International Journal of Water Resources and Arid Environments 1(6): 397-410, 2011
ISSN 2079-7079

2-D Electrical Tomography for Mapping of Aquifers at the New Campus of King Faisl University, Al Hassa, KSA

Ahmed S. El Mahmoudi, Khalid M. Al-Barrak and Massoud A. Massoud

Water Studies Center, King Faisal University, Al Hofuf, Saudi Arabia

Abstract: There is a growing concern in the Kingdom of Saudi Arabia to exploit water resources of acceptable quality to meet demands in domestic, industrial and agricultural sectors. Al Hassa Oasis is one of the largest natural oases of the world and one of the main and old agricultural centers in the Kingdom Saudi Arabia. The enormous size of the farming area was made possible by the immense volume of groundwater discharging from the underlying aquifers. The underlying aquifer system at Al Hassa comprises Neogene aquifer complex, Dammam aquifer complex, Umm Er Radhuma aquifer and Aruma aquifer. The groundwater resources still contribute the largest share in the water budget of Al Hassa area. Nowadays, a new campus for King Faisl University (KFU) is executing at Al Hofuf and it is planned to drill 17 well at the KFU site to tape water from Umm Er Radhuma aquifer to meet the new campus demands for different purposes. So, the aim of this paper is to map the underlying aquifers systems at the study area and to help in choice of the best locations of the proposed site wells in the more potential areas. Two Dimensional (2-D) electrical imaging/tomography surveys, remote sensing, hydrogeological and Geographical Information Systems (GIS) are implemented to achieve the objectives of this study. One of the new developments in recent years is the use of 2-D electrical imaging/tomography surveys to map areas with moderately complex geology. A more accurate mode of the subsurface is a two-dimensional model where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line. In this study, (2-D) earth resistivity survey were conducted along five transects crossing the site of the (KFU) campus. These 2-D resistivity transects were extending in north-south direction for about 2 Km for each transect. At each transect, Dipole-Dipole, Wenner-Schlumberger and Pole-Dipole configurations were implemented and merged during the processing and the interpretation of resistivity data. Available wells data, geological and hydrogeological information were used to help in the interpretation of the resistivity tomograms. Resistivity tomograms of the five profiles indicate remarkably the different hydro-stratigraphic units of the principal aquifers, the aquitard (Rus Formation), karstified areas of the Neogene and Dammam aquifers and the hardpan layer. The high potential area was found to be located to the southern part of the investigated site. A map based on this high resolution geophysical investigation was prepared and the sites of the proposed wells are re-located and the drilling program is started and the already drilled wells, so far, show excellent match between the 2-D resistivity tomograms and the well lithology and hydrogeology information.

Key words: *Water Resources · Aquifers, Groundwater exploration · Electrical resistivity tomography · GPS · Remote sensing · Al Hassa Oasis · Saudi Arabia*

INTRODUCTION

Water resources are essential and play a significant role in the development processes. The Kingdom of Saudi Arabia (KSA) is known by its arid conditions and limited renewable freshwater resources. To meet the increasing water demands in domestic, industrial and agricultural sectors, various alternative supplies are renewable groundwater resources, treated wastewater, desalinated water and non-renewable groundwater. Fresh water supply in arid regions is limited due to scarce precipitation and high evapotranspiration. When the limited supply is coupled with increasing demand for fresh water in these regions due to rapid population growth, it necessitates optimal development and management of water resources. Water resources management in arid regions has received considerable attention in recent years.

Corresponding Author: Ahmed S. El Mahmoudi, Water Studies Center, King Faisal University, Al Hofuf, Saudi Arabia

