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Vertical Electrical Sounding Investigation of Aquifer Description in the Area between Elbutana Bridge and Elsasareeb, River Atbara Valley, Sudan

K. Nayl[1], A. Elsheikh[2], A. Elbahari[3] and I. Babiker[4]

[1]Groundwater and Wadies Directorate, Ministry of Water Resources, Kassala State, Suda,
[2]Department of Hydrogeology, Faculty of Petroleum and Minerals, Al Neelain University, Khartoum, Sudan
[3]Arab consult for Geology and Environment, Riyadh, Saudi Arabia
[4]Taibah University, College of Science, Department of Geology, Al-Madina Al-Monawara, Kingdom of Saudi Arabia,

The main objectives of the study are to obtain more detailed information about the depth of the basement rocks underlying the alluvial deposit, to find out the thicknesses and resistivity of the different layers, to identify the aquifer thickness & boundaries, and to select suitable sites for drilling successful boreholes. Vertical electrical sounding (VES) technique was applied using Schlumberger Array (configuration), with a maximum half separation AB/2 = 600 -700m. Sixteen borehole data were collected. The study area was covered by (35) points of vertical electrical sounding (VES) measurements. Six geo-electrical sections were constructed in the study area in E-W and N-S directions. The geophysical investigations confirmed that the study area consisted of five to seven layers: superficial deposits, sand, clay, River Atbara sediments, and the basement complex, in addition to intruded basaltic rocks. Moreover, the geophysical investigations indicated that the depth of the basement rocks varies between 45-68m. River Atbara sediments are considered the main water-bearing formation in the study area. The thickness of the aquifer varies between 10-30m and is controlled by the thickness of the clay cover, which lies directly over the aquifer zone

Keywords: Geophysical exploration; electrical resistivity; groundwater occurrences; eastern Sudan

I. INTRODUCTION

There are many geophysical methods known worldwide applied in geological exploration such as gravity, magnetic, electromagnetic, seismic, and resistivity methods. Geophysical methods can help solve the problem by detecting the occurrence, depth, and thickness of the subsurface layers (El-Galladi *et al.*, 2007). The geo-electric method is regularly used in the identification of the depth, thickness and boundary of an aquifer that helps in the determination of groundwater potential (Omosuyi *et al.*, 2007; Oseji *et al.*, 2005; Ismailmohamaden, 2005). The resistivity method is the most common method used in groundwater exploration. The electrical resistivity methods helped to identify aquifer lithology, saturation, salinity and porosity (Shaaban, 2002). These properties have been successfully used to explore groundwater and its condition (Al-Garni, 2009). The vertical electrical sounding technique is used to determine variations in electrical resistivity with depth and resistivity values of the layers. Whereas profiling techniques reflected lateral changes in electrical resistivity corresponding to variations in lithology, weathering, fracturing and water content (Okereke *et al.*, 1998). The most common arrays used for resistivity surveys are Wenner, Schlumberger, Three-Point, Dipole-Dipole, and Lee-Partition Spreading (Telford *et al.*, 1982). The choice of the "best" array for a field survey depends on the geological

*Corresponding author's e-mail: nail62964@yahoo.com

condition, the sensitivity of the resistivity meter, and the background noise level (Hago, 2000). The Wenner configuration discriminates between resistivities of different geo-electric lateral layers, while the Schlumberger configuration is used for the variations of depth layers (Olowofela *et al.*, 2005). Geophysics aims to reduce the high cost of drilling and achieve the above-mentioned objectives (Milsom, 2003). The vertical sounding method has the capability to distinguish between saturated and unsaturated layers. However, the VES data generally reflect the relation between the groundwater occurrence and the resistivity of the water-bearing formation. The main task of the electrical sounding method in this study is to identify resistivity zones related to groundwater occurrences. The River Atbara is characterised by a special land platform called the Karab. The saturation zone in the study area extended under this Karab needs more investigation. The study area has never been subjected to previous hydrogeological assessment except for some very minor efforts. Scattered studies in the area include geological studies, groundwater exploration, and groundwater quality investigations. An Italian company, RIKI (1900), during the construction of the Kassala–Haya highway, drilled 5 productive wells in the Karab zone of River Atbara at Adr Habib area after geophysical studies. Due to this study, five successful wells were drilled. The Groundwater Research Department of Khartoum, represented by the Technical Committee – Kassala (1982), conducted a geophysical study in an area of 80km^2 for a private enterprise (Elsweikit – Basahl) only at a distance of 12 km from (RIKI) wells in the plain area. The Technical Committee – Kassala (1987-1992) conducted a geophysical survey on the western bank of River Atbara (Elsharafa Village to Elgaffala Village). According to this study, 15 wells were drilled. These wells are now used for drinking water in 15 villages on the western bank of the River Atbara. Drinking Water Corporation of Kassala State, during the period 2002-2006, drilled about 6 wells in some villages for drinking purposes on the western bank of the River Atbara. The National Company Manufacturing Water Equipment of Kassala office, during the period 2006-2008, drilled several wells for drinking purposes in some villages on the eastern bank of River Atbara after a geophysical survey funded by the Red Crescent Kassala office. Ibrahim *et al.* (1992) carried out a combined geophysical and hydrogeological investigation to evaluate the groundwater potential in eastern Sudan. From their interpretations, two major basins were identified, namely, Wad Elhelew and Elshowak Basin. The first is an NNE – SSW trending basin with a maximum thickness of 2.2km, and the other is a shallower basin with a maximum thickness not exceeding 0.25km. Within these basins, groundwater occurs essentially in two major aquifers: the Nubian aquifer and the Neogene – Recent deposits aquifer. Fadull *et al.*, (1999) carried out a study to estimate the gross area of the Karab lands along the Atbara River and its tributaries. They estimate the rate of annual loss of arable land caused by gully erosion and its environmental effects.

