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RESISTIVITY METHODS FOR GROUNDWATER EXPLORATION IN THE CRETACEOUS-TERTIARY SEDIMENTARY SEQUENCE, EAST OF JEDDAH, SAUDI ARABIA

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Vertical electrical sounding (VES) and horizontal electrical profiling (HEP) were used to locate potential groundwater resources in the Cretaceous-Tertiary sedimentary sequence east of Jeddah, Saudi Arabia. The geo-electrical field measurements consisted of 41 vertical electrical sounding points and 104 horizontal electrical profile points using Schlumberger and Wenner arrangements respectively. Three areas were studied in details: Haddat Ash-Sham, Ash-Shamiya, and As-Suqah. Results showed that the sedimentary sequence in the study area contains three major zones for groundwater development and exploitation. The first is a shallow unconfined aquifer at a depth ranging between 10-60 m associated with alluvial gravelly sand deposits. The second is a deep confined aquifer at a depth ranging between 120-180 m associated with gravelly sandstone. The third is a middle fractured zone associated with faults and various types of rocks at a depth ranging between 35-60 m as also indicated by the exploratory drilling. The sandstone layers and the intrusive basaltic flow layers can be differentiated from the shale layers as high resistivity, low conductivity measurements. Conductive features are believed to be related to the saturated zones in the fractures. Drilling of three test boreholes confirmed the results of the geo-electrical investigation and indicated the availability of sustainable well yields. This information will add to the knowledge of the hydrogeology of the area and provide for improved groundwater exploration and management.

INTRODUCTION

The study area lies about 100 km east of the city of Jeddah; between longitude 39º 15´ E and 39º 55´ E and latitude 21º 35´ N and 21º 58´ (Figure 1). The climate is typically arid, annual rainfall average amounts to about 100 mm/yr and average evaporation rate exceeds 2000 mm/yr. Rainfall usually occurs during the months of December and January. Sporadic rainfall events may occasionally occur during the months of April and May.

Geologically the study area consists of Precambrian crystalline basement complex composed mainly of metamorphic and igneous rock of various types (Al-Shanti, 1966; Moore and Al-Reheili, 1989). According to their work, the basement complex rocks in the study area consist of basaltic to rhyolitic volcanic and volcanoclastics that have been multiply deformed, metamorphosed and injected as intrusive bodies.

The Cretaceous-Tertiary sedimentary sequence lies unconformably on the Precambrian Basement Complex. It is composed mainly of sandstone, siltstone and claystone members with oolitic ironstone bands (Karproff, 1955). Basalt lava flows form discontinuous caps overlying the upper levels of both the basement complex and the sedimentary rocks; the lavas either rest on peneplain or infilled ancient wadis. These sedimentary rocks are exposed beneath a cover of flat lying lavas and quaternary deposits. They are preserved in three north-northwest trending, asymmetric depositional troughs which are the Sham, Suqah and Shumaysi troughs. These troughs are bounded in the north by faults downthrown to the west, and in the west by an unconformity at the base of the easterly dipping strata. Zeidan and Banat (1989) showed that the major part of the sedimentary succession was deposited in a fluvio-lacustrine environment with water flowing into a braided river system running generally southeastward.