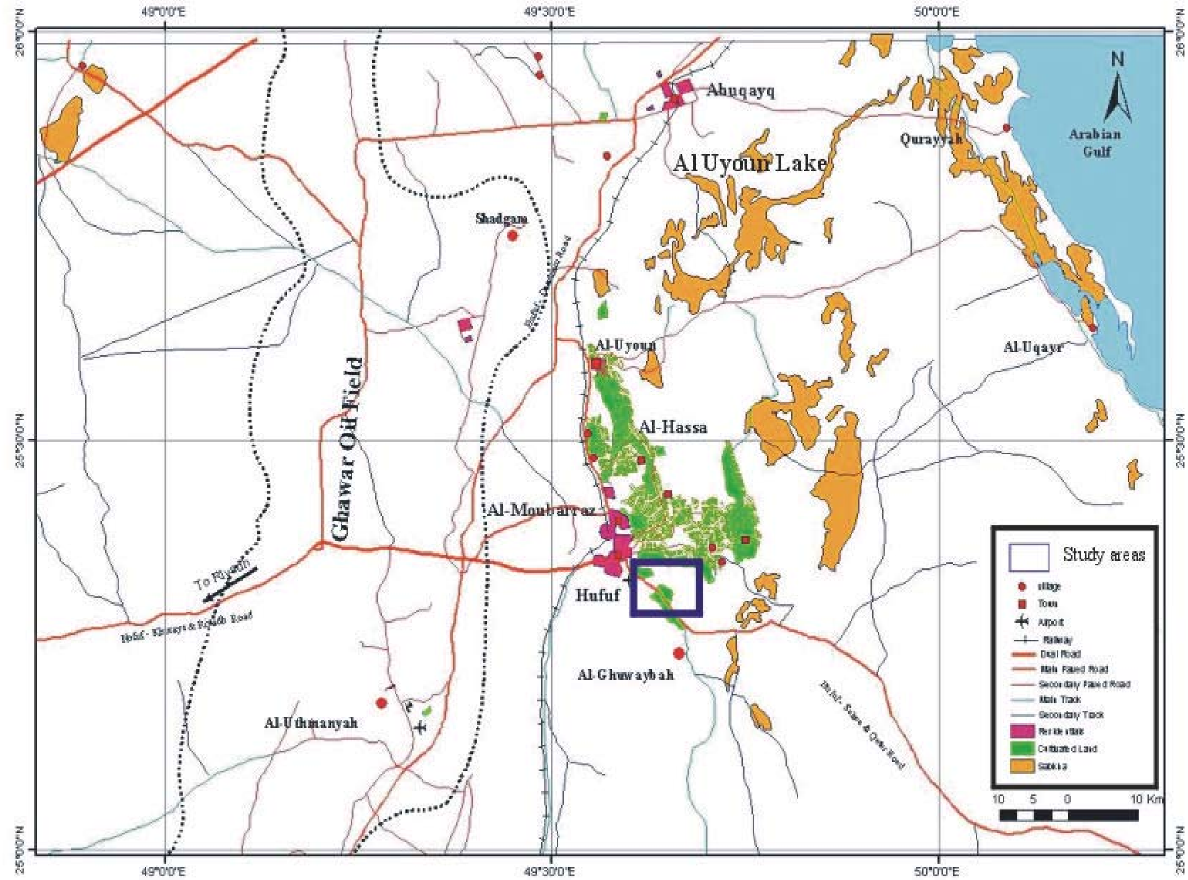


Fig. 1: Location map of the study area, Al Hassa, eastern province, KSA

The area of study is located at Al Hofuf (Al Hassa) city, Eastern province of Saudi Arabia which is located 70 km west of the Arabian Gulf (Figure. 1).

Al Hassa Oasis, where is the study area is located, is one of the largest natural oases of the world. The groundwater at Al Hassa is discharge originated from the underlying aquifer system, which comprises Aruma aquifer, Umm Er Radhuma aquifer, Dammam aquifer complex and Neogene aquifer complex. Due to the rapid economic growth, the water demand has increased since the middle of the last century, showing a dramatic increase after 1975. Most of the water demand was covered by groundwater. As a consequence of the overexploitation of the resources, a decline in groundwater levels is observed. The famous springs in the Al Hassa oasis were running dry. To satisfy the water demand deeper wells must be drilled. Furthermore, a deterioration of groundwater quality will occur, caused by up coning of deeper saline groundwater, [1].

Nowadays, a new campus for the King Faisl University (KFU) at Al Hofuf city is establishing and such campus needs water for domestic purposes and the only source for water is the groundwater. Ministry of water and electricity and water gave permission to the administration of KFU to drill 17 well to tape water from Umm Er Radhuma aquifer as the shallow aquifer (Neogene) is depleted due to over pumping by farmers at Al Hassa Oasis. Before this geophysical, investigation, the administration of KFU started with two drilled wells (No 1 and4, see Fig. 6 for location) in the northern part of the study area and unfortunately, these two wells found to be non productive wells. So, the aim of this paper is to map the hydrostratigraphic units of the underlying aquifers systems at the study area using Two-Dimensional Electric Resistivity Imaging (2-D ERI) technique and to help in choice of the best locations of the 17 proposed wells at Umm Er Radhuma aquifer. Such contribution will provide the technical support for planners of the new campus to put the right drilling program for the proposed wells and to meet the water demand of the new campus of KFU at Al Hassa.

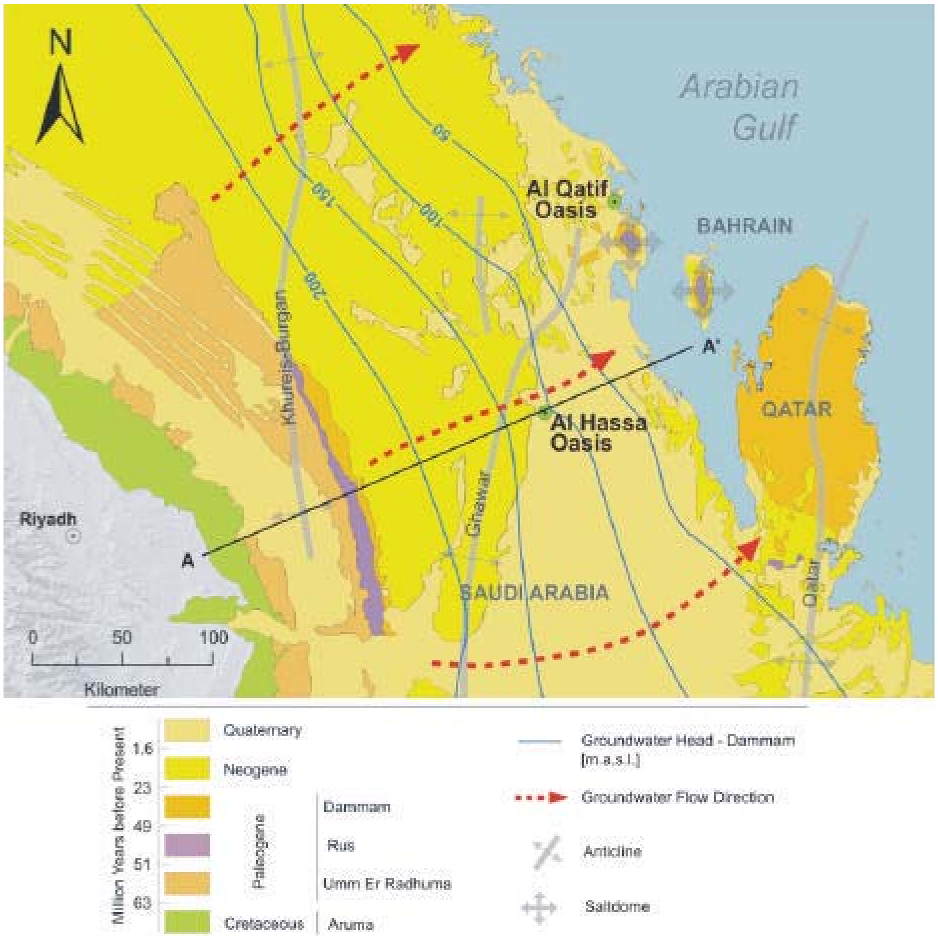


Fig. 2: Geology and hydrogeology of the study area (modified after [1]

Geological and Hydrogeological Setting of Al Hassa Area: Al Hassa area of the Eastern Province of Saudi Arabia is a part of the Shedgum Plateau, the eastern edge of the greater As Summan Plateau. The Shedgum Plateau is covered by a succession of Tertiary carbonates and evaporites of the Um Er Radhuma, Rus, Dammam, Hadrukh, Dam and Hofuf formations (Figure. 2). The Shedgum Plateau, including the Hofuf area, is dotted with numerous karstic features including sinkholes, solution cavities and caves [2, 3].