A. Study Area

The study area lies in Eastern Sudan in the Kassala State, between the latitudes 15.0° - 15.5° N and longitudes 35.40° - 36° E, at 70km southwest of Kassala city with a total surface area of about 500km^2 (Figure 1). Kassala, New Halfa, and Khashm El Girba are the most important towns in the area. They are well-connected with different towns and villages through a network of paved and unpaved seasonal roads. However, these seasonal roads are inaccessible during the rainy season due to the sticky clay soil cover. Kassala town itself is excellently connected via Port Sudan – Kassala – Khartoum Highway. The population in the study area was estimated to be 27,480 persons (Census, 2008), with an estimated increasing rate of 2.5% per year. The population is concentrated on the western bank of the River Atbara, where the New Halfa agricultural scheme is located. A few people live on the eastern bank of the river. The settlement is mainly governed by the availability of water, infrastructure, health and education services. The study area is located in arid and semi-arid zones where the climate is characterised by a long hot summer with a short cold winter and the winds usually come from the north (Saeed, 1969). The vegetation cover consists of a mixture of grasses and herbs, frequently associated with scrub bushes up to 6.5 feet (2 meters) high. The decrease in rainfall in recent years has produced species more tolerant to dry climate conditions. The study area consists mainly of a plain area gently sloping towards the west on the eastern side and slopes towards the east on the western side of River Atbara, with a general slope across the plain area from southeast to northwest. Near the River, the drainage pattern intersects and forms a special landform called The Karab, a typical characteristic of River Atbara deposits (Fadull *et al.*, 1999). Small Khors flowing in the direction of the river form a sort of dendritic to rectangular drainage pattern (Plate 1).

Plate 1. The Karab formation zone in the study area

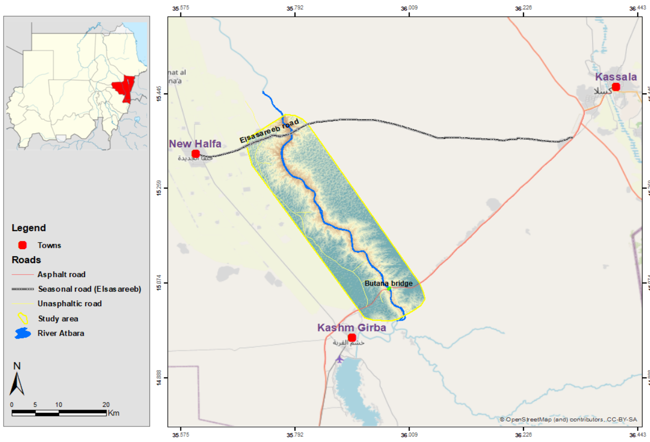

Figure 1. Location map of the study area

B. Geological and Structural Setting

Based on the findings from the carried geological and hydrogeological investigations in the study area (Hussein *et al.*, 1989; Eisawi & Schrank, 2009; Fadull *et al.*, 1999; Elsheikh *et al.*, 2014) and from the conducted field survey, the geology of the study area consisted of the following: superficial, unconsolidated Karab formation, River Atbara sediments, Cenozoic Basalts, and the basement complex. The basement complex, which forms a lower impervious boundary of the aquifer, is of the Precambrian age. It consists mainly of slates, schist, granitic gneiss, quartzite, and pegmatite dykes. It generally outcrops in the form of scattered hills on the western bank of River Atbara in the plain area near New Halfa town (Figure 2). The basaltic rocks occur in the form of dykes, sills, and flows. Most of this rock is fine to very fine grains. Miocene to Pliocene age was attributed to basaltic rocks weathering (Ibrahim *et al.*, 1992). Through the study survey, the basaltic rocks have been found only in the southern part of the study area (Figure 2). These rocks occurred as a thin layer intruded within the loose formation and sometimes overlain the basement complex.

A shallow graben structure developed possibly as a result of a combination of tectonic and erosional activities from the Late Tertiary to Early Quaternary period. This shallow graben is filled with River Atbara sediments. These deposits mainly consist of sands and silt; intercalated with clay and gravelly layers dominate this sequence. These deposits are usually underlain by the basement complex. The total thickness of this formation varies between 10-70m, the gravel and sands of this sequence seem to form the lower zone of aquifer formation and lie unconformable on the basement complex. Some authors relate this deposit to the formation of old Wadi sediments. The River Atbara is characterised by a special land platform called the Karab, which is always attached to the banks of the river, covering almost a distance of 2-3km from each bank (Figure 2). The word 'Karab' corresponds to a rugged topography limited to deposits in proximity to River Atbara and Setit. The age of this formation is Neogene to Quaternary (Ibrahim *et al.*, 1992). Karab refers to a typical bad land terrain that has developed and is characterised by extensive gullying along the rivers draining from the Ethiopian highlands (Fadull *et al.*, 1999). Masdar (I991) defined Karab as sloping land, severely dissected and eroded between the clay plain and the alluvial flood plain bordering streams and watercourses. Karab phenomena occurred as a result of erosional activities according to the considerable variation in the slope between the banks and the riverbed. The Karab is a part of the old sediments of River Atbara and overlays this sediment as a result of the leaching. The superficial deposits are mainly eluvial, colluvial, and alluvial deposits of Pleistocene to Recent age. They are mainly composed of clay, silt, sandy clay, clayey sand, and pebbly materials. The folds, faults, fractures, and joints are the main structural features characterising the area. In the study area, a major fault in the E-W direction has appeared near Butana Bridge around Korak village. This fault terminates the extension of the Cenozoic Basalts in the NW direction and ends at Butana Bridge. Some minor faults were distributed in the study area, controlling the scattered khors in the study area (Figure 2).

