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Full Length Research Paper

Aquifer boundaries explored by geoelectrical measurements in the Red Sea coastal plain of Jazan area, Southwest Saudi Arabia

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Geoelectrical measurements using the vertical electrical sounding (VES) method were conducted on the Eastern Red Sea coast in Jazan area, Southwest Saudi Arabia. The objectives of the study were (1) to map the Quaternary sediments in areas where little is known about the subsurface geology and to infer shallow geological structure, and (2) to identify formations that may present fresh aquifer waters, and subsequently to estimate the relationship between groundwater resources and geological structures. Data collected at 9 locations were interpreted first with curve-matching techniques, using theoretically calculated master curves. The initial earth models were double checked and reinterpreted using a one-dimensional inversion program in order to obtain final earth models. Resistivity measurements show four zones with different resistivity values, corresponding to four different bearing formations: (1) A resistive surface layer at the top; (2) A basalt flow layer in the northern parts; (3) Strata saturated with fresh to brackish groundwater; and (4) A water-bearing formation containing Red Sea saltwater.

Key words: Salt-water/fresh-water, geoelectrical measurements, Red Sea coastal plain, Saudi Arabia.

INTRODUCTION

The problem of the salination of groundwater aquifers arises in coastal areas, where the excessive pumping of unconfined coastal aquifers by water wells leads to the intrusion of sea water. This negative effect of human activity has been recorded in many areas of the world. Hence, this problem is likely to arise in areas like Saudi Arabia coastal that has poor water resources (low precipitation and high evapotranspiration) and has mismanagement of water resources. In old wells located within the coastal area (Figure 1) drilled by the Ministry of Water and Electricity of Saudi Arabia was encountered saline water (TDS > 5,000 mg/L) at a depth range from 5 to 40 m. Due to the scarcity of deep boreholes which could provide information on the configuration of the different water bodies on the Eastern Red Sea coast in Jazan area, Southwest Saudi Arabia, vertical electrical sounding (VES) survey utilizing a Schlumberger array were performed on 9 sites with several aims:(1) Verification of the presence of the different water-bearing formations and estimation of their depth and thickness; (2) Finding the relationship between the resistivity variations and the different configurations of the water-bearing formations; and (3) Mapping the water table in the shallow coastal aquifer.

Geology and hydrogeology

Geologic setting

Physiographically, the study area lies between latitude 16° 45' N to 17° 30' N and longitude 42° 15' E to 43° 00' E, Southwest Saudi Arabia (Figure 1). The climate of the region is hot and humid in all year days with an annual average precipitation of 200 to 500 mm in the coastal plain area and 500 to 700 mm in the Eastern Precambrian Mountains (Saudi Presidency of Meteorology and Environment (2011), personal communication). Rainfall generally occurs during the spring and

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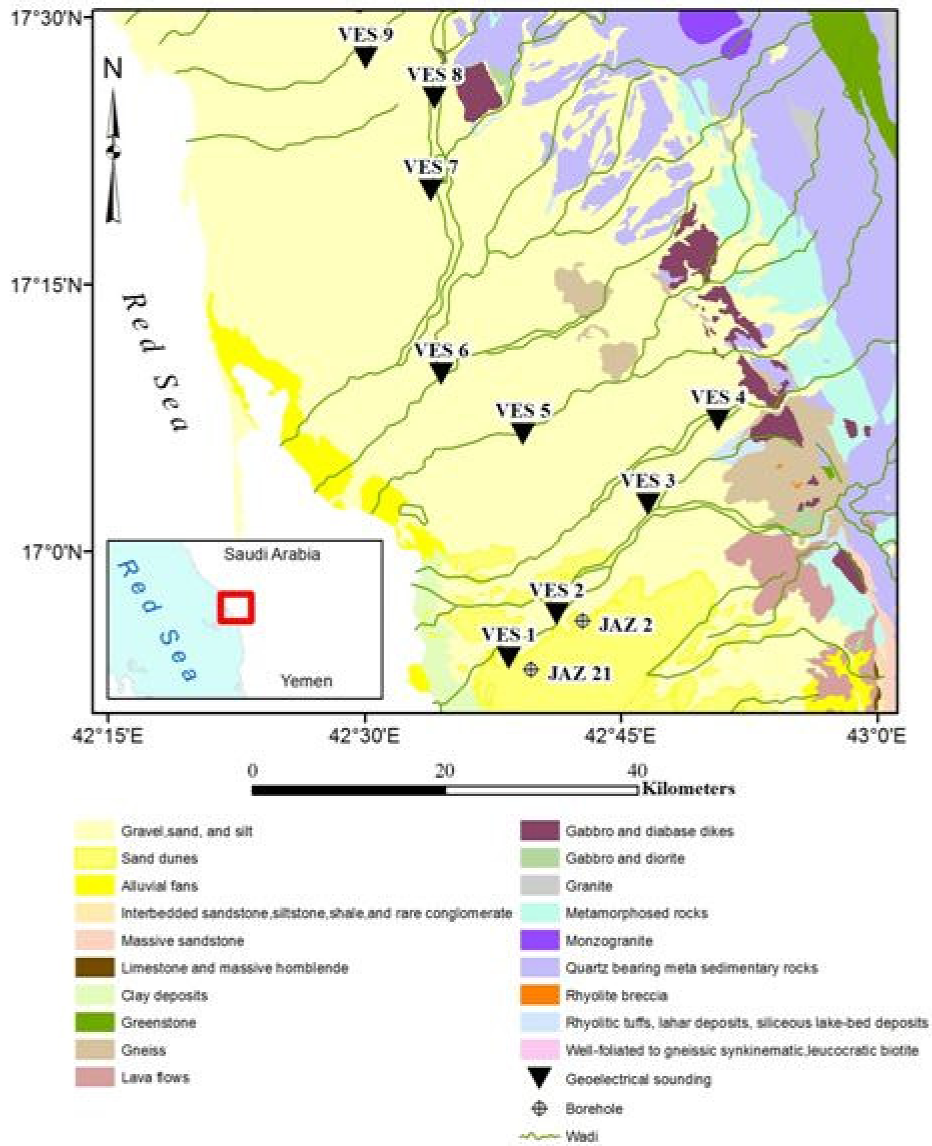