The sedimentary succession consists of carbonates (limestone and subordinate dolomite), sulphates (anhydrite and gypsum) and subordinate marls and shales (Figure 2). The total thickness ranges from 800 m to 2,500 m, increasing towards the Arabian Gulf. In general, the formations are dipping from the outcrop areas in the west towards the east. The constant dip of the formations is only interrupted by a series of mainly north-south trending anticlines and synclines, which represent the major tectonic elements.

Structurally, Al Hassa oasis lies on the eastern flank of the north-south trending Ghawar anticline which, structurally, dates back to the Eocene time [4, 5].

The Paleocene and part of the Early Eocene are represented in the stratigraphic section by the Um Er Radhuma limestone which indicates the prevalence of normal marine conditions over the Eastern Province during that time. The Ypresian Age (of the Early Eocene) witnessed the introduction of a widespread deposition of anhydrite [6, 7]. The deposition of anhydrite probably, while took in low synclinal place areas anticlinal areas were sub aerially exposed due to regression of the sea at that time [4].

In early Eocene, marine conditions Middle and prevailed again and the Rus is overlain by shale and limestone in the western outcrop area and by limestone in the study area. All units deposited in that period are thinner on top of the Ghawar anticline than in the surrounding areas. This suggests that during that time a continuous tectonic keeping the Ghawar movement was anticline shallower than the surrounding localities.

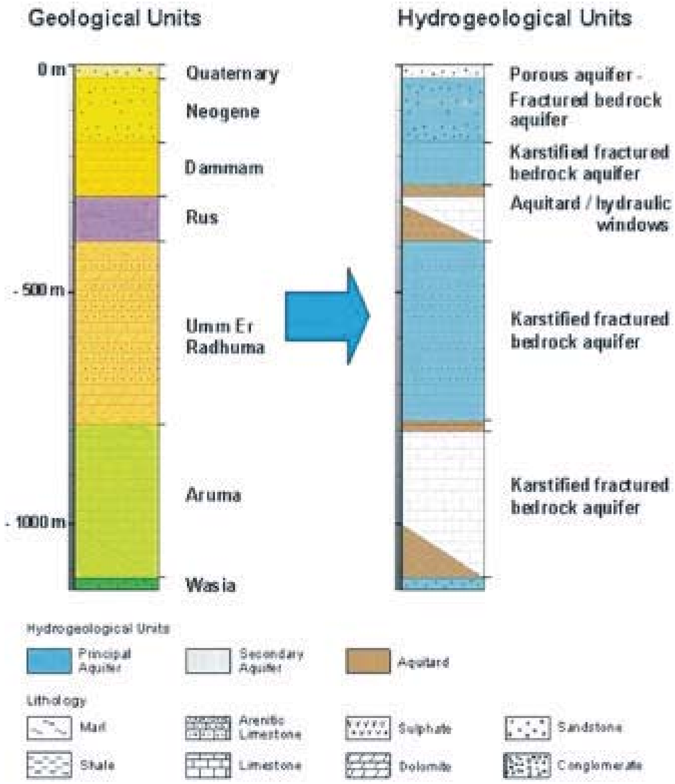


Fig. 3: Schematic sketch, illustrating the hydrogeological units of the aquifer system at the area of study (after [1])

Marine conditions have ended by a regional regression of the sea in Middle Eocene and followed by a long period of erosion marked by the Pre-Neogene Unconformity.

Erosion was very active particularly on top of anticlines as indicated by the removal of the whole Dammam Formation from some localities on top of the Ghawar anticline.

Following the period of erosion was a period of deposition of deltaic, fluviatile, lacustrine and marine sediments that took place under rapid transgressive and regressive conditions probably caused by minor tectonic activities [6]. This period of time is represented by the Neogene Group. During the Quaternary, the sea regressed to its present position and no significant transgression has taken place since that time.

The aquifers are partly interconnected. The Umm Er Radhuma aquifer and the Dammam aquifer are separated by the Rus formation that consists of evaporites, marls and limestones. The Rus formation, which generally acts as an aquitard between both aquifers, forms a joint aquifer in some areas where it is represented by fissured carbonates or where dissolution of evaporite layers has created secondary permeabilities. The lower part of the Aruma formation, which consists of shales and clay, acts as an aquitard, separating the aquifer system from the underlying Wasia aquifer. The groundwater system in the study area consists of four partly interconnected aquifers (Figure 3). These are:

- Neogene aquifer complex at the top-a mixture of karstified fractured bedrock aquifers and unconsolidated porous clastic aquifers,
- Dammam aquifer complex- a partly karstified fractured bedrock aquifer,
- Umm Er Radhuma aquifer-a karstified fractured bedrock aquifer and
- Aruma aquifer at the base-a karstified fractured bedrock aquifer of minor importance.

The main groundwater flow of the aquifer system is directed from the outcrop areas in the west towards the Arabian Gulf. The groundwater movement within the aquifer system occurs primarily through secondary openings, such as joints, fractures and bedding-plane openings, which are often enlarged by solution processes.

In Al Hassa region the groundwater has salinities between 1,000 and 2,000 mg/l. The increase in salinity is accompanied by a shift in the major ion facies:

While calcium-bicarbonate waters prevail in the outcrop area, calcium-sulphate waters occur in the central region of the aquifer system. In the coastal area sodium and chloride are the major ions. Salinities of the Dammam and Neogene aquifers are in the same range like Umm Er Radhuma and Aruma aquifers, but salinity distribution is patchier and does not follow a west-east trend [8, 9].

Karstification plays an important role within the aquifer system, consisting predominantly of carbonates. Karst phenomena like sinkholes and caves are observable in the outcrop areas of the Aruma and Umm Er Radhuma formation [10]. Moreover, evidence of sub-surface karstification could be frequently encountered during drilling, particularly within the Umm Er Radhuma carbonates. The karst of the studied formations is mainly the result of palaeokarstification, developed under wetter climatic regimes in the geological past. Karstification of the Umm Er Radhuma Formation at its western extent started already shortly after its deposition and the subsequent regression during the Lower Eocene, while to the east marine sedimentation continued.