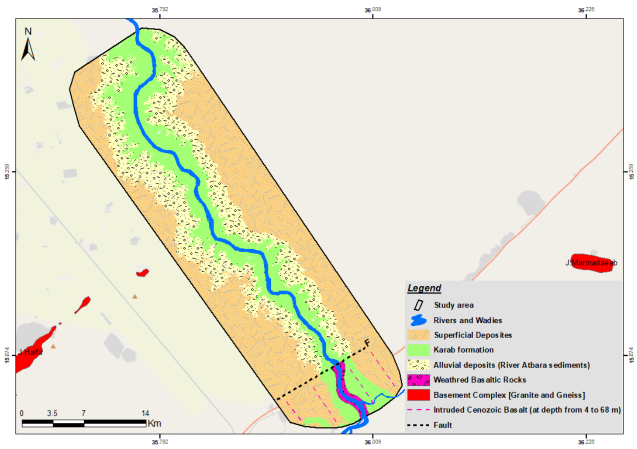

Figure 2. The Geological map of the study area reflecting five geological sequences

II. MATERIALS AND METHOD

The material and methods of the study were planned to achieve the research objectives. They include the collection of previous data, enhancement of remotely sensed data, conducting field works for the monitoring of the piezometric and observation wells, measurements of hydrogeological and geophysical parameters, and the office and laboratory work for data analyses and manipulations. In the current investigation, the Electrical Resistivity method has been used. Vertical electrical sounding (VES) techniques are considered the most significant techniques for groundwater exploration to detect the vertical variations of subsurface sequences, which were conducted to verify the goals of this research. Schlumberger Array (configuration) was used throughout the survey.

The study area was covered by (35) points of vertical electrical sounding (VES) measurements evenly distributed to cover the study area at both sides of the River Atbara, (Figure 3). The VES points are distributed to fill the gaps where there are no wells and to detect the boundary of the aquifers. The VES measurements have been conducted using an ABEM SAS-1000 Terrameter (Sweden). The VES curves are interpreted with IPI-2WIN software. All data were processed and analysed using relevant techniques and software where: Arc-GIS version 10.2 was used for preparing the maps and plotting the VES points, Arc Hydro groundwater tool (AHGW) version 3.3.1, a package of GIS 10.2 was used for preparing boreholes and geo-electric cross sections, GMS version 10.1.5 is also used for preparing lithological cross-sections, Google Earth version 6.0.5001 was used to locate the sites on the maps, the digital Elevation model Acquisition (DEM) version was used for preparing drainage and watershed maps of the study area. The location of the resistivity measurements is displayed in Figure 3. A number of (16) well-log descriptions have been collected from the Groundwater and Wadies offices in Gedaref and Kassala states (Figure 3).

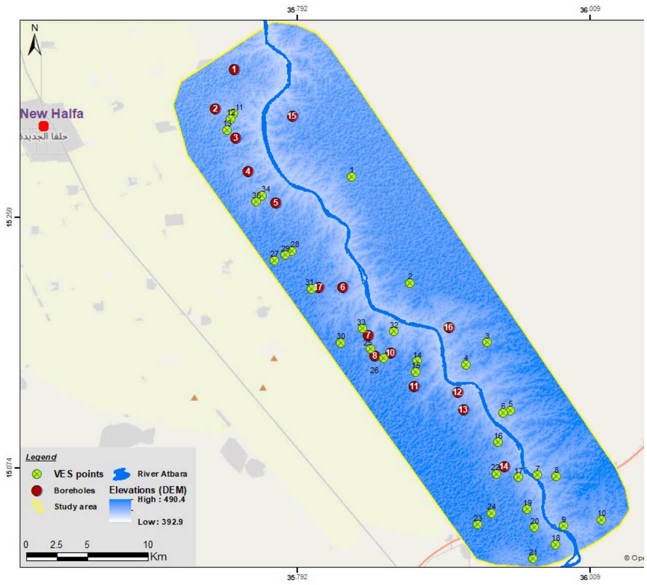

Figure 3. Location of the Vertical Electrical Sounding Points and boreholes in the study area

III. RESULT AND DISCUSSION

The acquired measured resistivity data was analysed qualitatively based on the shapes of the plotted curves and quantitatively by measuring the layer's resistivity values and depths through IPI2WIN software.

A. Qualitative Interpretation

The geological knowledge of the study area is the most important in qualitative interpretation, in which the general shape of the curves and the primary apparent resistivity of various formations were recognised. The shape of the field curve is observed to assess the number of layers and their resistivity. It gives information about the number of layers and their continuity throughout the area, and it reflects the degree of homogeneity or heterogeneity within the individual layer. Most field curves are in H, KH, HKH, QH, HA, and A types, reflecting 4 to 6 layers (Figures 4 and 5). 22 VES points out of 35 VES points are classified as (H) type, which represents the dominant curves of the stud area. 6 VES points are (QH) type, 3 VES points are (KH) type, 2 VES points are (A) type, 1 VES point is (HKH), and 1 VES point is (HA) type. Sometimes (QH) curve type, especially in the south part of the study area, indicates 5 layers which reflect the existence of basaltic rocks with relatively high resistivity values. The resistivity values curve for the aquifer in a range between (5 – 132) Ωm. The smooth shape curves indicate the homogenous geological formations. The very low resistivity values range between (0 -5) Ωm, indicating saline water or a clayey layer.