Figure 1. Location of VES sites (black triangle) in relation to geology. Also shown is the location of the two boreholes JAZ 2 and JAZ 21. The inset map shows the location of the investigated area on Saudi Arabia.

summer months (May to September). Detailed geological studies on the western coastal area of Saudi Arabia are relatively scarce but the regional aspects of geology for this area have been subjected to regional investigations by many authors as a part of the western geologic terrain of Saudi Arabia (Ramsay, 1986). According to these previous works, the study area is covered by Precambrian to Holocene rocks (Figure 1). The Precambrian and Cambrian rocks have been deformed and metamorphosed and in some places intruded by intrusive rocks of different ages and composition. From Cambrian through Quaternary, the area had been subjected to different tectonic activities which were accentuated with the opening of the Red Sea (Oligo-Miocene). The prominent structural features in the area are faulting and jointing. NE-SW faults form elongated grabens and horsts in the area (Basahel et al., 1983). The most outstanding structures in the study area are the NE trending faults that is believed to belong to the Precambrian E-W compressions. Tertiary tectonics is represented by NNW and EW faulting as well as NNW with its long fracture set as the source of the tertiary basaltic flow. Tertiary rocks are present in many parts of the area forming a thick sequence of clastic sedimentary rocks that are more probably deposited in faulted bounded troughs and covered in many places by tertiary-quaternary basaltic flow. Pleistocene to Holocene deposits are widely spread especially along the coastal

