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Groundwater Exploration for Water Well Site Locations Using Geophysical Survey Methods

Haile Arefayne Shishaye[1*] and Semir Abdi[2]

[1]*Department of Water Resource and Irrigation Engineering, Haramaya University, Ethiopia*

[2]*Hydrogeologist in Harar Regional Water Supply and Sewerage Bureau, Ethiopia*

***Corresponding author:** Haile Arefayne Shishaye, Department of Water Resource and Irrigation Engineering, Haramaya University, Ethiopia, Tel: +251925920594; E-mail: haile.4.hiwot@gmail.com

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Abstract

Groundwater exploration is the investigation of underground formations to understand the hydrologic cycle, know the groundwater quality, and identify the nature, number and type of aquifers. There are different groundwater exploration methods. Surface geophysical method is one of the groundwater investigation methods. One of the surface geophysical methods is therefore the vertical electrical sounding method. Vertical electrical sounding (VES) is one to provide valuable information regarding the vertical successions of subsurface geo-materials in terms of their individual thicknesses and corresponding resistivity values. It is rapid and much effective in estimating aquifer thickness of an area and is cost effective technique for groundwater study. The objective of this study was therefore to locate two well site locations using surface geophysical methods for water supply purposes. However, hydrogeological and geological investigations were also incorporated in addition to the geophysical surveying activities for the betterment of the project. Finally, the intended well site locations with their corresponding thickness and resistivity values were identified using the integrated approaches.

Keywords: Groundwater exploration; Geophysical survey; Water well; Haramaya University; Lake Haramaya watershed

Introduction

Water is an essence food and basic component of life. The need for water is strongly ascending and has a diversified function, which is not only important for drinking purposes but is also vital for any developmental activities. Nowadays, the use and sustainability of water is getting more complex due to population growth, urbanization and industrialization. Any development is related either directly or indirectly with water utilization.

For any developmental activity, both surface and groundwater sources are the main components depending on their quality and availability. In an area where surface water is not feasible for the desired activity, groundwater is the second alternative, if it has the anticipated amount and quality. Therefore, site investigation/exploration, sometimes called a pre-construction evaluation, has to be performed primarily for an effective and sustainable utilization of groundwater resources.

Groundwater has become immensely important for the different water supply purposes in urban and rural areas of both the developed and developing countries [1]. However, groundwater exploration in hard rock terrain is a very challenging and difficult task, if the promising groundwater zones are associated with fractured and fissured media [2]. In such an environment, the groundwater potentiality depends mainly on the thickness of the weathered/fractured layer overlying the basement.

Groundwater can be explored using different methods. The four major groundwater exploration methods are the areal method, surface method, subsurface method and esoteric methods. Among these methods, esoteric method is not based on science, mostly based on traditional indicators. Each of the above listed groundwater exploration methods have different sub-methods under them. Geophysical survey is therefore one of the sub-methods under the surface method of groundwater exploration [1]. This method is very important for both groundwater resource mapping and water quality evaluations [1]. Its application for groundwater exploration purposes has increased over the last few years due to the rapid advances in computer packages and associated numerical modeling solutions [2].

Geophysical survey incorporates the Vertical Electrical Sounding (VES) and Horizontal Profiling (HP) activities. The Vertical Electrical Sounding (VES) is currently being very popular with groundwater investigations due to its simplicity [3,4]. This geophysical survey method is the detection of the surface effects produced by the flow of electric current inside the earth [2,5]. It provides depth and thickness of various subsurface layers and their relative water yielding capacities [5].

The water supply for the Haramaya University community and the farmlands within the university campus comes from the wells drilled within the university compound. There are eight previously drilled wells within the university (Figure 1), excluding the newly drilled wells (new well 1 and 2, i.e., these two wells were drilled based on this study). However, the yield of the eight wells was not able to balance the gap between the demand of the university community and the current potential of the water supply.

Therefore, the objective of this study was to identify potential well site locations and to know the overall groundwater conditions of the study area using surface geophysical survey. More specifically, the study was aimed to understand the nature, number and type of aquifers within the study area so as to identify the potential well sites that could balance the water demand and supply.