B. Quantitative Interpretation

In general, some geophysical data can be used directly in geologic interpretations. Other geophysical data require considerable processing for interpretation (Zohdy *et al.*, 1980). The VES curves will be able for quantitative interpretation. The available data of (16) wells log descriptions have been used to calibrate the VES points interpretation. Based on apparent resistivity variations of various formations and sequences, the data reveal that that area can generally reflect four, five, and six-layered as follows;

1. Alluvium formation zone

Five layers occur in the alluvium formation, with the resistivity of the surface layer ranging between (4–2431) Ω.m and are typically indicative of a dry layer (superficial deposits) with topsoil variation. This layer reaches a maximum of 14m thickness at VES27 and about a minimum of 0.329m at VES7. The second layer is characterised by relatively low resistivity values of (2–92) Ω.m and is considered a clay layer. The thickness of this layer varies greatly from one locality to another, with its maximum thickness of 33m as recorded at VES22 and its minimum thickness of 0.859m at VES17. The third layer is characterised by relatively high resistivity values of (16-644) Ω.m. This is interpreted as a dry layer of sand. The thickness of this layer varies, with a maximum of 28 m thick occurring at VES13 and a minimum of 0.629 m at VES4. The fourth layer is characterised by relatively low resistivity values of (6-132) Ω.m. This layer is a water-bearing formation consisting of sand and gravel (River Atbara sediments), which is represented as the aquifer layer in the study area. The thickness of this layer varies from 7.28 to 51 m, which is observed at VES22 and VES7, respectively. The resistivity of the 5th layer ranges from (109-16168) Ω.m was interpreted as basement rocks composed of granitic and gneiss rocks that extended below.

Table 1. The interpreted resistivity curve types of the alluvium formation zone

Layer	**Thickness (m)**	**Resistivity (Ω.m)**	**Lithological description**
1	0.329 -14	4–2431	Superficial deposits
2	0.859 -33	2–92	Clay, sticky and compact
3	0.629 -28	16-644	Dry friable sediments
4	7.28 -51	6-132	River Atbara sediments
5	>1	109-16168	Basement complex (granite and quartzite)

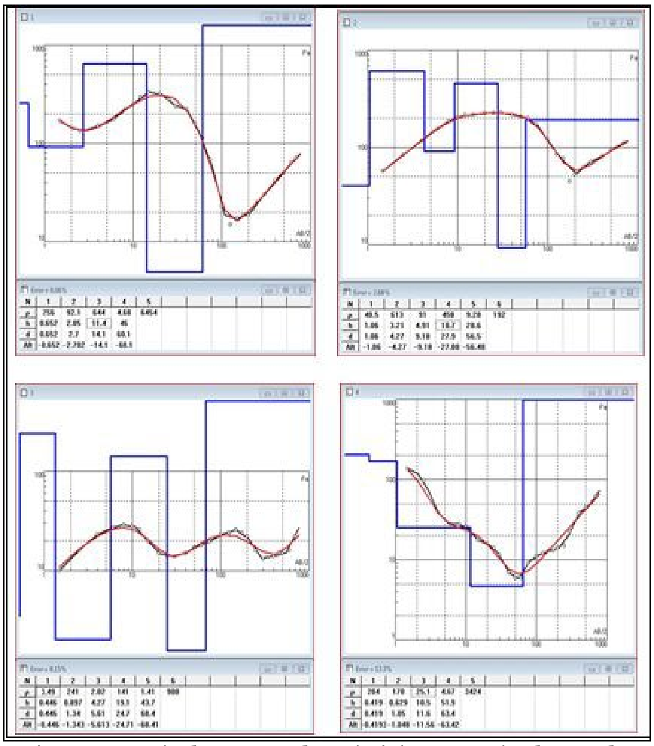

Figure 4. Typical Measured Resistivity Curve in the Study Area (Alluvium formation zone)

2. Basaltic rocks zone

There are five layers in the Basaltic rocks zone, the first layer having resistivity variation from (21-13465) Ω.m and typically indicative of a dry layer (superficial deposits) with topsoil variation. This layer reaches a maximum of 2.4m thickness at VES24 and about a minimum of 0.333m at VES21. The second layer is characterised by relatively high resistivity values of (42-1687) Ω.m. This is a dry layer of sand. The thickness of this layer varies with its maximum of 23m occurring at VES23 and VES24 and a minimum of 0.643m at VES 10. The third layer is characterised by relatively low resistivity values of (0.9–73) Ω.m, and it is considered a clayey layer. This layer reaches a maximum thickness of 12.7m and is recorded at VES9, and its minimum thickness is 1.18m at VES19 (Figure 3). The fourth layer is characterised by relatively high resistivity values (13-1345) Ω.m. This layer is composed of basaltic rocks, which are usually dry and sometimes a water-bearing formation in the weathered fractured zones and occurred only at the VES points located attached to the river. The thickness of this layer varies from 1.56 to 56m and occurred at VES19 and VES8, respectively. The resistivity of the 5th layer ranges from (221-6549) Ω.m was interpreted as basement rocks composed of granitic and gneiss rocks. The thickness of this layer varies from 1 m to ∞