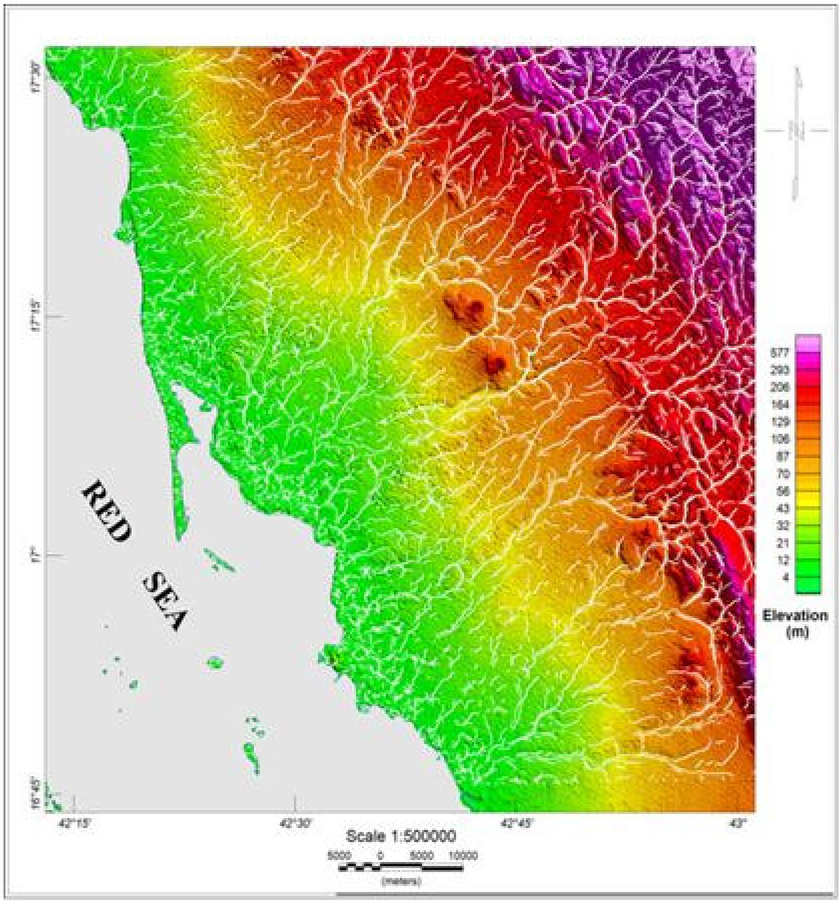

Figure 2. Drainage systems of the Jazan province coastal area.

plain, including raised terraces, reef limestone, quaternary sand, alluvial deposits, gravel and some recent evaporates.

Hydrogeology

The primary sources of water in Saudi Arabia are aquifers and basins that receive feeding/recharging from annual rainfall. Generally, two types of groundwater aquifers have been identified by researchers (Basahel et al., 1983; Hussein and Ibrahim, 1997; Hussein and Bazuhair, 1992; Al-Bassam and Hussein, 2008) in Saudi Arabia; the shallow alluvial aquifers beneath the wadi systems, and deep rock aquifers, usually hosted by sandstone and limestone. The deep rock aquifers are usually confined, having large areal extent and contain reasonable quality of fossil groundwater.

The coastal plain of Jazan area (Figure 1) is approximately 50 km wide and is accessible from one modern highway joining Yemen in the south with Saudi Arabia to the north. The alluvial shallow aquifer is the primary source of water for agriculture, domestic and industrial uses in the region. The recharge to this aquifer takes place either along the elevated areas in the east and southeastern sides, or due to local surface water infiltrations. The drainage system is generally a rectilinear nature with subordinate parallel to the Red Sea. A typical main wadi channel is characterized by a width that ranges from about 100 to 1,000 m and the average thickness of the water bearing unit varies from about 3 m in the upstream part to about 40 m or more in the downstream (Hussein and Ibrahim, 1997; Al-Amri, 1998; Al Hazmi, 2005; Al-Bassam and Hussein, 2008). The alluvial deposits making up the aquifers are a heterogeneous assemblage of unconsolidated blocks, cobbles, gravels, sand and silt. The coarse units predominate in the upstream areas and grain size decreases in the downstream direction towards the coastal plain. Water levels vary from about 110 m above sea level in the head waters to about 5 m in the coastal plain. The groundwater occurs in the area within two geologic units; the alluvial deposits of the wadi systems and the clastic coarse members of the cretaceous-tertiary sedimentary succession (Hussein and Bazuhair, 1992). The drainage systems in the coastal area are shown in Figure 2. This map is based on topographic data of the terrain elevation model (http://dap.geosoft.com/geodap/home/ default.aspx). The map shows three distinctive

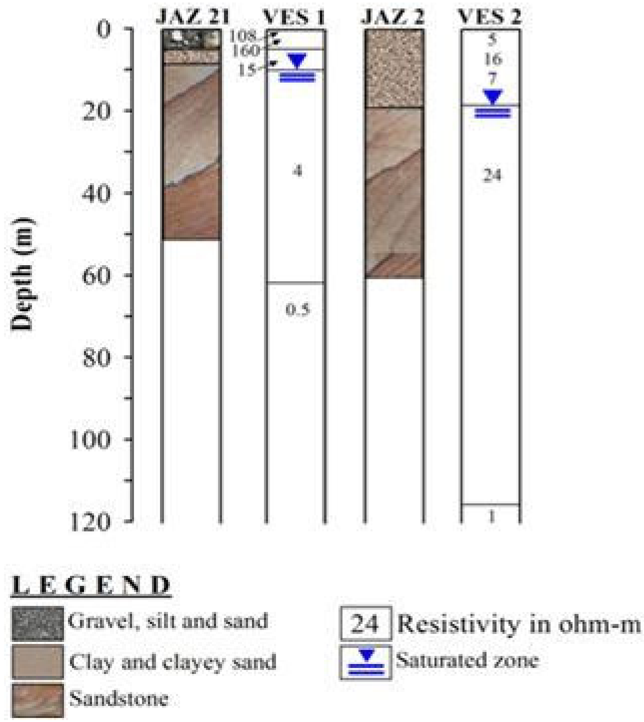

Figure 3. Correlation between sounding curves and boreholes well lithology.

drainage patterns in the directions NE, NW and E-W trends

FIELD MEASUREMENTS AND METHODS OF INTERPRETATIONS

Surface resistivity methods have been used in groundwater research in different parts of the world. Earth resistivity is related to important geologic parameters including types of rocks, types of soils, porosity, and degree of saturation. The detailed description of these methods is available in Zhdanov and Keller (1994). These methods have been applied in the investigation of coastal aquifers in different parts of the world, such as in the Netherlands by Van Dam and Meulenkamp (1967); in Belgium by De Breuk and De Moor (1969); in New England by Urish and Frohlich (1990); and in Jordan by Batayneh (2006) and Batayneh et al. (2010).