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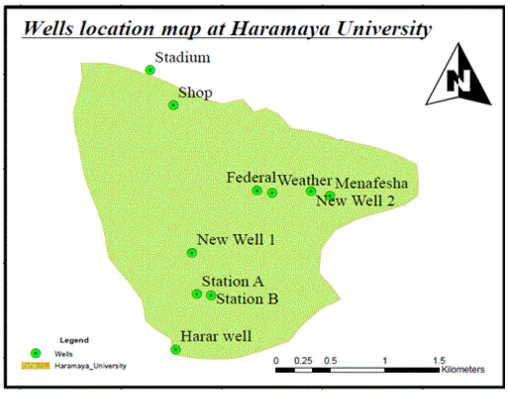

Figure 1: Locations of previously drilled and new wells.

Materials and Methods

Description of study area

Haramaya University is located in the Lake Haramaya watershed. Lake Haramaya Watershed (Figure 2) is situated in the Eastern Ethiopia, found in Haramaya and partly in Kombolcha districts, Eastern Hararghe Zone, Oromia Regional State at 505 km East of Addis Abeba and 20 km north-west of Harar town. The university is therefore found in the Haramaya district. It lies at 9°22'03"- 9°27'12" North and 41°58'14"- 42°05'26" East.

The average annual rainfall in the watershed is 801 mm. The dry period (less than 30 mm per month) extends from October to January; while, the wettest month is August with an average rainfall of 144 mm. According to Shimelis [6], the annual average effective rainfall of Lake Haramaya watershed is about 673 mm.

Moreover, the annual mean temperature is 18°C. The months of October to January tend to be slightly warmer; while, June to September is the coolest period. The daily temperature in the study area ranges from around 10°C to 25°C.

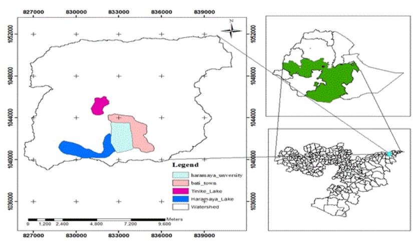

Figure 2: Location of Haramaya University within the Lake Haramaya Watershed [11].

Desk study

The study was conducted integrating both the desk study and field work activities. The desk study in this project involves evaluation of regional and sub-regional hydrogeological maps and evaluation of the previously developed Geological and hydrogeological maps of the watershed. Furthermore, it also involves investigations based on the enhanced Thematic Mapper satellite images at a resolution of 15 × 15 meters and evaluation of Geological and Hydrogeological map of Ethiopia (1:2,000,000).

Previous geological and hydrogeological work: Physiographically, the study area is part of the Harar Plateau areas, which is the upper part of Wabi-Shebele Basin (Figure 3). It is characterized by three major stratigraphic units including the Precambrian crystalline basement (mainly granite), Mesozoic sedimentary rocks (sandstone and limestone) and Quaternary sediments from old to young [7]. The Precambrian basement complex includes the high grade metamorphic gneisses and migmatites, and the intrusive granites [8]. The sandstone rock unit outcrops on the eastern and western side overlying by limestone that is dipping towards west and underlined by the basement rocks (Figure 4). The quaternary sediment is covering the low lying area that comprises lacustrine sediments, alluvial and eluvial sediment (Figure 4).

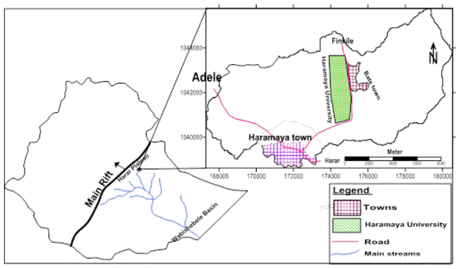

Figure 3: Location map of the Haramaya Well Field (Guesh et al.).

Groundwater occurrence, circulation and storage properties of the area are determined greatly by the type of geology, geological contacts, geomorphology and rainfall patterns. The main aquifer system in the area is the unconsolidated material composed of loose coarse grained sand, pebbles and rock fragments, silt and clay materials [9], which is characterized by high-moderate to low productivities.

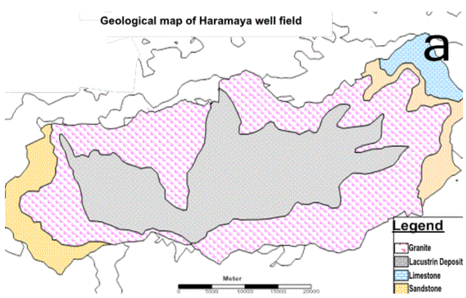

Figure 4: Geological map of Haramaya well field [9].