Table 2. The interpreted resistivity curve types of the Basaltic rocks zone

Layer	Thickness (m)	Resistivity (Ω.m)	Lithological description
1	0.333 -2.4	21 – 13465	Superficial deposits
2	0.643 -23	42-1687	Dry friable sediments
3	1.18 -12.7	0.9–73	Clay, sticky and compact
4	1.56-56	13-1345	Cenozoic basalts
5	>1	221-6549	Basement complex (granite and quartzite)

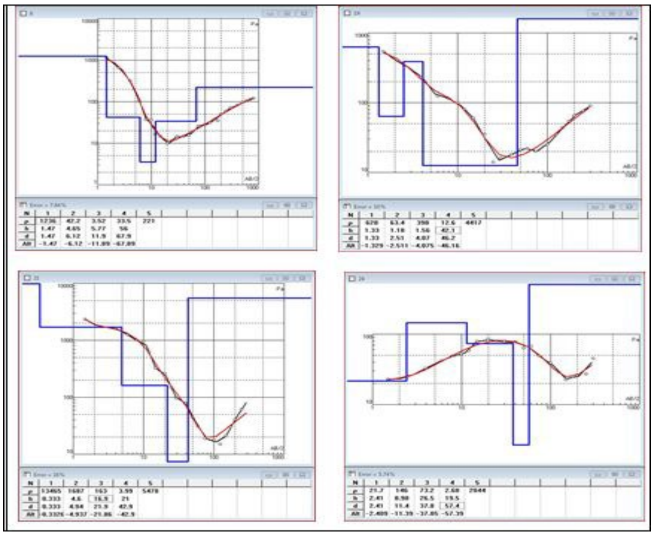

Figure 5. Typical Measured Resistivity Curve in the Study Area (Basaltic rocks zone)

3. The geo-electrical sections

The geo-electrical sections in the study area were constructed based on the interpretation of (VES) curves and the existing borehole data. Six geo-electrical sections were constructed in the study area in N-S and E-W directions (Refer to figures below). The geo-electrical sections A, B, C, and D are in the E-W direction, while the geo-electrical sections E and F are in the N-S direction (Figure 6).

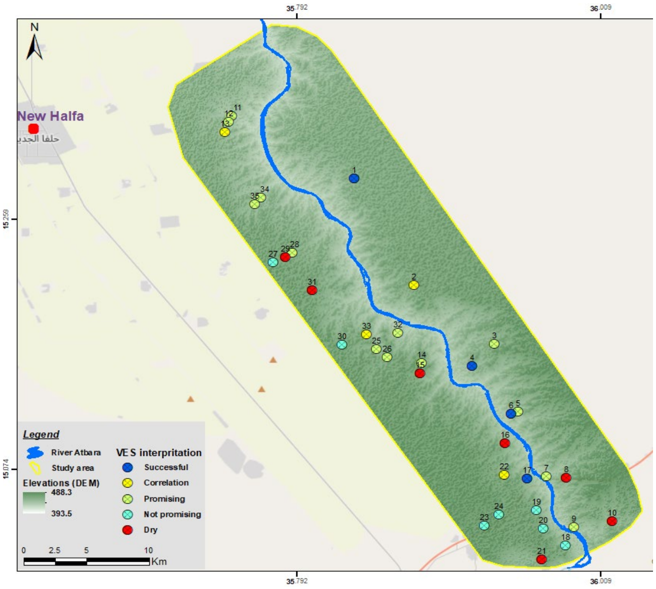

Figure 6. Location of the geo-electrical sections in the study area

Geo-electrical section A1-A2: this section includes VES27, VES29, VES28, and VES1. The section started from the western bank of the river which, extended in the W–E direction. This section consists of 5 layers. The top layer is composed of superficial deposits with thicknesses ranging between (0.652-14) m with resistivity values ranging between (4.16-256) Ω.m. A confining layer of clay underlies the superficial deposits layer with a thickness ranging between (2.05–24.2) m with resistivity values ranging from 7.51 to 92.1 Ω.m. A thin layer composed of dry sand underlies the clay layer with a thickness ranging between (7.45-17.1) m with resistivity values ranging from 16.6 to 644 Ω.m. The sandy layer is underlain by a partly saturated layer composed of River Atbara sediments with thicknesses ranging between (30 -48) m and resistivity values ranging from 4.68 to 11.8 Ω.m. The lowest layer in this section is the basement complex at a depth ranging between (41- 60) m with resistivity values ranging from 973 to 8932 Ω.m. The aquifer zone in this section is characterised by the River Atbara sediments at (VES1 and VES28) and disappeared at (VES 27 and VES 29). Generally, this section is affected by geological structures. VES1 was confirmed by drilling with a good yield well, while VES28 represents the promised site for drilling a borehole. VES29 was confirmed by drilling and found a dry well, and VES27 was not recommended it is located out of the aquifer zone (Figure 7).