In general, the resistivity method involves measuring the electrical resistivity of earth materials by introducing an electrical current into the ground and monitoring the potential field developed by the current. The most commonly used electrode configuration for geoelectrical soundings, and the one used in this field survey, is the Schlumberger array. Four electrodes (two current and two potential) are arranged symmetrically along a straight line with the outer two for current injecting. Vertical sounding, in Schlumberger array, were performed by keeping the electrode array centered over a field station while increasing the spacing between the current electrodes, thereby increasing the investigation depth.

A total of 9 VES stations were established across the study area. The VES soundings were conducted with the help of ELREC-T resistivity instrument (IRIS Instruments, France). The layout of the survey stations is superimposed on the geologic map in Figure 1. The locations of the VES sites were considerably restricted by logistical difficulties. The presence of narrow valleys and topography prevents more widespread coverage. The VES were recorded up to a maximum current electrode separation of 1,000 m.

The sounding curves were subjected to a preliminary interpretation using the partial curve matching technique of Zohdy (1965) and Orellana and Mooney (1966). In a second analysis method, the layer parameters (resistivities and thicknesses) derived from the graphical curve matching was then used to interpret the sounding data in terms of the final layer parameters through a 1-D inversion technique (that is, IPI2Win, GEOSCAN-M Ltd, Moscow State University, Geological Faculty, Department of Geophysics, 2001).

FIELD RESULTS

The geoelectric resistivity of sediments is one of the most variable physical properties, especially in a very complicated sedimentological environment that dominates such alluvial areas. Therefore, the ambiguities in interpretation may occur and become very necessary to calibrate the observed VES data with the available borehole data (Batayneh, 2010, 2011). This enables us to assign the geoelectric units to the corresponding lithologic units and consequently put a reliable control on the interpretation of the subsurface sequence in the study area. Data from two boreholes (JAZ 21 and JAZ 2, Figure 1) were analyzed and used to correlate the results of the VES geoelectrical surveys. Correlation between VES stations 1 and 2 and boreholes JAZ 21 and JAZ 2 lithology was performed (Figure 3) in order to determine the electrical characteristics of the rock units with depth.

Table 1. Summary of results from computer modeling for all sounding stations.

VES no.	Resistivity of layers (Ω-m)					Thickness of layers (m)			
Figure 1	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4
01	108	160	15	4	0.5	1.1	1.5	4.9	55.5
02	5	16	7	24	1	1.1	2.8	13.7	10.1
03	100	50	120	22	7	1.0	2.1	22.8	28
04	205	23	85	31	700	0.8	3.6	17.6	41
05	160	106	27	10	-	1.0	10.1	58.4	-
06	580	31	50	13	3	0.8	4.2	10	41
07	460	106	660	160	9	1.4	3.5	11.2	38.5
08	68	34	333	140	240	0.9	3.1	42.1	113.2
09	140	16	64	155	-	0.8	5.8	59.4	-

Based on the lithological log of boreholes JAZ 21 and JAZ 2, the geological interpretation of the geoelectrical model for VES 1 and VES 2 (Figure 3) is: (1) A moderate high resistivity layer (100 to 160 Ω-m) consists of a mixture of gravel, silt and sand; (2) a thin clay and clayey sand layer having resistivity values 5 to 20 Ω-m; (iii) saturated sandy layer with brackish water having resistivity values 4 to 24 Ω-m; and (iv) saturated sandy layer with brine water having resistivity values 0.5 to 1 Ω-m. Results from the computer modeling of geoelectric data are presented in Table 1.