The basement (granite) unit has low permeability and productivity [7,8]; while, the sandstone and limestone units are characterized by moderate range of permeability and productivity [10]. The subsurface boundary condition of this porous, single-unconfined aquifer system is the replica of surface topography except on the North boundary [9].

Climate: Surface and subsurface water potential is dependent on various factors. These factors include the climate, geology, vegetation, topography, elevation and etc. Among the above listed factors, climate

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plays a great role in influencing meteorological parameters such as rainfall, temperature, relative humidity, evapotranspiration and wind speed, which are very important parameters for water resources evaluation.

Water is constantly evaporated from the earth and is precipitated back on the earth in the form of rain, snow, etc. Part of this precipitation infiltrates into the ground, raising the water table, and the major part flows as runoff; and the rest is lost in the form of evaporation and transpiration. The interaction between precipitation, infiltrated water, runoff and groundwater is rather complex. It is affected by physiographic, geologic, meteorologic and hydrologic factors as well as by human activities such as water use and pollution.

The study area belongs to the summer and spring rainfall region of the country. Rainfall comes through the Southwester lies. During the summer season (June, July and August) the sun is overhead north of the equator. The cyclone or low pressure cells are in southwest Asia. The anticyclones or high pressure cells are on the Atlantic and Indian Ocean around the Tropic of Capricorn. The Inter-Tropical Convergence Zone (ITCZ) is just north of Ethiopia or northeast of Ethiopia on the Red Sea and Gulf of Aden (Figure 5) and the area is under the influence of Atlantic equatorial westerlies and southern winds from the Indian Ocean. Both the Atlantic and Indian Oceans are sources of rainfall. The main source being the Atlantic as the southerlies from the Indian Ocean lose most of their moisture as rainfall over the Kenyan highlands. These southwester lies ascend over the western highlands of Ethiopia to produce the main rainy season; as a consequence the rainfall is mainly orographic. The summer rainfall has a wide coverage and all of the highlands and lowlands of the basin receive rain in varying degrees starting from June up to mid-September.

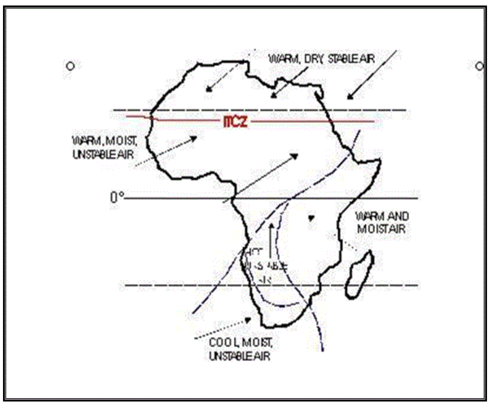

Figure 5: Mean Position of ITCZ in July.

Aspects of groundwater recharge and discharge

Recharge: Groundwater recharge may be defined in a general sense as the downward flow of water reaching to the water table, and forming groundwater reservoir. Recharge may occur naturally from precipitation, rivers, canals, lakes, or as man induced phenomena (irrigation and urban recharge). Assessment of the mechanism and amount of recharge is fundamental for sustainable groundwater resources utilization and management. However, estimating the different recharge processes is not simple. It requires understanding the various processes that affect recharge and quantifying the spatial and temporal variability. Unfortunately, there is no direct means of measuring groundwater recharge at regional and sub-regional level.

Recharge estimation requires accounting the different factors. These include:

Topography and geology

Precipitation (magnitude, intensity, duration, spatial distribution)

Runoff and ponding of water

Irrigation (nature of irrigation scheduling, losses from canals and water courses, etc.)

Rivers (rivers flowing into and leaving out of the area under consideration, rivers gaining water from or losing water to the aquifer, etc.).

Soil zone (nature of the soil, depth, hydraulic parameters, variability of the soil spatially and with depth, rooting depth of the soil, and cracking of soil on drying out or swelling due to wetting)

Unsaturated zone between soil and aquifer (flow mechanism through unsaturated zone, zones with different hydraulic conductivity, etc.)

Ability of aquifer to store water and variation of aquifer condition with time

The recharge conditions for any area may comprise the above all types of recharge. However, the encountered types of recharge at the study area and its vicinity are:

Direct recharge - Water added to the groundwater reservoir in excess of soil moisture deficits and evapo-transpiration, by direct vertical percolation of precipitation through the unsaturated zone. In this case, the ultimate source of groundwater recharge in the site was found to be precipitation.