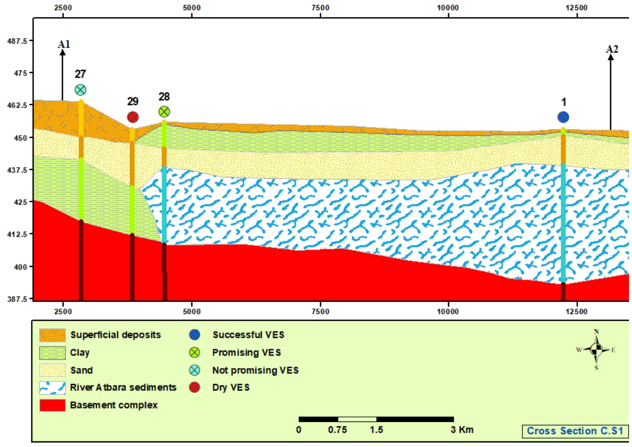

Figure 7. Geo-electrical section A1-A2

Geo-electrical section B1-B2: This section contains VES30, VES25, VES26, VES15, VES4, and VES3 that started from the Western side of the River Atbara and extended in the W - E direction. The section is constructed from 5 layers; the top layer consists of superficial deposits with thickness ranges from 0.419 to 6.07 m and high resistivity values ranging between (3.49-949) Ω.m, indicating the existence of dry sand. A thin layer composed of dry sand underlies the superficial deposits with a thickness ranging between (0.629-14.1) m of resistivity values ranging from 46.1 to 328 Ω.m. The sand layer is underlain by a clayey layer with thickness ranges from 2.02 to 35.7m with resistivity values ranging between (4.27-53.5) Ω.m. The clayey layer is underlain by a saturated layer composed of River Atbara sediments with thicknesses ranging between (17.4-51.9) m and resistivity values ranging from 4.67 to 141 Ω.m. This layer was detected by all VESes except at VES30. The lowest layer in this section is the basement complex at a depth ranging between (52.7 and 68.4) m with resistivity values ranging from 289 to 16168 Ω.m. Generally, this section is not affected by structural activity and VES 25, VES 26 and VES 3 are located in the saturated River Atbara sediments zone (Figure 8), they are recommended for drilling boreholes. The VES 30 is not recommended because it is situated at the boundary of the aquifer. VES 4 is confirmed by drilling with a good yield well, while VES 15 is a dry well, although it is located within the aquifer zone where it is not reaching the recommended depth.

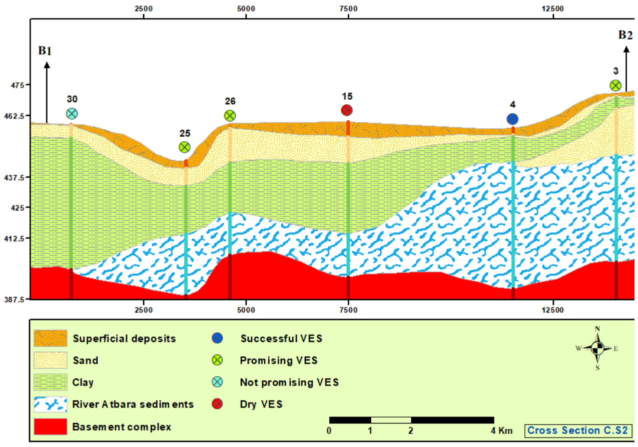

Figure 8. Geo-electrical section B1-B2

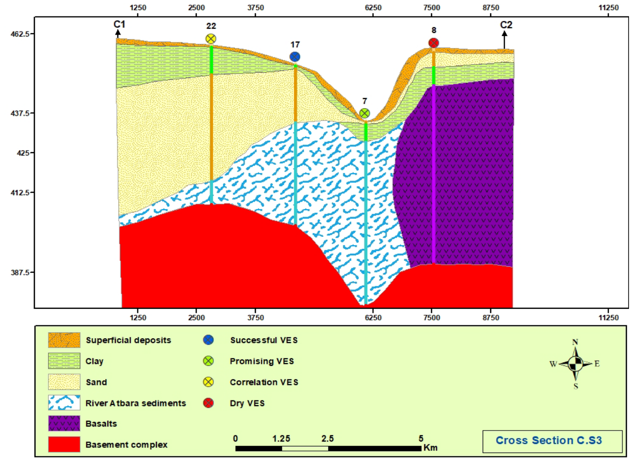

Figure 9. Geo-electrical section C1-C2

Geo-electrical section C1-C2: This section includes VES22, VES17, VES7, and VES8, extended in the W–E direction. The sequence in this section has 6 layers. The top layer in the section was superficial deposits, and the resistivity values of this layer range between 74.4 to 1236 Ω.m. The average thickness of this layer is about 1m. A dry sandy layer underlies the top layer with resistivity values ranging between 42.2 to 141 Ω.m., the thickness of this layer ranges between 0.746 to 11.6 m. A confining layer of clay underlies the sand layer with resistivity values ranging between 3.52 to 45.5 Ω.m., the thickness of this layer ranges between 0.859 to 33.4m. These top layers (superficial deposits of sand and clay) are underlain by the aquifer formation composed of River Atbara sediments defined by VES22, VES17, and VES7, this layer is barren at VES8 and a thick layer of injected basaltic rocks with resistivity value reach 33.5 Ω.m. It reaches 56m thick, which occurred at this VES point instead of River Atbara sediments, which explains the dry drilled well at this location. The depth to the basement complex ranges between (50.2-67.9) m, and the resistivity values range from (44.8-12904) Ω.m. Generally, most of these VES points are confirmed by drilling; VES17 and VES22 are successful wells with good yield, and the last one was used as a correlation VES point. At VES8, a dry well is located in the hard basaltic zone and out of the aquifer zone (River Atbara sediments). While VES7 represents a promising site for drilling (Figure 9).