Analysis of VES curves

Owing to the differing character of features in the field apparent resistivity curves, the VES stations show different types of curves (Figure 5). These types were defined in terms of the number of geoelectrical layers and their resistivity relationship. Among these types of curves and with the exception of the shallow subsurface units whom apparent resistivity values vary considerably at different VES locations, mainly due to the fact that resistivity depends on the soil moisture content and lithology, five field curves at VES stations 1, 3, 5, 6, and 7 show similar shape of field curves with layer resistivities decreasing with depth. Such curve behaviour undoubtedly proves the presence of a low-resistivity layer at the bottom of the section. Those field curves generally show: (1) A relatively thin surface layer of coarse grained loose sand and gravel existing below the ground surface having apparent resistivity of 100 to 600 Ω-m, followed by (2) The presence of sand, clay, sandy clay and gravel of varying grain size (fine to medium) of 30 to 160 Ω-m apparent resistivity; (3) A low-resistivity third layer at VES stations 1, 5 and 6 with apparent resistivity 15 to 50 Ω-m, indicating clay and clayey sand unit or a moderate to high-resistivity third layer at VES stations 3 and 7 with apparent resistivity 120 to 660 Ω-m, indicating basalt rock unit; (4) Saturated sandy layer with brackish water having resistivity values 4 to 24 Ω-m; and (5) A sandy formation saturated with brackish groundwater at VES stations 1, 3, 5, and 6 having resistivity values 5 to 20 Ω-m and with fresh water at VES station 7 having resistivity value 160 Ω-m; and (6) Saturated sandy layer with brackish/brine groundwater having resistivity values 0.5 to 10 Ω-m. Two of the field curves at VES stations 4 and 8 that were made in the eastern parts of the study area reflect the presence of five geoelectric layers where the layers resistivity relationship as $\rho_1>\rho_2<\rho_3> \rho_4<\rho_5$ (Figure 4). The field curves at VES stations 4 and 8 describe qualitatively a model composed of (1) a thin surface layer of coarse grained sand and gravel having apparent resistivity of 70 to 200 Ω-m, followed by (2) the presence of clay and clayey sand of 20 to 30 Ω-m apparent resistivity; (3) a relatively-high resistivity third layer of coarse grained gravel and sand with apparent resistivity 80 to 330 Ω-m; (4) a sandy formation saturated with fresh groundwater having resistivity values of 30 to 140 Ω-m; and (5) a basement rocks having resistivity values of 250 to 700 Ω-m. The remaining two field curves at VES stations 2 and 9 are differ. VES station 2 reflects the presence of five geoelectric layers were the layer resistivity relationship as $\rho_1<\rho_2>\rho_3< \rho_4>\rho_5$, while VES station 9 that were made in extremely north of the study area reflects the presence of four geoelectric layers were the layer resistivity relationship as $\rho_1>\rho_2<\rho_3< \rho_4$ (Figure 4). The sounding curve of VES station 2 describe qualitatively a model composed of (1) a thin surface layer of clay existing below the ground surface having low apparent resistivity (5 Ω-m); followed by (2) the presence of clay and clayey sand of 20 Ω-m apparent resistivity; (3) a low-resistivity third layer with apparent resistivity 10 Ω-m, indicating clay unit; (4) a sandy formation saturated with brackish groundwater having resistivity value of 25 Ω-m; and (5) saturated sandy layer with saline groundwater having resistivity value of 1 Ω -m. While the sounding curve of VES station 9 generally shows:

(1) A thin surface layer of sand and gravel below the ground surface having moderate high apparent resistivity (140 Ω-m);

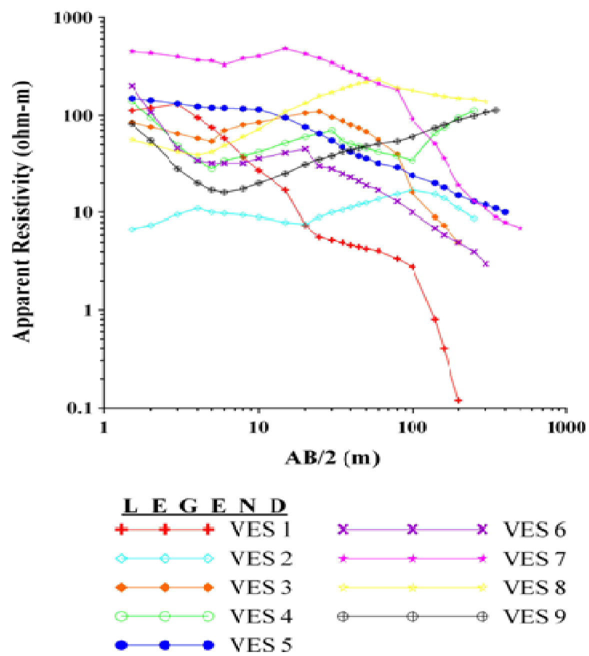

Figure 4. Apparent resistivity curves.