The karstification continued throughout the entire Eocene period and prevails in the westernmost areas until today. Beside the exposed Umm Er Radhuma on the palaeo-main-land to the west, emerged areas also existed in the east during this period, which was due to the tectonic uplift movements of anticlinal structures. Sporadic emersion of at least one of these structures, the Ghawar Anticline, occurred. Consequently erosion of the already deposited Rus and karstification of the exposed Umm Er Radhuma was enabled. In addition, the development of karst above the uplifted structures was promoted by the higher degree of fracturing in this zone due to bending of strata. Further karstification occurred in post-Eocene times, after the final, widespread emersion of the Arabian Platform, [1].

Hydrogeology and Hydrochemistry of groundwater of Al Hassa area have been reported in a number of studies [11-16,1 17].

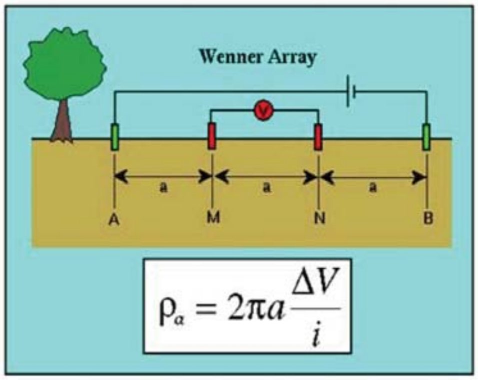
MATERIALS AND METHODS

Surface-geophysical methods offer quick and inexpensive means to characterize the subsurface hydrogeology [18, 19]. They provide information on the subsurface properties, such as thickness of layers and saturation zones, depth to bedrock, location and orientation of bedrock fractures, fracture zones and faults. Surface and borehole geophysical methods may form a part of preliminary site evaluation for groundwater investigation. The data from geophysical surveying can guide the selection of the sites of test borings and provide data to correlate between them. The electrical methods, in general, include different techniques and instruments depending on the nature of the method used in prospecting. Some of these methods make use of natural currents and others depend on injection of artificial currents into the earth. For more details about these different techniques reference is made to [20-25].

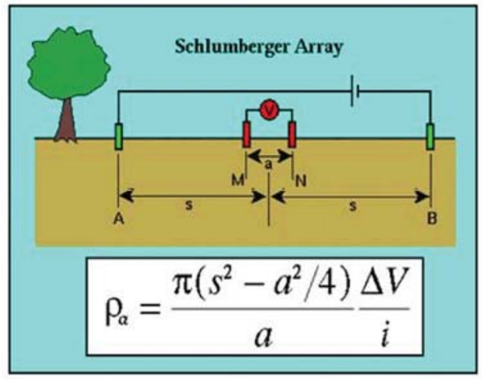
The DC- resistively methods of geophysical exploration are popular and proved to be successful and have many implications in the fields of geoenvironment and hydrogeology. Electrical resistively methods were developed in the early 1900s, but have become widely used since the 1970s, primarily due to the availability in the search for suitable groundwater sources. These methods have also been used to monitor types of groundwater pollutions; in engineering surveys to locate sub-surface cavities, faults and fissures permafrost, mineshafts and in archaeology for mapping out the real extent of remnants of buried foundations of ancient buildings, amongst many other applications.

One of the new developments in recent years is the use of 2-D electrical imaging/tomography surveys to map areas with moderately complex geology [26]. A more accurate mode of the subsurface is the two-dimensional (2-D) model, where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line are recorded. 2D dc-resistivity profiling is carried out by making many measurements at different locations along the profile and at different offsets. The 2D dc-resistivity profiling data are inverted to create a tomogram-like model of resistivity along a section of the subsurface that can be used to detect water zones of different salinities.

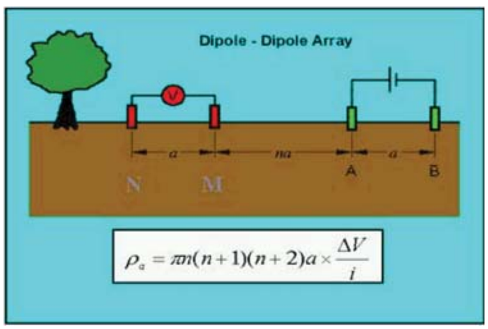
Two-dimensional Resistivity Data Acquisition: In this study, the 2-D electrical resistivity measurements were carried out using SuperSting R8/IP 8 channel multi-electrode resistivity and IP imaging system with 112 electrodes at 18 meter spacing manufactured by AGI Advanced Geosciences, Inc. Five 2-D resistivity transects were extending in north-south direction for about 2 Km for each transect. At each transect, a combination of Dipole-Dipole, Wenner-Schlumberger and Pole-Dipole configurations were implemented and merged during the processing and the interpretation of resistivity data. Figure (4) shows the most common electrode arrays used in DC resistivity surveys. Total Station Sokkia 510 (Fig. 5,a) was used for the setting of the 2-D resistivity profiles and to adjust the iner-electrode spacing along the five measured profiles. The coordinates of the conducted 2-D profiles was measured by using high accuracy differential Trimble 5800 GPS system (Fig. 5,b).



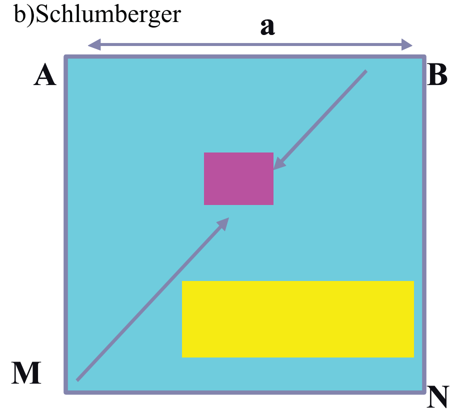
a)Wenner Array



b)Schlumberger



c) Dipole-Dipole



d)d)Saquare

Fig. 4: Common electrode arrays used in DC resistivity and their corresponding geometric factors.