Indirect recharge - Percolation to the water table following runoff and localization in joints, as ponding in low lying areas and/or through the beds of surface water resources such as lakes and reservoirs.

Localized recharge - Resulting from horizontal surface concentrations of water in the absence of well-defined channels.

Discharge: Discharge of groundwater is manifested as springs, pumping, seepage zones and base flow of rivers. Groundwater discharge areas are often present in lowlands, local and regional depressions, and along the banks of rivers. Discharge areas are intimately linked with groundwater flow lines and the existence of geological structures. However, the main groundwater discharge in the study area was found to be pumping.

Aquifer characteristics: The aquifer characteristics of study areas are classified based on similar or nearly similar hydrogeological characteristics of geological structures. One of the basic elements of Hydrogeological study is production of hydrogeological map. The map has to include hydrogeological characteristics of hydro stratigraphic units, basically the geological characteristics of the area that includes degree of fracturing and degree of weathering, geological structures that favorite groundwater storage and movements and other parameters play significant role in designing capture and dewatering systems of groundwater. Besides schematizing the natural hydrogeological conditions, it is important to know the hydraulic/hydrogeological parameters.

There are several important physical properties that govern the capability of an aquifer to store, transmit, and yield groundwater. Reliable interpretations and conclusions about the whole aquifer performance in an area are not possible without the accurate determination of these basic aquifer's physical properties.

According to Guesh et al. [9], the calculated transmissivity near existing wells in the study area was found ranging between 28.6-237.76 m^2/day; while, values computed from pumping test result ranges between 41.67 m^2/day and 336.9 m^2/day. Moreover, the average hydraulic conductivity in the area was also found to be 4.85 m/day. Accordingly, the hydrogeologic nature of the aquifer in the study area was found to be favorable to drill water wells in.

Fieldwork

In this study, the field work was conducted to investigate topography, local geological and hydrogeological conditions of the project area in relation to the developed maps. Moreover, geophysical investigations were also conducted using the SARIS 1000 Terrameter, which has digital LCD earth resistivity measuring instrument.

Hydrogeological and geophysical investigations: Groundwater potential evaluation for a given area/basin requires integrated approach. Detailed quantification of the amount of groundwater demand a detailed water balance study and defining the boundary conditions, establishment of the lateral and vertical extent of aquifers and confining beds. In the absence of detailed hydro meteorological and hydrogeological data, groundwater potential evaluation tends to be more semi-quantitative mainly based on geophysical investigation.

The method followed in this study, for the most part, was depending on the short-term field hydrogeological investigation and surface geophysical surveying. Both approaches provide information on the availability of groundwater in a semi-quantitative sense.

Geophysics provides no information on the exact amount of groundwater available in the subsurface. The amount can only be estimated when the geophysical survey is supported by the local hydrogeological features such as recharge potential, availability of permeable rocks, catchments areas, etc.

All the interpretations shown in the geophysical part of this study are made semi-quantitatively by integrating the hydrogeological field observations with the geophysical signature obtained from the VES data. The recommendations of the likely depth of drilling are made on the basis of the VES data and the nearby well data. The supervisor/hydro geologist can recommend the accurate drilling depth during the drilling operation. For instance in some sites where geophysics does not give conclusive answers on the total depth of the aquifers, yield of the well can be defined by using provisional tests with the compressor of the drilling machine.

Data analysis and interpretation

Computer assisted iterative interpretation packages like IPI2 and Win RESIST software's of Schlumberger analysis were used to interpret the resistivity data gathered from the field. i.e., they were used to identify the thickness and depth of each hydro stratigraphic layer in the study area. Moreover, ArcGIS 10.2 was also used to locate the VES points and well locations within the study area.

Results and Discussion

The Vertical Electrical Soundings were carried out at the selected areas. A total of eight VES points were surveyed. The UTM coordinates, i.e., Easting and Northing, of the sounding points were obtained with the help of a GARMIN II GPS receiver in Adindan datum.

The Vertical Electrical soundings were made using the following equipment:

Canadian made SARIS 1000 Earth Resistivity Meter, which is powered by a rechargeable battery

Wires and Reels

Stainless steel electrodes

Accessories such as alligator clips and hammer

The Schlumberger electrode configuration with maximum half-current electrode separation (AB/2) of 100 to 150 m was used for the sounding survey. Current is injected into the ground using two current electrodes, A and B, placed at a distance AB/2 apart; and the potential drop that occurs between two other electrodes, M and N, placed near the center of the current electrodes is measured (Figure 6). The current electrode separation, AB/2, is progressively increased in steps so as to increase the depth of investigation, and at each step the measured current and potential readings are used to obtain the apparent resistivity of the ground.