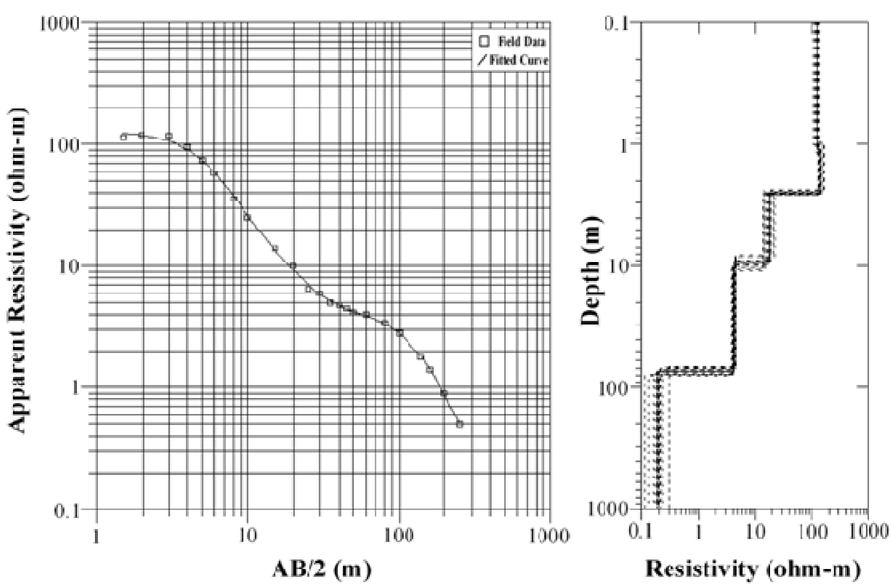

Figure 5. Typical electrical resistivity sounding data and best-fit four layer model interpretation for VES 1. On the left, Figure 5 shows the Schlumberger apparent resistivity curve with data (points) superimposed on the best match 1-D inversion (solid line). On the right, the figure shows the interpreted results in terms of resistivity and depth together with the allowable of equivalence (dashed lines).

(2) The presence of clay and clayey sand of 20 Ω-m apparent resistivity;
(3) A sandy formation saturated with fresh groundwater having resistivity value of 65 Ω-m; and
(4) A basement rocks having resistivity values of 160 Ω-m.

Figure 5 is a typical sounding data plot and best-fit model for one sounding data corresponding to the sounding point VES 1. It is of interest to note that the sounding of Figure 5 was derived from the eastern part (VES 1). The best-fit models are derived along geoelectrical sounding