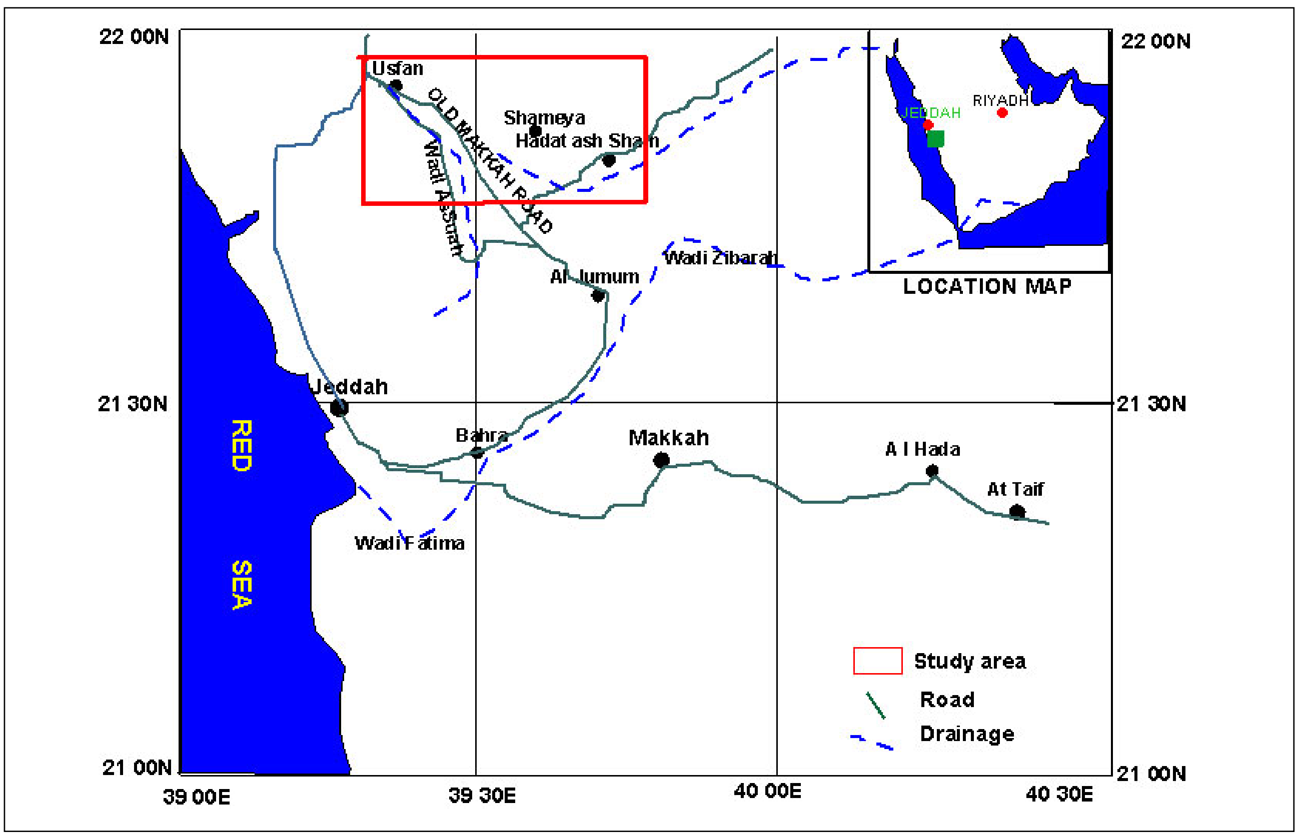

Figure 1. Location map for the study area.

STRUCTURAL SETTING

The Precambrian rocks of the area northeast of Jeddah City have been affected by polyphase deformation events including folding shearing and faulting. Two main structural trends (NNE-NE and N-NNW) appear very well in the satellite images and aeromagnetic data (Moore and Al-Reheili, 1989). The N-NNW trends reflect faulting, fracturing and shearing, which are associated with the Red Sea Tertiary rifting. The NNE-NE trends are less common and are attributed to the Precambrian compression with possible rejuvenation in younger ages. Figure 2 shows the major structural elements in the study area. Faulting seems to be the dominant structural element in the study area.

The Red Sea fault system has affected most of the rock units in the study area, from the Precambrian to the Quaternary. The system forms three main sets of mostly normal faults. These have NW, NE and N trending directions; which in many cases represent rejuvenation of Precambrian faults. The NW trending faults are the oldest and seem to have controlled the depositional troughs in the area. Figure 3 illustrates the stratigraphic sequence in the study area. The detrital units within this sequence represent potential water-bearing horizons.

GROUNDWATER OCCURRENCE

Significant water-bearing formations occur in two different lithological units; namely the alluvial deposits and the Cretaceous-Tertiary sedimentary succession. The physical and hydrogeological properties of both units vary widely from place to place. Hussein and Bazuhair (1992) indicated that

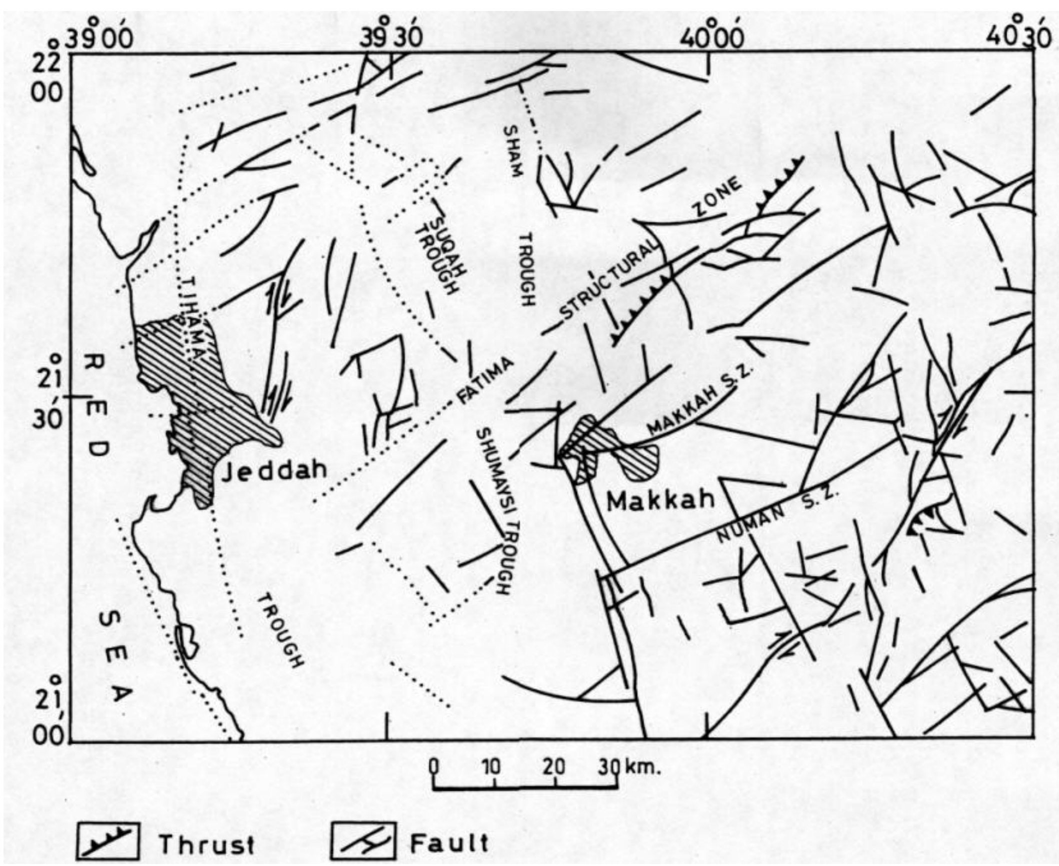

Figure 2. Illustration of the major structural elements in the study area.