(a)

(b)

Fig. 5: Using the total station Sokkia 510 and the 5800-GPS for 2-D profiles setting

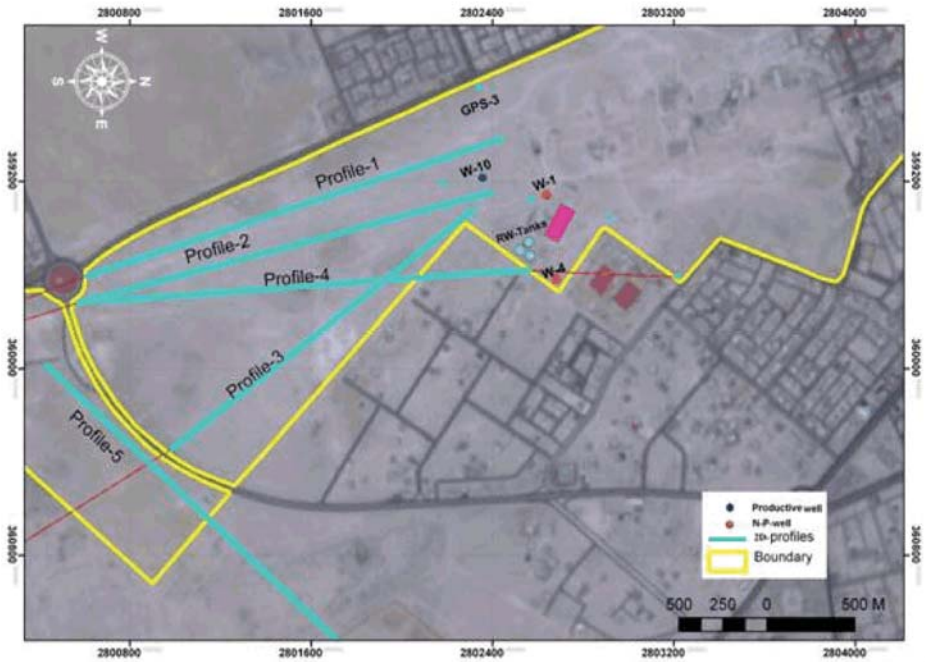


Fig. 6: Base map showing the locations of the conducted (2-D) profiles and the drilled wells, New Campus, KFU, Al Hassa.

Figure (6) shows the base map of the five conducted 2-D profiles and the locations of the far pole (which used in pole-Dipole array to achieve maximum dpeth of penetration) for each profile and the refrence point KFU-GPS-3 station which used as a reference point for 5800-GPS measurements. The GIS Software ArcGIS 9.3 and ERDAS IMAGINE 8.3 as image processing software were used for preparation of the location map of the conducted 2-D profiles and the available wells in the study area. at the new campus, KFU Al Hassa (Fig. 6).

The apparent resistivity data were inverted to create a model of the resistivities of the subsurface using AGI EarthImager 2D Software. With this software data collected with the AGI SuperSting earth imaging resistivity instruments can be interpreted into easy to read 2D earth sections.

RESULTS AND DISCUSSION

To relate the inverted 2-D resistivity tomograms with the lithologic and hydrogeologic conditions, previous works done by different authors (see for example [12, 1] have been correlated with 2-D inverted resistivity tomograms. Also, lithological and hydrogeological data of recently drilled well (Well No. 10) at the study area has been correlated with the interepretd resistivity tomograms. Figure (7) shows the the lithologic log of well number 10 drilled at the study area (Fig. 6, for location). The lithology of this well shows a complicated stratgraphic sequence and different lithologic units from the ground surface to a depth of 420 m. Moreover, the general stratgraphic and the hydrogeological units of the aquifer system at the area of study shown in Figure (3) helped in the interepretations of the 2-D resistivity profiles.

The pumping test which carried out for well no. 10 and this test were done for ten hours continuously. The results of these pumping test is shown in Figure (8).The results of this test and the inferred parameters indicates that static water level is 206.01 m and the dynamic water level is 207.2 m and the maximum draw down was of 1.06 m and the productivity of 200 Gallon/min and the calculated transmissivity is 922 m^2/d. It is worth to mention that a continuous loss is observed during drilling from depth of 310 to 420 m, (Fig. 7). This continuous loss indicates a karstified limestone of Um Er Radhuma formation.

By using an iterative smoothness-constrained least-squares inversion method [27,28], apparent resistivity data collected by the 2D dc-resistivity system are inverted to create a model of subsurface resistivity that approximates the true subsurface resistivity distribution [29]. The 2D dc-resistivity field-data (upper part of the section), resistivity models (middle part of section) and synthetic-data inversions (lower part of the section) for profile-1 are shown in Figure (9).

