**Vertical Electrical depth Sounding points**	**Percentage**
0 – 5	192	49.2
5 – 10	135	34.6
10 – 15	41	10.5
15 – 20	12	3.1
20 – 25	4	1.0
25 – 30	3	0.8
30 – 35	3	0.8
TOTAL	**390**	**100**

4.4 Schematic hydrogeological cross-sections of the study area

With the objective of delineating detail shallow aquifer configuration, schematic hydrogeological cross-sections along five cross-sectional profiles were drawn as shown in Figure 3. Table 4 shows the various Sections with communities along respective sections.

Table 4: Communities along respective cross-sectional profiles

Section	**Communities along profile line**
1 – 1	Sirigu, Sirigu Basarfo Abola, Sirigu/Gunwokgor, Kadare/Yua, Abokobisi, Sambulungu.
2 – 2	Mirigu Nyong, Kandiga Bembisi, Gunworkgor, Zorkko Kordorogo,Zorkko Goo, Kadare
3 – 3	Kandiga Longho, Kandiga Kurigu, Kurigu/Gabrigo, Gamboringo, Zorkko Gamoringo
4 – 4	Kaase Amaboka, Kaase Akamo, Akamo, Akamo/Kologo, Atiyure, Gamboringo
5 – 5	Kandiga, Atiyuroum, Kologo

Schematic diagrams to represent the depth to water table, depth to bedrock and saturated thicknesses of aquifers in the study area along the five cross-sectional profile lines are shown in Figure 5. It can be observed form these diagrams that the regional aquifer system lays above the first impervious layer or stratum.

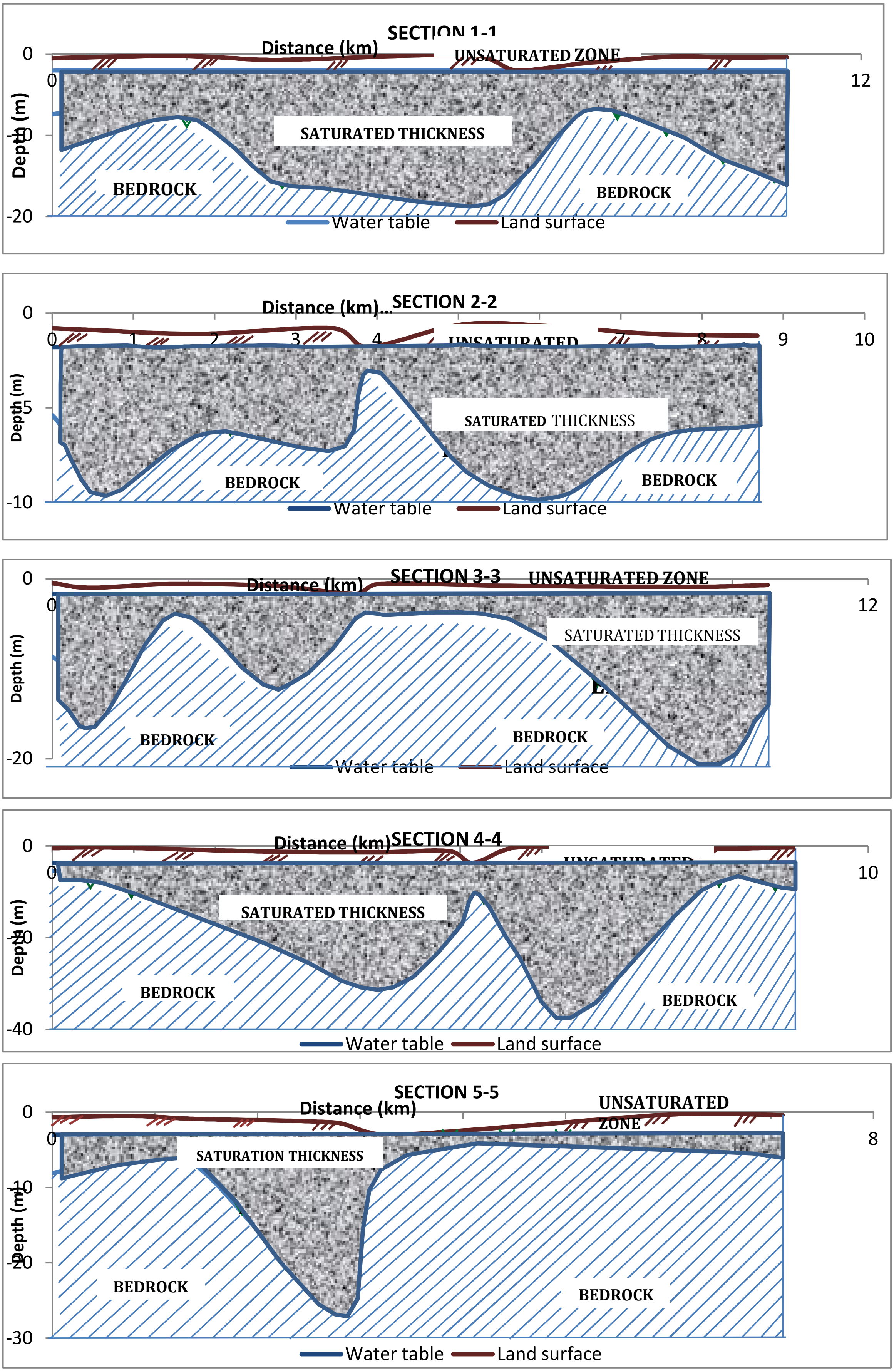


Figure 10. Schematic cross-sections of study area along the profile lines

4.5 Estimated Groundwater Storage

The results of the cross-sectional areas of the various sections which were estimated from the Simpsons rule are shown in Table

Table 5: Computed values of estimated cross-sectional areas along the profile lines

Cross-section	**Section 1-1**	**Section 2-2**	**Section 3-3**	**Section 4-4**	**Section 5-5**	**Average area**
Area, m^2	80,066.67	51,440.00	66,400.00	88,066.67	60,100.00	69,214.67

From the table, the average estimated cross-sectional area of the study area is **69,214.67 m^2** whiles the longitudinal length across study the study area is **20,415 m**. The mean porosity of the study area according to Barnie (2010) is **26.24 %.** The product of these values gives the total groundwater storage of the Atankwidi sub-basin as **370,777,191.2 m^3**. The White Volta Basin is reported to have groundwater storage of 3.9×10^{10} m^3 (Kortatsi, 1997) suggesting that, the groundwater storage of Atankwidi sub-basin (that falls within Ghana) represents about 0.95 % of that of the White Volta Basin as a whole.

5. Conclusion

This paper recognizes the need for the delineation of the shallow aquifer geometry in Atankwidi sub-basin of the White Volta Basin to really assess the nature or type of aquifer and also to know the potential storage of the aquifer. Currently the extent of the shallow aquifer system and its potential storage in the area is not known which makes it difficult to know the sustainability of SGI in the area. This study has therefore delineated the shallow aquifer geometry in the area and its potential groundwater storage to help decision-makers prioritize to develop the groundwater resource for irrigation.

The aquifer geometry in the Atankwidi sub-basin as delineated using geoelectrical (electromagnetic, EM and vertical electrical depth sounding, VES) techniques is indeed shallow and lies above the first impervious layer or stratum and hence susceptible to pollution. The regional shallow aquifer system in the area is unconfined with very shallow depth to water table and has a high storage potential which if properly managed can be abstracted for large-scale irrigation. However further research should be conducted to estimate the safe yield of the aquifer in the study area in order to know the volume of water that can be abstracted safely.

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