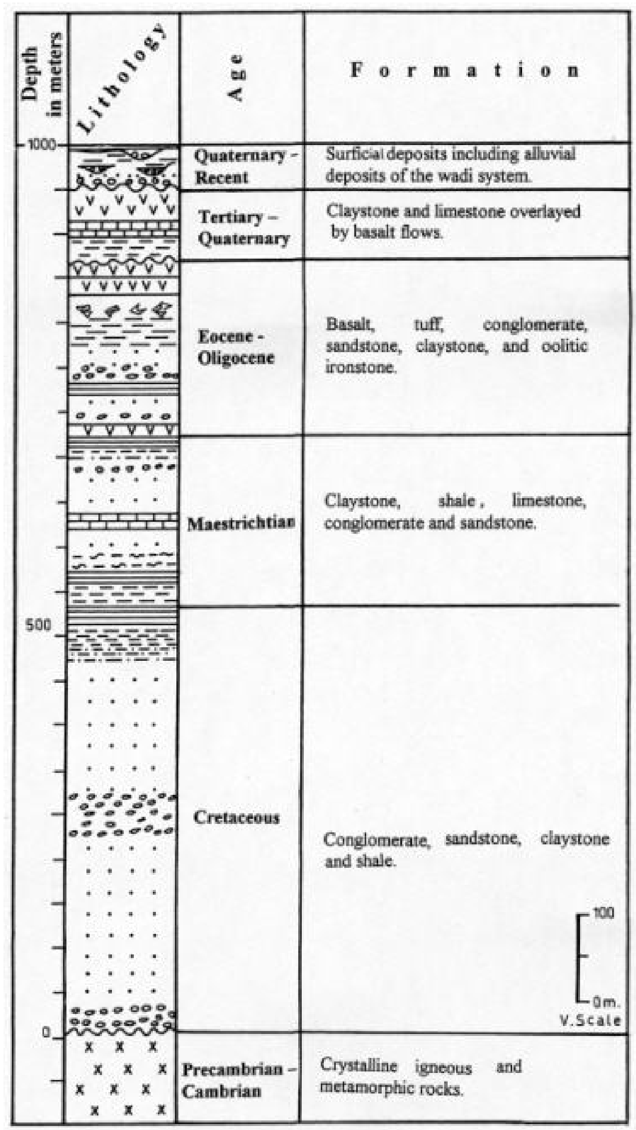

Figure 3. Sequence of the major stratigraphic units in the study area.

the clastic coarse members of the Cretaceous-Tertiary sedimentary succession in the Haddat As-Sham area form a lower confined aquifer underlying the upper alluvial aquifer. Groundwater occurring in the confined unit is controlled by the complexity of the geological elements, including the block faulting mechanism that affected the sedimentary succession and the lithological facies variation. The transmissivity values reported by Hussein and Bazuhair (1992) for the clastic sediment range between 51 and 316 m^2/day; while the storage coefficient ranges between $5.3x10^{-4}$ and $1.12x10^{-3}$.

The alluvial deposits are less than 25 m in thickness, with the exception of few isolated locations where they can no longer be considered water-bearing zones.

FIELD PROCEDURE

Two basic types of electrical resistivity field procedures are commonly used in groundwater exploration. These are resistivity profiling and resistivity sounding. The latter procedure, which is used in the current study, is generally referred to as Vertical Electrical Sounding (VES). In resistivity sounding, the electrode spacing interval is changed while maintaining a fixed location for the center of the electrode spread. Since the depth of investigation increases with increasing electrode spacing, VES is preferred when resistivity variation with depth is investigated. The electrode positions for two readings (two values of symmetry remain fixed with the increase of electrode spacing) are shown. A set of sounding data would continue using 10 to 20 different values of electrode spacing. Several measured stations make a resistivity profile.

The instrument used in this study is ELREC-T resistivity system capable of generating a 2.5-ampere current, using a 1200w AC/DC converter with maximum output voltage of 800 volts. The operation and principles of the equipment are provided by IRIS Instruments (France). The ground resistivity fieldwork carried out in the alluvial plain consisted of 41 VES stations. Maximum current electrode half-spacing (AB/2) is 500 m, which was adequate to ensure exploration depth to the target. The vertical electrical sounding field data were then analyzed and interpreted using two computer programs, the ATO program deployed by Zohdy (1975, 1989) and RESIX-plus software by Interprex Limited Company (1992). From the VES data, the thickness and resistivity values of the layers were determined and the interpretation of true resistivity for underground geological structures and groundwater data was conducted.

Ten profiles were chosen in the study area based on previous knowledge, field observation and several reconnaissance field trips. The location of each profile is shown in Figure 4. Every profile consists of several sounding stations. Forty-one VES (Schlumberger arrangement) were measured in total. In the Schlumberger soundings, measurements of the current electrode spacing (AB)