Geo-electrical section D1-D2: This section was constructed from VES23, VES20, VES9 and VES10. It is extended in the W – E direction. It contains 5 layers; from top to bottom, the first layer is superficial deposits with thickness ranging between (0.626- 1.98) m with resistivity values ranging from 241 to 821 Ω.m. The second layer consists of dry sand with a thickness ranging between (0.643- 23.2) m and resistivity values ranging from 143 to 6971 Ω.m. The third layer is clay with thickness ranging between (1.88- 33.4) m and resistivity values ranging from 0.989 to 5.19 Ω.m. The fourth layer is intruded basaltic rocks with thicknesses ranging between (4.96 – 24.4) m and resistivity values ranging from 13.8 to 317 Ω.m. The fifth and last layer is the basement complex at a depth ranging between (30.7-56.6) m, and resistivity values range from 4255 to 6549 Ω.m (Figure 10). In this section, the basement complex is shallower compared with the other sections. The layers detected in this section are non-water-bearing formations except at VES9, where a limited water-bearing zone was encountered close to the river and not far from 300m, with a secondary aquifer of weathered basaltic rocks with low resistivity, which is directly recharged from the river.

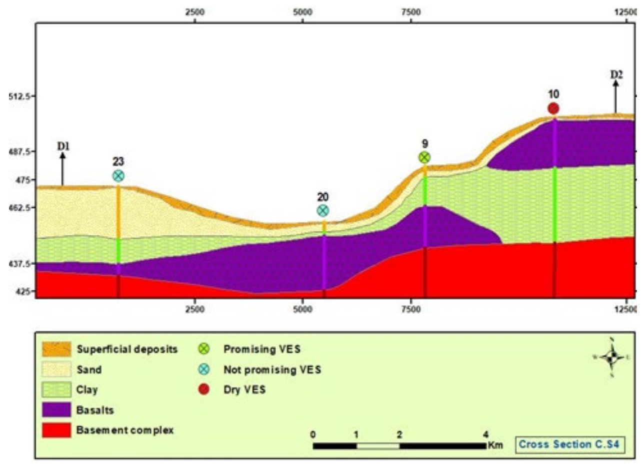

Figure 10. Geo-electrical section D1-D2

Geo-electrical section E1-E2: This cross-section is constructed based on VES10, VES8, VES5, VES4, VES2, and VES1 extended in the N-S direction and located on the eastern bank of the River Atbara. The section shows six layers, starting from a thin layer of superficial deposits at the top with thickness varies (0.419-1.47) m with resistivity values ranging from 40.5 to 1470 Ω.m. A dry sandy layer of thickness ranging between (0.629-11.4) m and resistivity values ranging from 42.2 to 6971 Ω.m. A confining layer of clay underlies the sandy layer with a thickness ranging between (2.05-33.8) m and resistivity values ranging from 3.52 to 92.1 Ω.m. A layer consisting of River Atbara sediments, partly saturated (gravel and medium to coarse sand) extended within the River Atbara bank and represents the main aquifer in the middle and north part of the study area, with thickness ranging between (28.6-51.9) m and resistivity values ranging from 4.6 to 11.7 Ω.m. A very thick layer of basaltic rocks occurs in the southern part of the study area, with thicknesses ranging between (21.5-56) m and resistivity values ranging from 33.5 to 317 Ω.m. The depth to the basement complex ranges between (49.7-67.9) m, and resistivity values range from 192 to 8281 Ω.m. The depth of the basement complex is exceeding at the centre of the section (middle part of the study area) and reaches its maximum value (Figure 11). Generally, most of these VES points are confirmed by drilling and found as follows: VES1, VES4, and VES2 are successful wells with good yield, and VES2 was used as a correlation point, VES8. The dry well is located at VES10 in the hard basaltic zone and out of the aquifer zone. While VES5 represents the promised site for drilling boreholes with low yield expectation