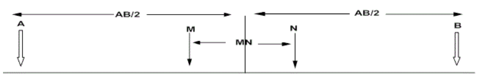

Figure 6: Representation of Schlumberger electrode configurations.

Data processing and presentation

The VES is done by injecting a low current into the ground through stainless steel electrodes and then after the resistance of the earth material is measured during the passage of the current simultaneously. The VES data collected in the field was initially interpreted using IPI2 window based resistivity software just to get the layer parameters. The layer parameters so obtained have been used as starting models in an iterative least squares inversion program, and then the software automatically displays the layer resistivity, thickness and depth of the layers from the ground surface.

Interpretation results

Vertical Electrical Sounding (VES) Data and interpretation

Array: Schlumberger, Azimuth: E-W, Instrument: SARIS 1000, VES Location UTM E: 174362, N: 1041581, Gr. Elevation: 2027 m.a.s.l, VES I.D. No.: 1.

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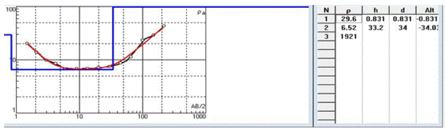

Figure 7: Resistivity variation curve of VES point 1.

Site description: The VES was conducted at the flat land at Haramaya University within the Haramaya Well field. The VES was conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. On the bases of the geophysical data, a well can be drilled at this point to a maximum depth of 34-44 meters. This is because of the maximum depth of drilling in such a case can be extended up to ten plus the total depth of the layers found from the interpreting packages. The thickness of the productive aquifer in this case is 33.2 m (Figures 7 and 8).

Array: Schlumberger, Azimuth: E-W, Instrument: SARIS 1000, VES Location UTM E: 174130, N: 1041423 Gr. Elevation: 2023 m.a.s.l, VES I.D. No. 2.

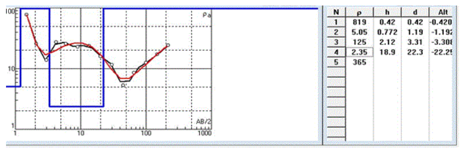

Figure 8: Resistivity Variation curve of VES Point 2.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature displays five resistive layer, the most promising aquifer zone is located at the fourth layer. However, the thickness of the aquifer is 18.9 m. So, on the bases of geophysical data, the well in this site can be drilled to a maximum depth of 23-33 meters (Figure 9).

Array: Schlumberger, Azimuth: E-W, Instrument: SARIS 1000, VES Location UTM E: 173923 N: 1041590, Gr. Elevation: 2022 m.a.s.l, VES I.D. No. 3.

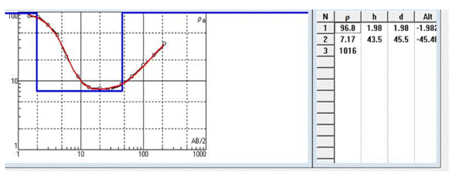

Figure 9: Resistivity Variation curve of VES Point 3.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature in this case displays three resistive layers; the most promising aquifer zone is located at the second layer. The thickness of the promising aquifer is around 43.5 m. On the bases of geophysical data, a well at this site can be drilled to a maximum depth of 45-55 meters (Figure 10).

Array: Schlumberger, Azimuth: E-W, Instrument: SARIS 1000, VES Location UTM E: 174612 N: 1041877, Gr. Elevation: 2027 m.a.s.l, VES I.D. No. 4.

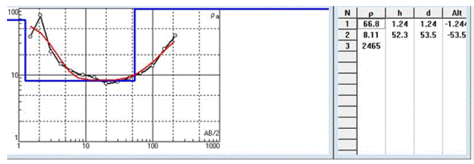

Figure 10: Resistivity Variation curve of VES Point 4.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES was conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature displays three resistive layers; the most promising aquifer zone is located at the second layer. The thickness of the most promising layer is 52.3 m. Thus, on the bases of geophysical data, the well at this site can be drilled to a maximum depth of 54-64 meters. Accordingly, "New Well 2 (Figure 1)" was drilled at this site. The actual depth of the well, the location of the basement from the ground surface, was found to be 50 m (Figure 11).