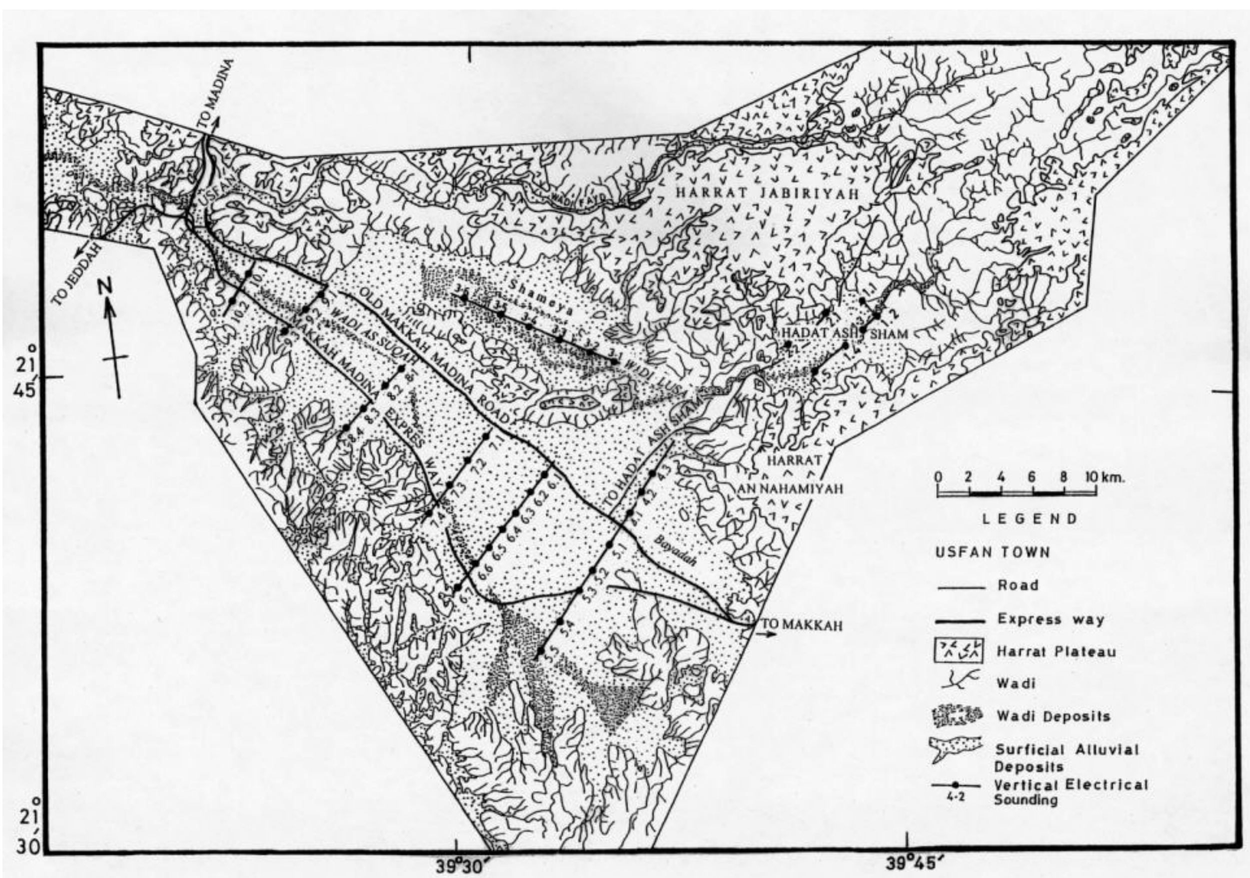

Figure 4. Geologic map showing the location of the VES geo-electric profiles.

extended up to 700 m from the center. Seven soundings were made in the Haddat Ash-Sham area. Six others were investigated in the Wadi Ash-Shamiya area. Three soundings were measured in the Wadi Bayadah area. Twenty-five resistivity soundings were measured in the Wadi As-Suqah area.

In the Haddat Ash-Sham area two profiles were carried out. The first consists of five vertical electrical sounding measurements. The distance between each two soundings (VES) is 800 m. The second profile contains two VES; the distance between these two soundings is 2 km. In the Wadi Ash-Shamiya area one long profile (5 km in length) was carried out. Six resistivity soundings were measured in this profile with a distance of 1 km between each sounding. In the Wadi Al-Bayadah one profile, consisting of three resistivity soundings, was carried out. The distance between each two soundings is 1 km. In the Wadi As-Suqah area six profiles were carried out across the Wadi. The distance between the profiles is 5 km. The first profile consisted of five resistivity soundings; the distance between the soundings is 1 km. In the second profile seven resistivity soundings were measured and the distance between the soundings is 1 km. Four resistivity soundings were measured in the third profile where the distance between soundings 1, 2 and 3 is 1 km and between 3 and 4 is 2 km. The fourth profile consisted of four resistivity soundings. The distance between soundings 1 and 2 is 1 km and between 2, 3 and 4 is 2 km. In the fifth profile three resistivity soundings were measured; the distance between the soundings is 2 km. The sixth profile was taken downstream where two resistivity soundings were measured and the distance between the soundings is 2 km.

The traverse numbers of each area and their corresponding VES numbers as well as their location are given in Table 1.

RESULTS AND INTERPRETATION

A detailed investigation that included resistivity measurements and test drilling, was carried out in the three selected study areas. Three boreholes were drilled in each of the selected areas. The locations of the boreholes were based on the resistivity results. Horizontal Electrical Profiles (HEP) were carried out to determine the thickness of the alluvial deposits. The interpretation of the HEP shows lateral variation in the alluvial deposits. In the Haddat Ash-Sham area the alluvial deposits are composed of sandy gravels with a thickness ranging between 12 and 20 m. The Ash-Shamiya alluvial deposits are mainly silty sands with a thickness between 20 to 25 m; while the As-Suqah alluvium consists of clayey materials about 25 m in thickness.

The interpretation of the vertical electrical soundings shows that there are two types of curves. The first is observed in the Haddat Ash-Sham and Ash-Shamiya areas. It is a four-layer curve resulting from a four geo-electrical layer section. The upper layer possesses high electrical resistivity, greater than 100ohm-m; which is interpreted as being composed of gravel and sands. The second layer has a moderate resistivity value and is believed to be a mixture of mudstone and silty sandstone. The third layer has a low resistivity value where it is believed to be saturated with groundwater and is interpreted as the upper unconfined aquifer. This layer is composed of gravelly sandstone and the water table varies between 10 and 60 m. The fourth layer has a higher resistivity value, representing sandstone. The second type of sounding curves is a three-layer type, which is observed in the Wadi As-Suqah area. In this type, the topsoil is dry, highly resistive and composed of silty sands. The middle layer possesses a low resistivity value and is composed of mudstone. The third layer is a very thick sedimentary succession consisting of an intercalation of sandstone and shale.