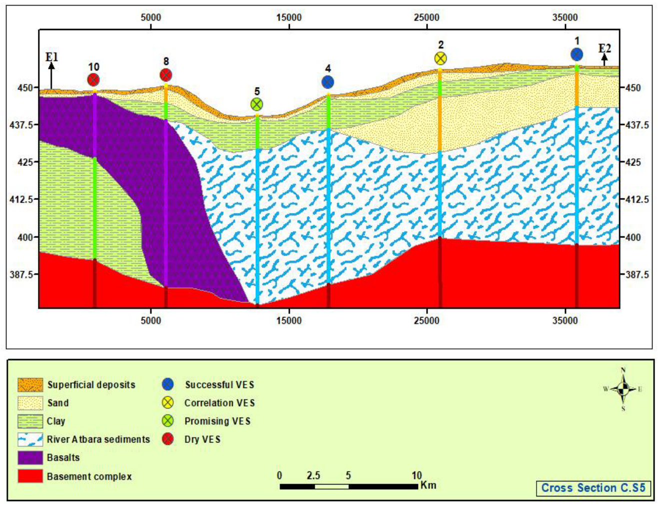

Figure 11. Geo-electrical section E1-E2

Geo-electrical section F1-F2: This section was constructed through VES23, VES30, VES31, VES29, and VES35 and extended in the N-S direction. This section indicates six layers. The top layer in the section is superficial deposits and is dominated by clay at VES31. The resistivity values of this layer range between 20.9 to 582 Ω.m. The thickness of this layer range between 0.466 to 5.26m. A dry sandy layer underlies the upper layer with resistivity values ranging between 16.6 to 357 Ω.m, the thickness of this layer ranges between 5.38 to 23.2 m. A confining layer of clay underlies the sandy layer with resistivity values ranging between 1.27 to 40.7 Ω.m. The thickness of this layer ranges between 1.86 to 53.5 m. The layer consists of basaltic rocks underlying the sandy layer, which occurred only at VES23. The resistivity values of this layer reach 18 Ω.m, and the thickness reaches 4.96m. The water-bearing formation layer composed of River Atbara sediments has been encountered only at VES35 with a thickness reaching 48.3 m and resistivity values reaching 20.7 Ω.m. The basement complex occurred beneath with resistivity values ranging between 109 to 9853 Ω.m, and the thickness of the basement complex is between 40-59.4 m (Figure 12). Generally, this section is non-water bearing except at VES35, which is located in the aquifer zone of River Atbara sediments and confirmed by successful drilling; it is used as a correlation point, while the dry wells are located at VES31 and VES29. According to the above cross-sections constructed from VES points, it was found that the main hydrogeological factors affecting the spatial variation of aquifer characteristics are the vertical and lateral facies changes in the study area.

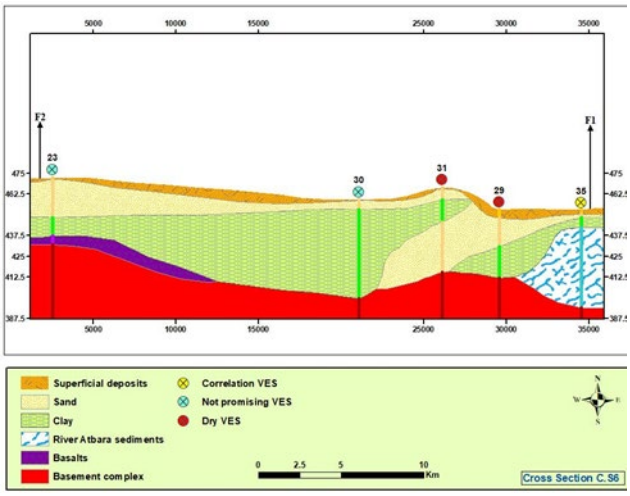

Figure 12. Geo-electrical section F1-F2

4. Geophysical findings

The water potentiality map (Figure 13) was constructed based on the result of the (35) vertical electrical soundings. The findings are summarised as follows; (17) points are promising for drilling boreholes, (4) points were confirmed by successful drilling, (7) points are not promising based on data interpretation, (4) points were conducted at productive boreholes for calibration, and (7) points were conducted at dry boreholes for calibration and to avoid drilling failure.

- The Aquifer extends under the Karab formation and covers most of the area attached to the river. The promising and productive zones consisted of:

- River Atbara sediments extended along the River Atbara from the North to the southern part of the study area, except the area that is covered by basaltic rocks and located south of the Elbutana bridge.

- Saturated fractured basaltic rocks covered the area attached to the River Atbara banks and recharged directly from the river.

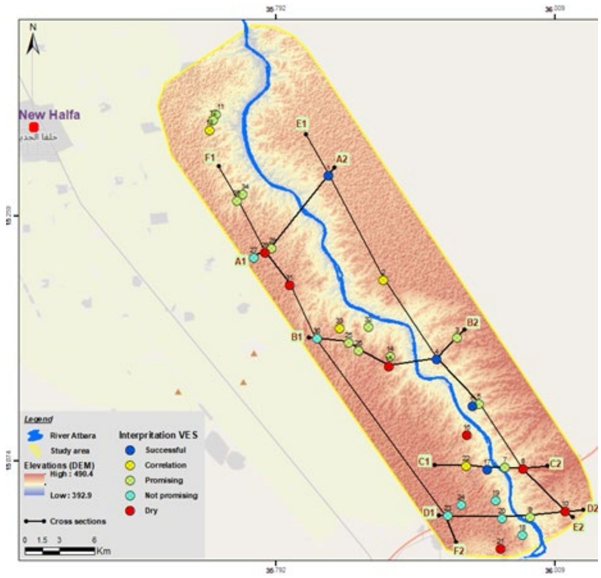

Figure 13. Water potentiality map confirmed by drilling data

IV. CONCLUSION

The geophysical investigations confirmed that the depth to the basement rocks as an aquitard unit of the groundwater varies between (45-68) m in the alluvium formation zone and (32-45) m in the basaltic rocks zone.

The aquifer systems in the study area consist of the River Atbara sediments and saturated fractured basaltic rocks. The River Atbara sediments extend along the River Atbara from the northern part to the southern part of the study area and are terminated before the area, which was covered by basaltic rocks and located south of the Elbutana bridge. The saturated fractured basaltic rock covered the area attached to the River Atbara banks only at the southern part of the study area and recharged directly from the river.

The thickness of the aquifer varies between (10-30) m. The aquifer in the study area seems to be wider in the northern part and gets narrower in the southern part of the study area, which ranges from 3 to 4km away from the eastern banks of the river. On the western bank, the aquifer does not exceed 6-7km within the Karab Zone.

The vertical electrical sounding (VES) technique indicates that the aquifer thickness of River Atbara sediments is controlled by the thickness of the clay, undulations of the basement complex configuration, and lateral and vertical facies changes in the area.

The saturation of the basaltic rocks is affected by the distance from the river, which increases the saturation near the Atbara River.

It was found that vertical electrical sounding (VES) is the best and most appropriate technique for identifying and describing the aquifer system in the study area.

The cross sections constructed from VES points indicate that the main hydrogeological factors affecting the spatial variation of aquifer characteristics are the lateral and vertical facies changes.

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