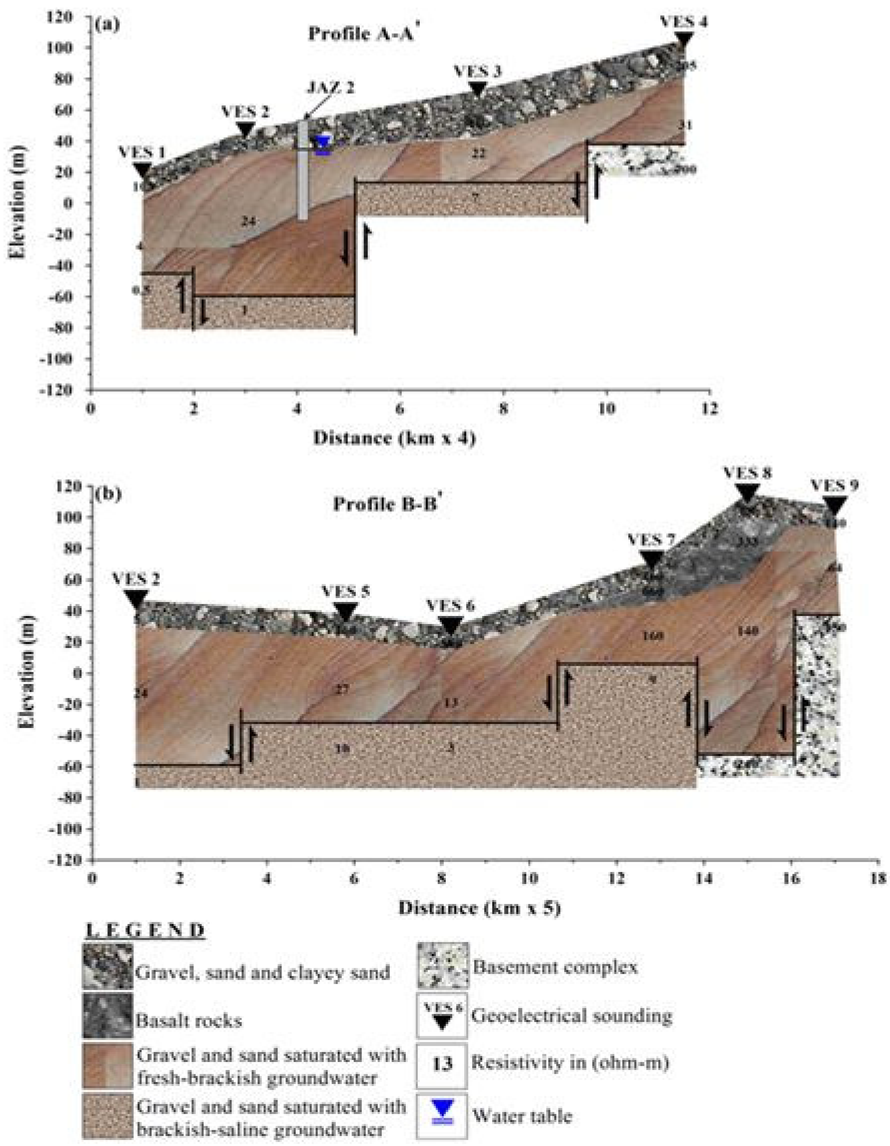

Figure 6. Two-dimensional electrical cross section inferred from geoelectrical sounding data along A-A′ and B-B′ profile lines (Figure 1 show profiles location).

point with lower and upper bound models (1 to 5% error).

Litho-resistivity units

The results from the one-dimensional inversion of the geoelectrical soundings along two profile lines A-A′ and B-B′ (Figure 1) are illustrated as resistivity-vs-depth cross section in Figure 6. Both the lateral and vertical resistivity variations are depicted on this figure in a manner that facilitates the interpretation of the resistivity section into geologic and structural units.

Cross section A-A' (Figure 6a) represents the behavior of the southern side of the study area. It covers a length of approximately 40 km, extending from sounding stations VES 1, VES 2, VES 3, and VES 4. The main features of the derived structure, from the surface downward, may be summarized as follows: (1) A surface layer of 5 to 205 Ω-m resistivity that is about 8 to 25 m thick.

The resistivity of this unit is corresponding to a stratum which is mainly composed of fine to coarse grain gravel, sand and clayey sand layer at the surface. In general, the layer thickness increases landward; followed by (2) A layer of gravel and sand formation saturated with brackish-to-fresh groundwater (4 to 31 Ω-m). It is resistivity increasing landward; followed by (3) A layer of gravel and sand unit saturated with brackish-to-saline groundwater of 0.5 to 7 Ω-m; (4) Basement complex rocks of high resistivity of 700 Ω-m at site (Figure 6a, site

4).Cross section B-B' (Figure 6b) represents the behavior of the northeastern, central and southern parts of the study area. It covers a length of approximately 80 km, extending from sounding stations VES 9, VES 8 and VES 7 in the northeastern parts, VES 6 and VES 5 in the central parts and VES 2 in the southern side. The main features of the derived structure, from the surface downward, may be summarized as follows: (1) The surface layer show resistivity values in the range 5 to 580 Ω-m resistivity that is about 10 to 15 m thick. The resistivity of this unit is corresponding to a stratum which is mainly composed of fine to coarse grain gravel, sand and clayey sand layer at the surface; followed by (2) A layer of basalt rocks at sites 7 and 8 (333 to 660 Ω-m) and thickness of about 15 to 25 m; followed by (3) A layer of gravel and sand unit saturated with fresh-to-brackish groundwater of 13 to 160 Ω-m; (4) A gravel and sandy formation saturated with brackish-to-saline groundwater (1 to 10 Ω-m); followed by (5) Basement complex rocks of moderate resistivity values of 150 to 250 Ω-m (Figure 6b, sites 8 and 9). As seen from Figure 6, the alluvial system within the Jazan coastal area, can be divided into two main stratigraphic sequences having different thicknesses, lithology contents, and geological structures: (1) The upper sediment unit consists mainly gravel, clay, clayey sand, and basalt rocks characterized by low to high resistivity values at shallower depths; and (2) The lower sediment represents the water-bearing unit and mainly consists of gravels and sands grading upward into clay and clayey sand. This unit indicates more dynamic and humid environment than is currently seen within the Jazan coastal area. Abundant of clay that correlates with low resistivity values in the upper unit may reflect depositional within a deep lacustrine environment. These alluvial sequences may represent large scale flooding events over a relatively short time period, or long-term depositional environments of higher energy due to extended periods of cooler and moisture climate. It is not plausible that tens of meters thick of gravels and sand were altered in one long episode. Several periods of pedogenesis, intense evaporation of enhanced groundwater flow, or a combination of both more likely created such thick sediments. The sediments then grade upward to clay and clayey sand (upper sediment unit) that may represent a gradual drying and increased aeolian activity.