Five geo-electrical cross-sections based on the interpretation of the vertical electrical soundings were constructed to determine the water-bearing horizons in the investigated area. The geo-electrical cross-section in the Haddat Ash-Sham area (Figure 5) comprises the result and interpretation of

Table 1. The Traverse Number of Each Area and Their Corresponding VES Number and Location

Area	Traverse Number	VES Number	Location	
			Latitude	Longitude
Haddat As-Sham	1	1.1	N21° 49′ 03.8′′	E39o 43′ 38.8′′
		1.2	N21° 48′ 36.2′′	E39° 43′ 46.1′′
		1.3	N21° 48′ 26.6′′	E39° 44′ 02.4′′
		1.4	N21° 48′ 08.8′′	E39° 44′ 08.4′′
		1.5	N21° 47′ 12.1′′	E39° 43′ 16.9′′
Wadi Al-Shamiya	2	2.1	N21° 47′ 40.0′′	E39° 35′ 28.0′′
		2.2	N21° 47′ 53.0′′	E39° 35′ 08.0′′
		2.3	N21° 48′ 05.6′′	E39° 34′ 39.2′′
		2.4	N21° 48′ 16.6′′	E39° 34′ 08.9′′
		2.5	N21° 48′ 22.9′′	E39° 33′ 30.9′′
		2.6	N21° 48′ 49.6′′	E39° 32′ 40.0′′
Wadi As-Suqah	5	5.1	N21° 42′ 34.1′′	E39° 33′ 28.9′′
		5.2	N21° 42′ 08.1′′	E39° 33′ 02.6′′
		5.3	N21° 41′ 45.1′′	E39° 32′ 33.9′′
		5.4	N21° 40′ 32.2′′	E39° 29′ 10.2′′
		5.5	N21° 40′ 25.8′′	E39° 28′ 37.9′′
	6	6.1	N21° 44′ 49.2′′	E39° 31′ 28.8′′
		6.2	N21° 44′ 37.2′′	E39° 30′ 58.1′′
		6.3	N21° 44′ 17.6′′	E39° 30′ 31.1′′
		6.4	N21° 44′ 08.6′′	E39° 29′ 58.8′′
		6.5	N21° 43′ 59.3′′	E39o 29′ 24.9′′
		6.6	N21° 43′ 41.9′′	E39° 28′ 34.1′′
		6.7	N21° 43′ 34.9′′	E39° 27′ 28.0′′
	7	7.1	N21° 47′ 19.2′′	E39° 28′ 58.1′′
		7.2	N21° 47′ 03.8′′	E39° 28′ 31.3′′
		7.3	N21° 47′ 16.4′′	E39° 27′ 06.9′′
		7.4	N21° 47′ 16.4′′	E39° 26′ 28.6′′

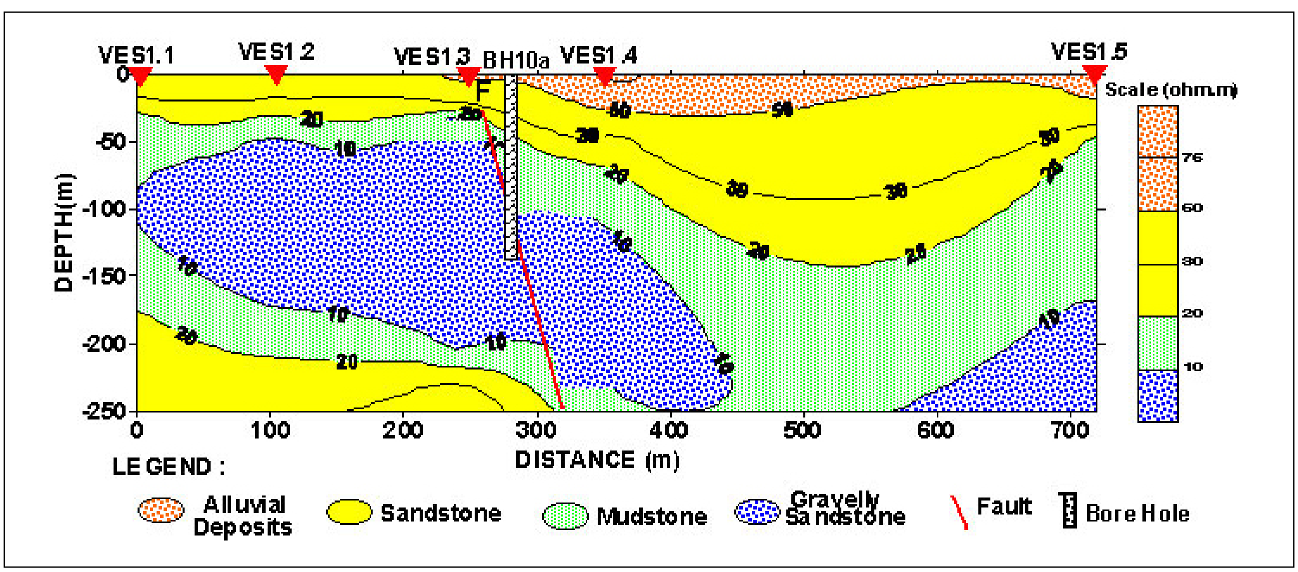

Figure 5. Haddat Ash-Sham geo-electrical cross-section.

VES1.1, 1.2, 1.3, 1.4 and 1.5. Resistivity soundings in this area clearly identify the nature of the lithological variation. Low resistivity zones, reflecting the water-bearing layer, vary in thickness and becomes thicker beneath VES1.3 and VES1.4. In the Haddat Ash-Sham area the groundwater occurs in two aquifers as indicated by the vertical electrical soundings. The shallow unconfined sandy gravel layers occur at a depth of about 20 m. The deep confined aquifer is gravelly sandstone, occurring at a depth of about 100 m. A test borehole was drilled at the location of VES1.3 to test the resistivity results (Figure 6a). The lithological log of the borehole shows a similar geological arrangement as that indicated by the vertical electrical sounding. Abundant groundwater was found in the borehole. Two saturated zones were found; the shallow aquifer at a depth of 14 m in the alluvial deposits and the deep aquifer at the interval 91-104 m in the gravelly sandstone layer. The borehole penetrated a weathered basaltic layer at 35 m depth. Good indicators of the presence of faults and fractures were found. These faults and fractures are in general tensional or open and favorable for groundwater flow.