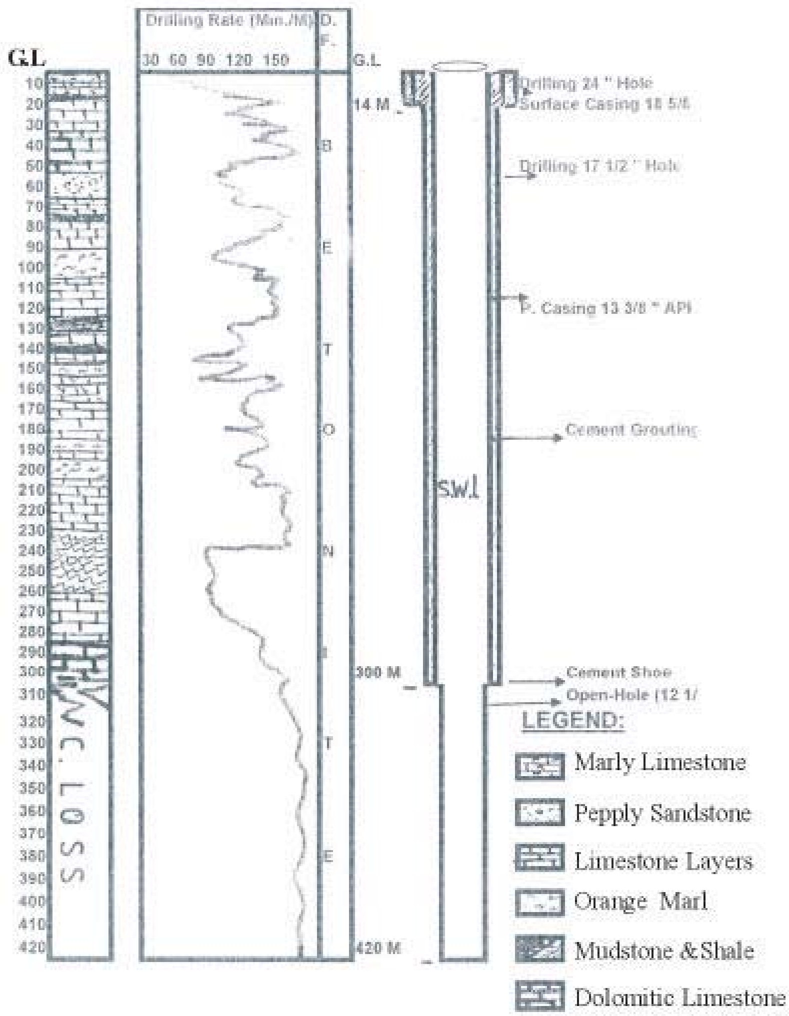


Fig. 7: Descriptive Log and Well Design of Well No 10 (See Fig. 6 for location)

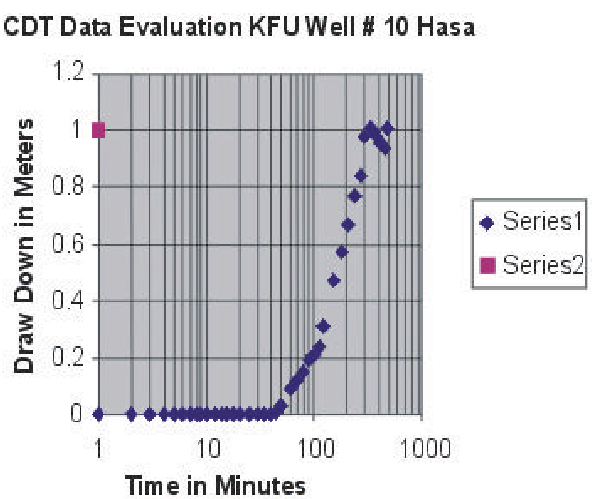


Fig. 8: Shows the results of Constant Discharge Test (CDT) and the changes in the water level Reading done for well No. 10.June 8, 20104

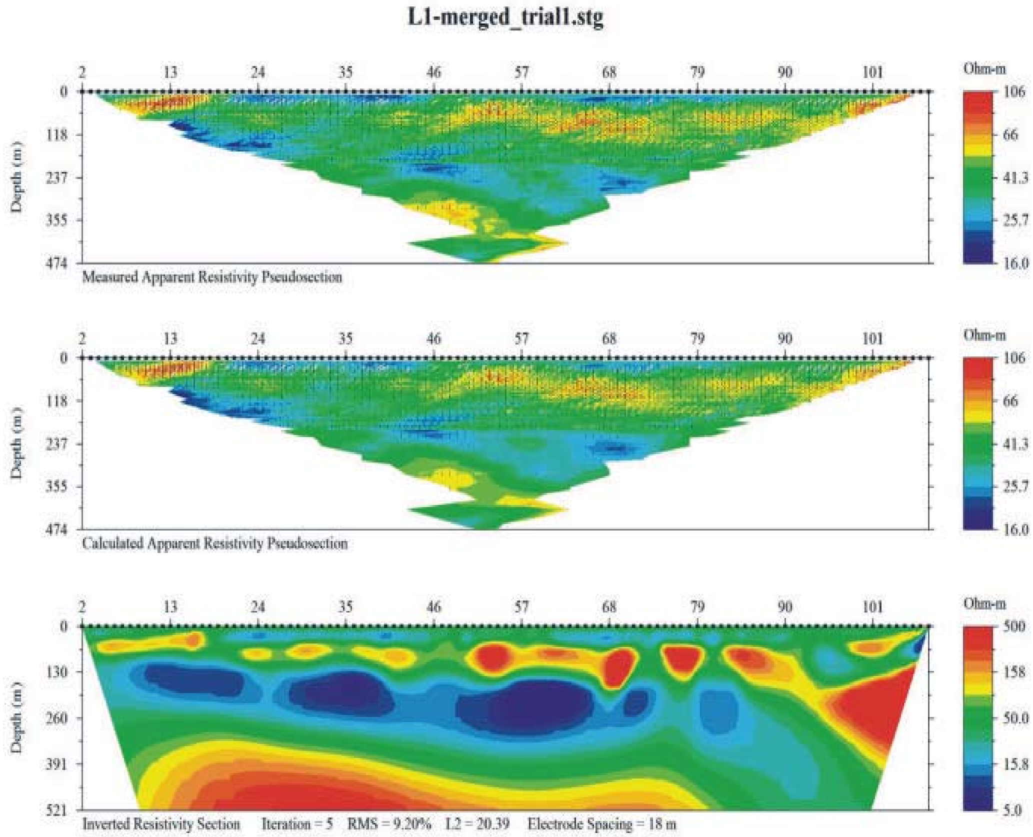


Fig. 9: Inverted resistivity section for two-dimensional for profile -1

The inverted data which are displayed as a cross section of resistivity data approximated the true subsurface resistivity distribution. The obtained information about the subsurface, along the resistivity profiles, is interpreted from the distribution of areas of high and low resistivities. Investigations of the inverted resistivity tomograms (Figs 10 to 14), reveals the following features:

- There is excellent match between the inverted resistivity tomograms (Figs 10 to 14), with the borehole data (Fig. 7 and the hydrogeological units reported by Al Tokhais and Rausch, 2008 shown in Figure 3.
- Lateral variation of lithological units is recognized along all five of these resistivity tomograms. This reflects how the area is complex from the stratigraphic and hydro geologic point of view.
- In general, the tomograms of profiles 1 to 4 (Figs 10 to 13) are characterized by a near surface layer of relatively low resistivity which is attributed to the existence of a shale layer which represents a hardpan layer and such layer were showed through the excavations at the area of study (Fig. 15). It is worth to mention such layer makes problem for constructions and it should be taken in engineers considerations. Existing of such layer usually makes geotechnical problems such as land sliding and in the agricultural areas of A Hassa Oasis,such hardpan layer causes water logging and affects the plant groowth.
- The underlying shale and mudstone of Rus formation are characterized by low resistivities depending upon the percentage of clay and are delineated along the five 2-D profiles. It is worth to mentions that this formation represents the aquitard/hydraulic windows for the hydrogeological units of the aquifer system at the study area. This formation is delineated along the five measured 2-D profiles (Figs 10 to 14). This layer has resistivity value below 20 Ohm-m.This may explain the reasons behind why the wells No 1 and 4 are not productive.