Conclusions

The geoelectrical stratification of the study area comprises three to four main units of high-, relatively high, relatively low-, and low-resistivity from the surface down. As indicated by the cross sections (Figures 6a and b), the basic structure beneath the eastern part of the study area (Figure 6a, VES site 4) comprises three units of moderate high, relatively low and high resistivity from the surface down. The surface resistive layer represents dry gravel, sand and clayey sand. The second layer, marked by relatively low resistivity of about 50 m thick could indicate gravel and sand with fresh groundwater. While, the main feature in the northern parts of the study area (Figure 6b, VES sites 7, 8 and 9) comprises four units of moderate high, relatively low and low resistivity from the surface down. The surface resistive layer represents dry gravel, sand and clayey sand. The second layer, marked by resistivities of some hundreds of ohm meters could indicate the presence of basalt rock. The relatively low resistivities in the third layer may be related to the presence of gravel and sand with fresh groundwater. The low resistivity in the fourth unit may correspond to the presence of gravel and sand with brackish groundwater. While, central and southern parts of the study area (VES sites 2, 5 and 6, Figure 6), comprises succession of gravel, sand and clayey sand of low to moderately high resistivity at the top surface, followed gravel and sand with brackish groundwater, followed by saline groundwater bearing gravel and sand formation. An important general result of this study is the existence of different coastal hydrogeological zones directly linked to geological subsurface structures, despite a monotonic surface cover the surface alluvial and wadi sediments. That is to say that the geological structures of coastal areas within active plate may significantly control the groundwater behaviour and knowledge of the tectonic history of the region is necessary to deal with its hydrogeology. The second important result is that the area is characterized by a thick clay and poorly permeable substratum that occurs in the central part. Such a result provides new ideas about the hydrogeology of the area. The results obtained are in a good agreement with the borehole data available.

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REFERENCES

Al-Amri A (1998). The application of geoelectrical vertical soundings in delineating the hydrostratigraphy of the southern Red Sea coastal area, Saudi Arabia. J. King Abdul Aziz Univ., 10: 73-90.

Al-Bassam A, Hussein M (2008). Combined geo-electrical and hydro-chemical methods to detect salt-water intrusions: A case study from southwestern Saudi Arabia. Manage. Environ. Qual., 19: 179-193.

Al Hazmi A (2005). Salt water intrusion in coastal aquifer in Jazan,

Kingdom of Saudi Arabia. MSc thesis, Dep. Geol. Geophy., King Saud Univ., Riyadh, p. 124.
Basahel A, Bahafzalla A, Mansour H, Omara S (1983). Primary structures and depositional environ of the Haddat Ash Sham sedimentary sequence, northwest of Jeddah, Saudi Arabia. Arab Gulf J. Sci. Res., 1: 143-155.
Batayneh A (2006). Use of electrical resistivity methods for detecting subsurface fresh and saline water and delineating their interfacial configuration: a case study of the eastern Dead Sea coastal aquifers, Jordan. Hydrogeol. J., 14: 1277-1283.
Batayneh A (2010). Mapping Quaternary deposits in the el-Jufr playa (southeastern Jordan Plateau) using geoelectrical techniques: implications for geol. hydrogeol. Sci. Res. Essays, 5: 3183-3192.
Batayneh A (2011). Hydrogeophysical investigation of groundwater potential in the southern Amman District, central Jordan. Arabian J. Sci. Eng., 36: 89-96.
Batayneh A, Elawadi E, Al-Arifi N (2010). Use of geoelectrical technique for detecting subsurface fresh and saline water: A case study of the eastern Gulf of Aqaba coast, Jordan. J. Coast. Res., 26: 1079-1084.
De Breuk W, De Moor G (1969). The water table aquifer in the eastern coastal area of Belgium. Bull. Int. Assoc. Hydrol. Sci., 14: 137-155.
Hussein M, Bazuhair A (1992). Groundwater in Haddat Al Sham-Al Bayada area, Western Saudi Arabia. Arab Gulf J. Sci. Res., 1: 23-43.
Hussein M, Ibrahim K (1997). Electric resistivity, geochemical and hydrogeologyical of wadi deposits, Western Saudi Arabia. J. King Abdul Aziz Univ., 9: 55-72.
Orellana E, Mooney H (1966). Master tables and curves for vertical electrical sounding over layered structures. Interciencia, Madrid.
Ramsay C (1986). Geology Map of Rabigh Quadrangle Sheet 22D. Kingdom of Saudi Arabia Deputy for Mineral Resources. Geologic Map GM-107C, Scale 1:250000, with explanatory notes, Jeddah, Saudi Arabia.
Urish D, Frohlich R (1990). Surface electrical resistivity in coastal groundwater exploration. Geoexplor., 26: 267-289.
Van Dam J, Meulenkamp J (1967). Some results of the geoelectrical resistivity method in groundwater investigations in the Netherlands. Geophys. Prospect., 15: 92-115.
Zhdanov M, Keller G (1994). The geoelectrical methods in geophysical exploration, methods in geochemistry and geophysics, Elsevier, p. 884.
Zohdy A (1965). The auxiliary point method of electrical sounding interpretation, and its relationship to the Dar Zarrouk parameters. Geophysics, 30: 644-660.