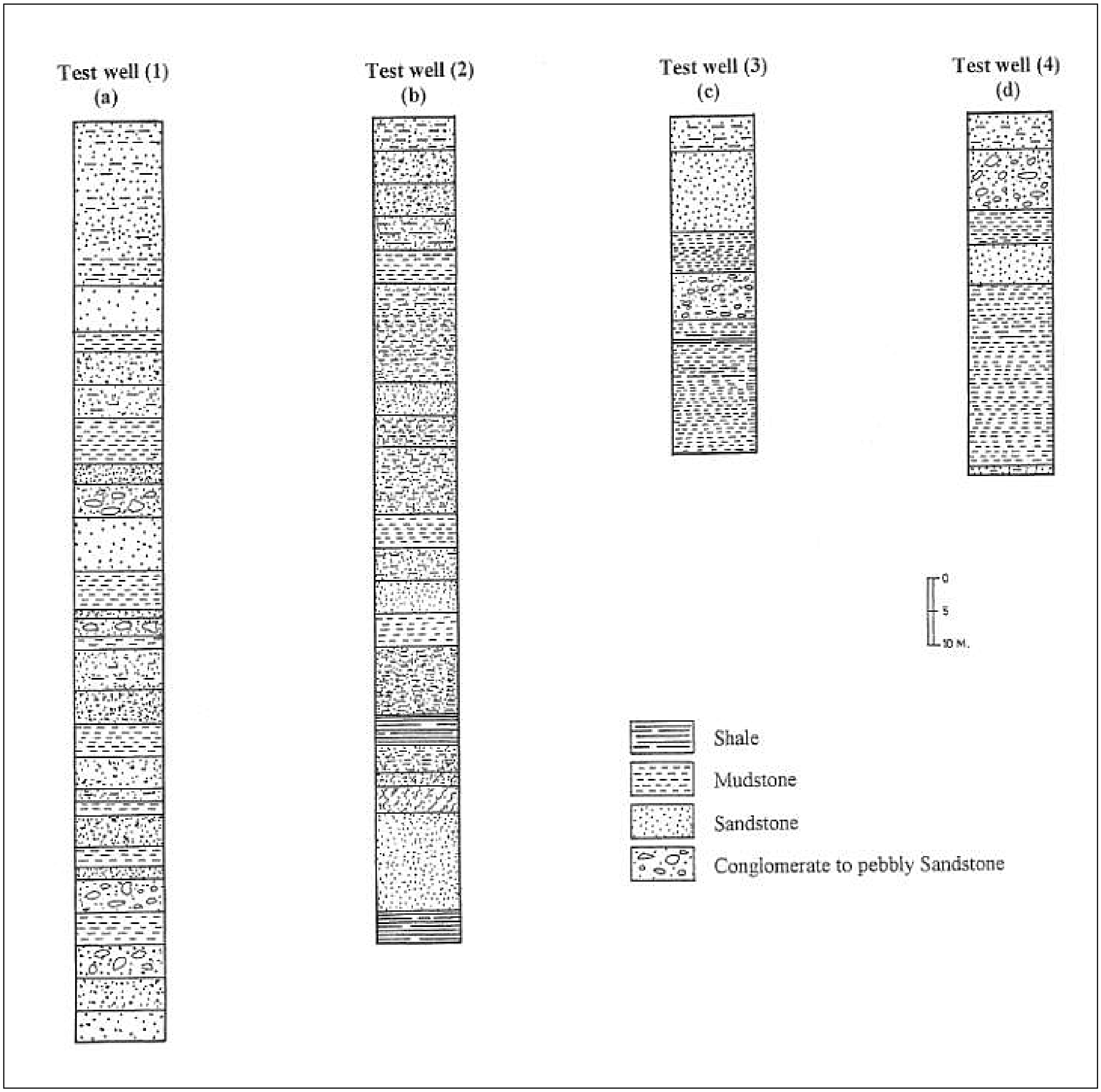

Figure 6. Results of test drilling in the study area.

The As-Shamiya geo-electrical cross-section (Figure 7) comprises the results and interpretation of VES2.1, 2.2, 2.3, 2.4, 2.5 and 2.6. The geo-electrical cross-section indicates that the groundwater occurs in two aquifers. A shallow unconfined aquifer is composed of alluvial deposits at 22 m depth, underlain by a weathered basaltic unit and a deep confined aquifer is found at a depth of about 150 m that is composed of gravelly sandstone. Block faults were encountered beneath VES2.2 and VES2.3; therefore soundings 2.2 and 2.3 represented the best two drilling sites. A test borehole was drilled at the location of VES2.2 where it penetrated two saturated zones; a shallow alluvial deposit unconfined aquifer at 20 m depth, and a deep gravelly sandstone confined aquifer associated with faulting at 120 m depth (Figure 6b). The static piezometric surface stabilized at 44 m and the drilling resulted in a productive well. The borehole information agreed well with the yield interpretation. The lithological log shows that a basaltic sill overlies the deep gravelly sandstone aquifer, which is underlain by mudstone.

In the As-Suqah area, three geo-electrical cross-sections were plotted across the wadi strike. The first section (Figure 8) shows the result and interpretation of VES5.1, 5.2, 5.3, 5.4 and 5.5. The second section (Figure 9) shows the result and interpretation of VES6.1, 6.2, 6.3, 6.4,6.5, 6.6 and 6.7; while the third section (Figure 10) shows the result and interpretation of VES7.1, 7.2, 7.3 and 7.4. These geo-electrical sections indicate that the groundwater aquifer possesses low resistivity values, less than 5 ohm-m, which is lower than that for the northern parts of the study area. These values usually correspond to saline water. The increase in groundwater resistivity towards the north, in the direction of the basement outcrop, may indicate the introduction of fresh water in that direction. This can be explained by the occurrence of recharge derived from rainwater in the mountainous catchment area. The old Makkah-Madina road appears to mark the interface in the study area. The topography and structure of the Harrat along the NW fault may control the contact between the fresh and saline water. The relatively small difference between the resistivity of the bedrock and the water horizon may suggest that the bedrock is most probably fractured. Two boreholes that were drilled in the As-Suqah area at the location of VES 6.3 and VES 7.2 confirmed that the groundwater is contaminated by saline connate water (Figures 6c and d).