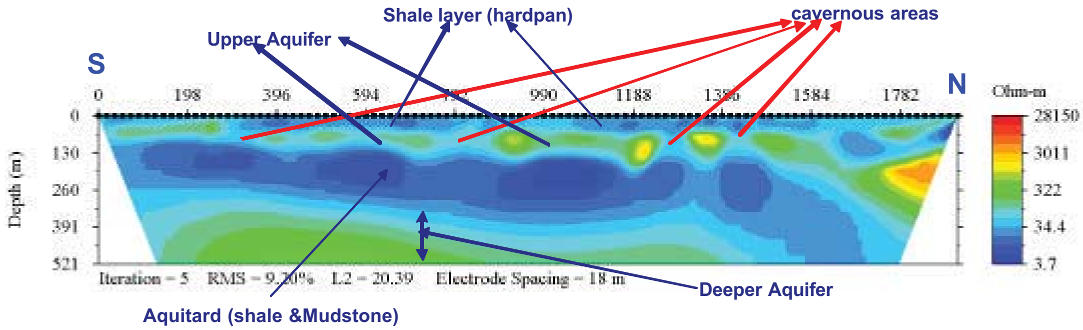


Fig. 10: Interpreted 2-D Resistivity profile along profile-1, (See Fig.6 for location).The stratigraphic succession of the resistivity values is indicated.

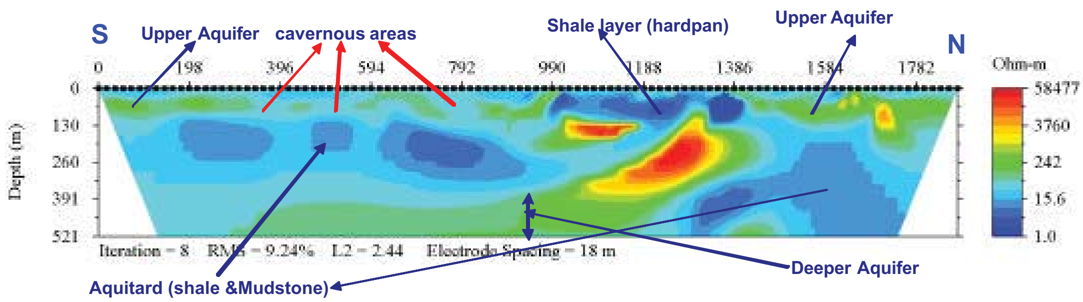


Fig. 11: Interpreted 2-D Resistivity profile along profile-2, (See Fig.6 for location).The stratigraphic succession of the resistivity values is indicated.

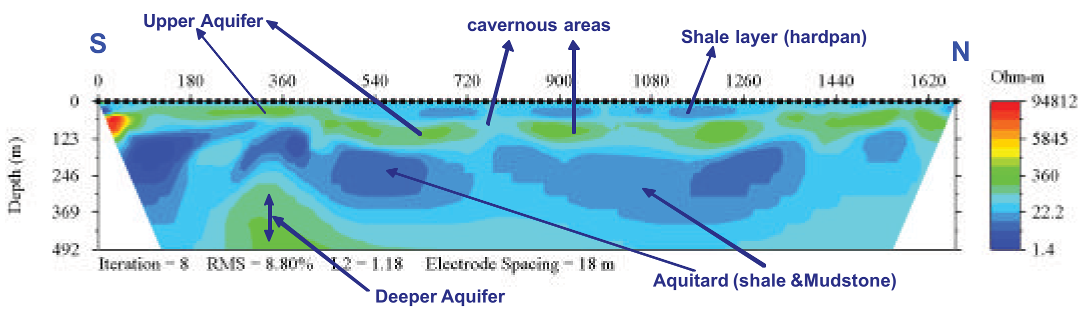


Fig. 12: Interpreted 2-D Resistivity profile along profile -3, (See Fig. 6 for location).The stratigraphic succession of the resistivity values is indicated.

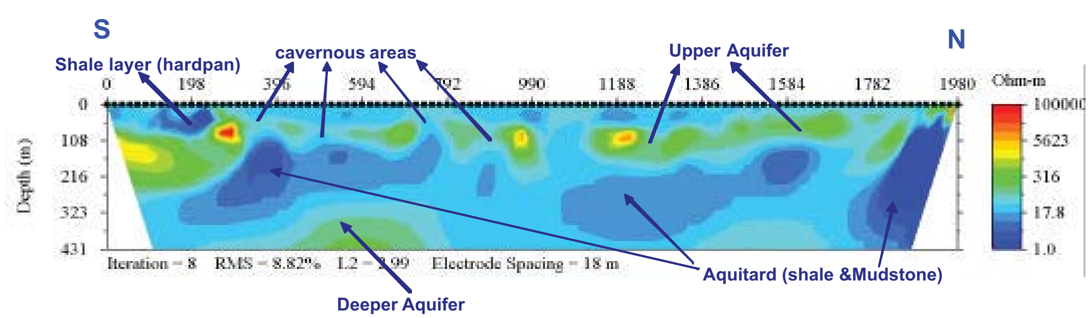


Fig. 13: Interpreted 2-D Resistivity profile along profile Four -4, (See Fig. 6 for location).The stratigraphic succession of the resistivity values is indicated.

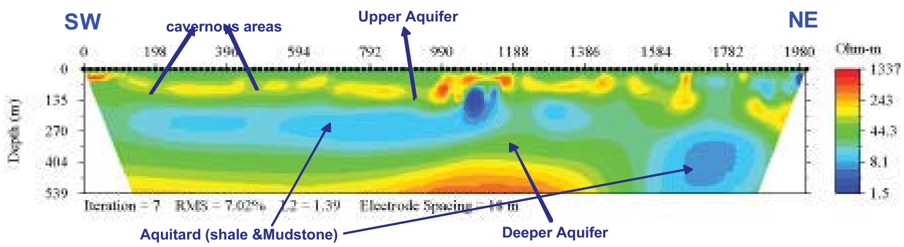


Fig. 14: Interpreted 2-D Resistivity profile along profile -5), (See Fig. 6 for location).The stratigraphic succession of the resistivity values is indicated.