Array: Schlumberger, Azimuth: E-W, Instrument: SARIS 1000, VES Location UTM E: 0174156 N: 1041783, Gr. Elevation: 2028 m.a.s.l, VES I.D. No. 5.

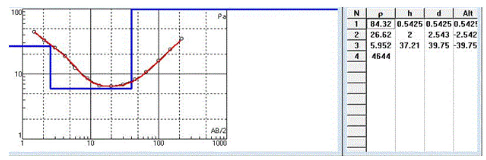

Figure 11: Resistivity Variation curve of VES Point 5.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature displays four resistive layers; the most promising aquifer zone is located at the third layer. The thickness of the most promising layer is 37.2 m. Thus, on the bases of geophysical data, the well at this site can be drilled to a maximum depth of 40-50 meters (Figure 12).

Array: Schlumberger, Azimuth: N-S, Instrument: SARIS 1000, VES Location UTM E: 174975 N: 1042072, Gr. Elevation: 2025 m.a.s.l, VES I.D. No. 6.

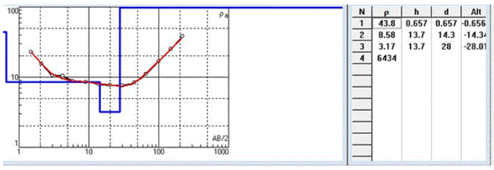

Figure 12: Resistivity Variation curve of VES Point 6.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature displays four resistive layers; the most promising aquifer zone is located at the third layer (Figure 13). The thickness of the most promising layer is 13.7 m. Thus, on the bases of geophysical data, the well at this site can be drilled to a maximum depth of 28-38 meters.

Array: Schlumberger, Azimuth: N-S, Instrument: SARIS 1000, VES Location UTM E: 173886 N: 1041482, Gr. Elevation: 2014 m.a.s.l, VES I.D. No. 7.

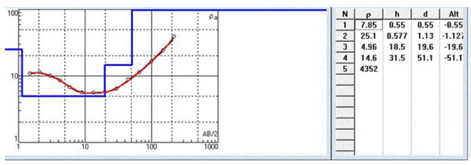

Figure 13: Resistivity Variation curve of VES Point 7.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature displays five resistive layers; the most promising aquifer zone is located at the fourth layer. The thickness of the most promising layer is 31.5 m. Thus, on the bases of geophysical data, the well at this site can be drilled to a maximum depth of 51.1-61.1 meters. Accordingly, New well 1 (Figures 1 and 13) was drilled in this site. The actual depth of the well was found to be 52 m.

Array: Schlumberger, Azimuth: N-S, Instrument: SARIS 1000, VES Location UTM E: 173519 N: 1043268, Gr. Elevation: 2007 m.a.s.l, VES I.D. No. 8.

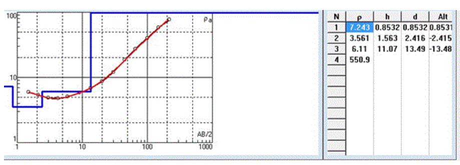

Figure 14: Resistivity Variation curve of VES Point 8.

Site description: VES was conducted at the flat land at the Haramaya University within the well field. The VES conducted to confirm the presence of geological structure, thereby to pinpoint appropriate site for drilling. The geophysical signature displays four resistive layers; the most promising aquifer zone is located at the third layer. However, the thickness of the most promising layer is 11.07 m. Thus, on the bases of geophysical data, the well at this site can be drilled to a maximum depth of 13.5-23.5 meters (Figure 14).

Conclusion

The main goal of the study was to select potential well locations for water supply purposes. Among the several disciplines the pre-construction study, i.e., site investigation, which includes geological, Hydrogeological and Geophysical investigations need special attention that helps to minimize the project cost and increase quality and quantity of water.

Accordingly, the work has resulted in the identification of two shallow well development sites (VES-4 and VES-7), where new well 2 and new well 1 were drilled in, respectively. As indicated above, the work is mainly based on the geophysical investigations conducted in the study area, the conventional hydrogeological investigations and remote sensing (satellite imagery), and limited previous works in similar areas. The geophysical signature indicates that the recommended groundwater drilling depth is for shallow wells. For these wells the maximum depth of drilling may reach up to 60 m. However, as it was done in VES 4 and 7 (locations of new well 2 and new well 1), this figure may be changed based on the available water obtained during drilling and it is to be checked with provisional tests with the compressor. This is to be decided by the supervisor/field Hydro geologist.

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