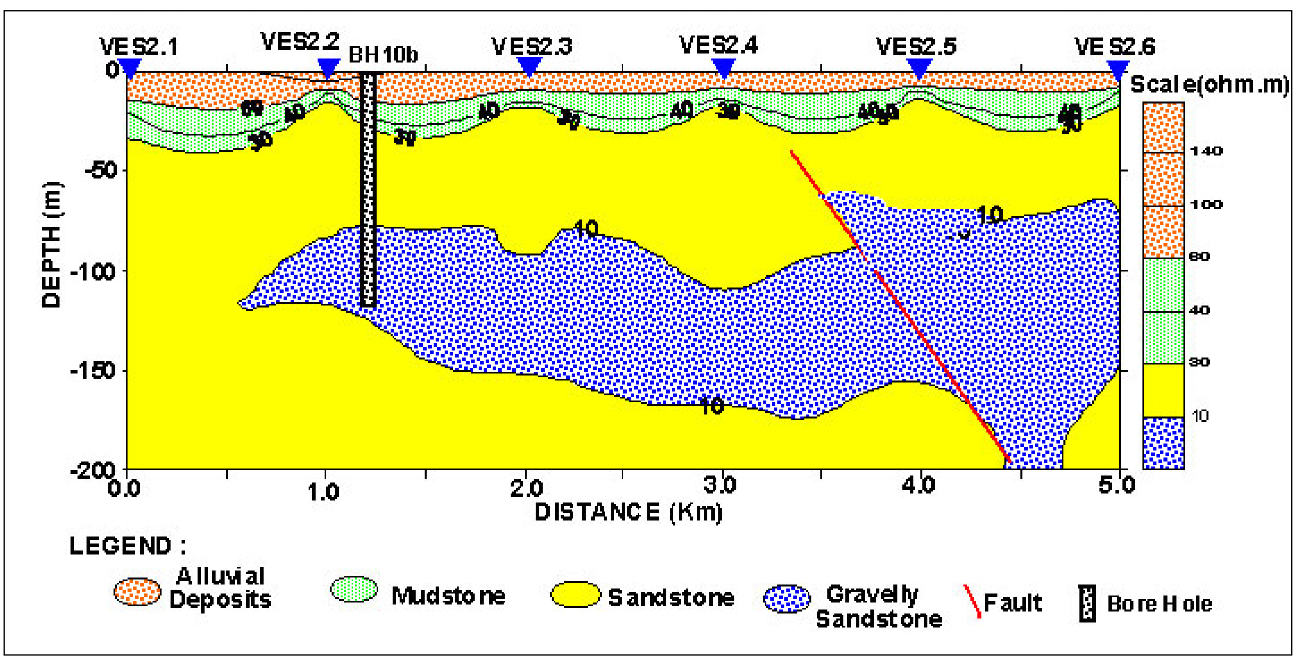

Figure 7. Shameya geo-electrical cross-section.

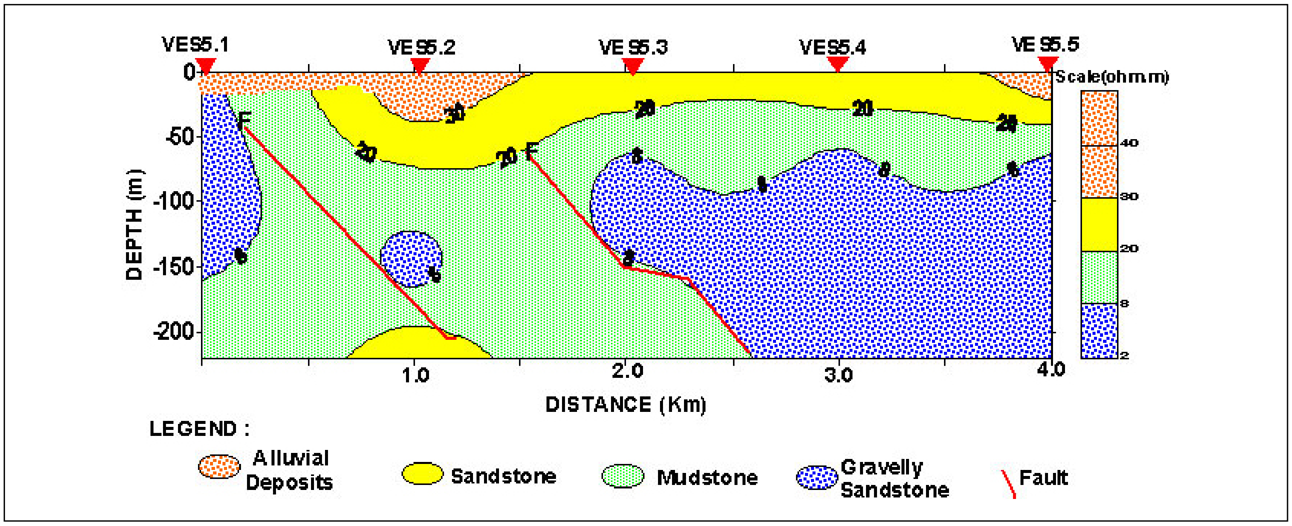

Figure 8. As-Suqah geo-electrical cross-section-1.

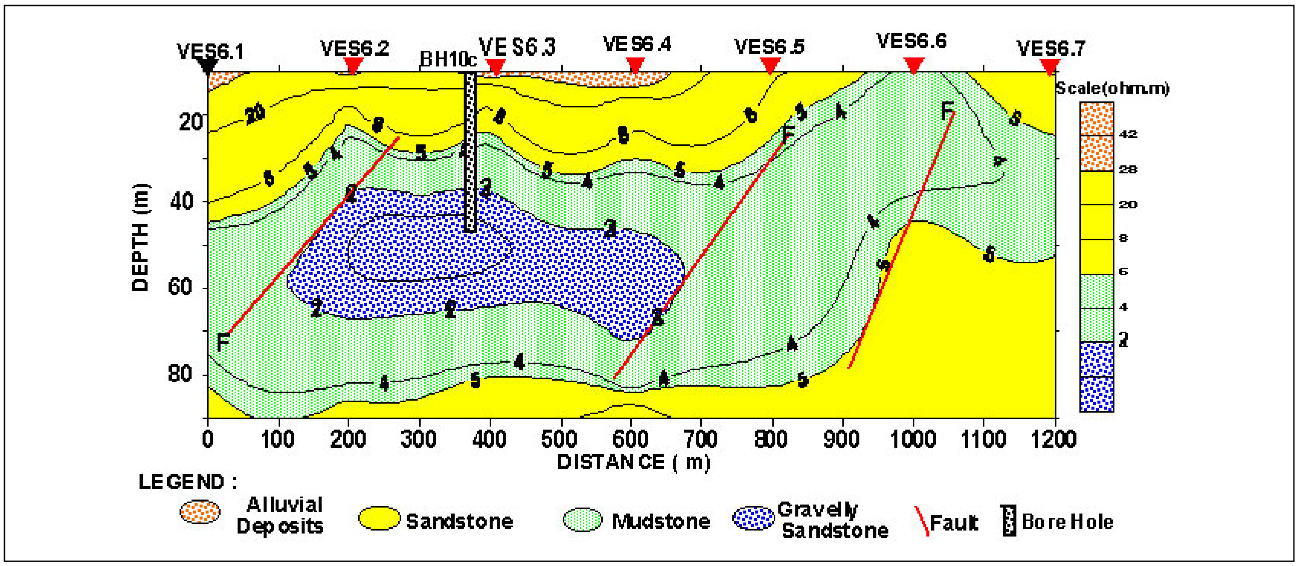

Figure 9. As-Suqah geo-electrical cross-section-2.

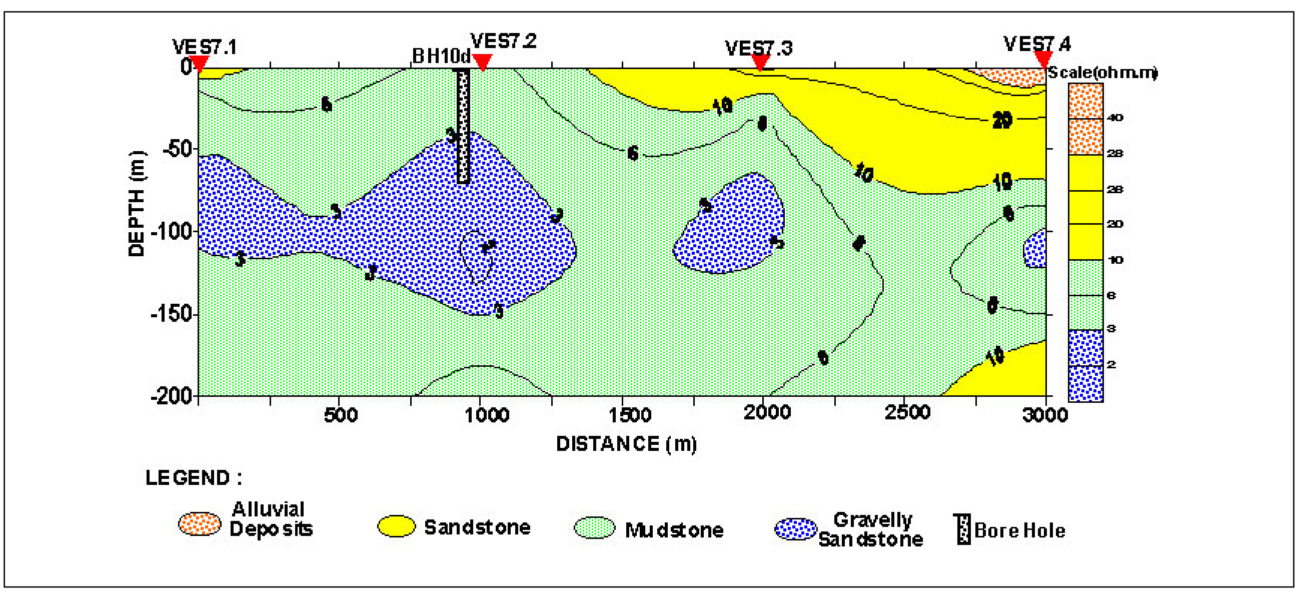

Figure 10. As-Suqah geo-electrical cross-section-3.

CONCLUSIONS AND RECOMMENDATIONS

The combinations of vertical electrical sounding (VES), horizontal electrical profiling (HEP), and drilling have made a valuable contribution to the identification of groundwater resources in the study area. Resistivity soundings in this area clearly identified the nature of the lithological depths and proved useful at identifying water-bearing zones. Abundant fresh groundwater was found in the northern part of the study area with the highest yield. Significantly, the majority of the groundwater was found within the deep confined gravelly sandstone aquifer, rather than in the shallow unconfined aquifer. The interface between fresh and saline water was delineated. The groundwater in the southern part was contaminated by saline connate water, therefore for such areas deep boreholes are recommended. Magnetic and gravity measurements are recommended in the study area to better delineate the likely existence of faults, igneous rocks intrusions, and to establish the basement configuration. This information will add to the knowledge of the hydrogeology of the area and provide for improved groundwater exploration and management.

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