Fig. 15: Shale (hardpan) layer at the near surface at the study area

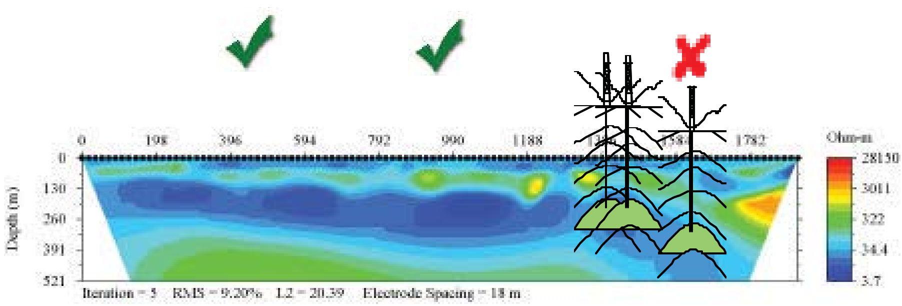


Fig. 16: The recommended sites for wells drilling along the profile –1

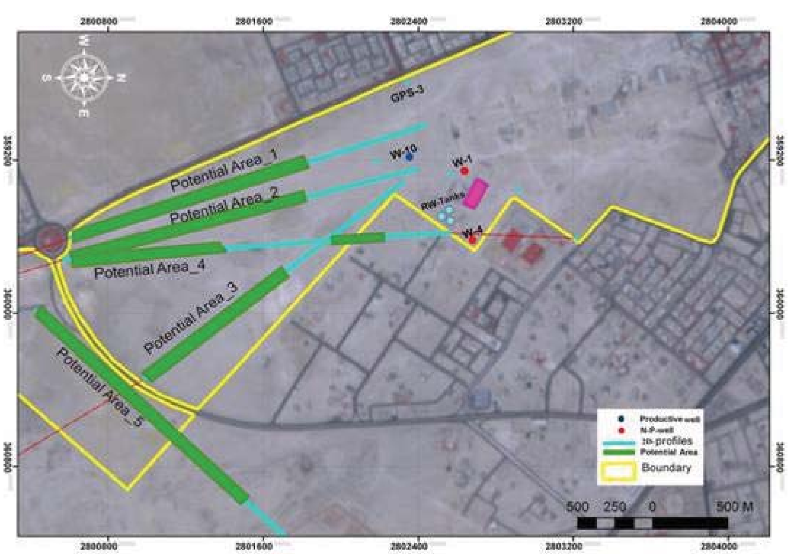


Fig. 17: The recommended areas (Solid, Dark green) along the five investigated profiles

Fig. 18: Following up of Wells drilling program by the authors based on the 2-D resistivity results

- The massive limestone that characterizes the Neogene, Dammam and Um Er Radhuma Formations is characterized by high resistivity. such zones are represented by red colour (resistivity ranges of more than 200 Ohm-m) .On the other hand, the karstified parts of the limestone of Neogene, Dammam and Um Er Radhuma Formation are characterized by moderate resistivity ranges (green areas on the 2-D profiles). Such areas represent the high-potential areas for groundwater capacity and wells should be drilled in such areas to tape water from Um Er Radhuma Formation. Such karstified fractured bedrock aquifers shows good potential areas at similar formation at UAE (see for example [30, 31].
- Along these profiles Um Er Radhuma Formation appears at depths averaging of 300 meters from the surface of the ground and extends up to a maximum depth achieved by this survey (around 550 m).
- Fractured and karstic limestone are recognized at the southern part of 2-D Profiles 1 to 4 (see the inverted interpreted tomograms of these profiles of figures 10 to 13. However, shale and mudstone of Rus formation are replacing at the northern parts of these profiles and extends to the maximum depth of penetration achieved at these survey. In some places in the deeper depth this zone (mudstone and shale would have resistivities of less than 5 Ohm-m probably due to the increase of salinity with depth.
- The areas of high potential of groundwater from Um Er Radhuma formation for each profile. Figure (16) shows the recommended sites to drill wells along profile-1), the area marked with (√) signs and the areas of no potential due to the existing of the shale and mudstone of Rus Formation is marked with (X) signs along this profile. All the recommended sites along the five measured 2-D resistivity profiles are delineated as shown in Figure (17). According to these results a new plan for the pre-planned 17 water wells is redesigned and the drilling program is started and a continuous follow up by the authors for the drilling of these wells (Figure, 18).

CONCLUSIONS

Groundwater in Al Hassa area is the only source of water in the area. However, water from Neogene aquifer has been over pumped excessively to meet the development activities and population growth. As consequences the depth to groundwater dropped dramatically and the alternative is to tape water from deep aquifer (Um Er Radhuma aquifer).The application of Two-Dimensional Electrical Resistivity Imaging (2-D ERI) proved to be a very successful technique for mapping the subsurface conditions of the aquifer system at new campus of King Faisl University, Al Hassa, KSA. Five 2-D resistivity transects were extending in north-south direction for about 2 Km for each transect and att each transect, a combination of different electrode arrays were implemented to achieve the maximum depth of penetration and to map Um Er Radhuma , the principal aquifer in the study area. Moreover, the available borehole data have been utilized along the 2-D resistivity profiles to enhance the interpretation of the resistivity data. Resistivity tomograms of the five profiles indicate remarkably the different hydro-stratigraphic units of the aquifer system in the area of study. Through the resistivity investigation, information about the depth of the main aquifers and the karst areas has been detected. Fractured and karstic limestone are recognized at the southern part of the study are. However, shale and mudstone of Rus formation are intervening with Um Er Radhuma at the northern parts of these profiles and extends to the maximum depth of penetration achieved at this survey and drilled wells at such locations are not productive.

According to these results a new plan for the pre-planned 17 water wells is redesigned and the drilling program is started and a continuous follow up by the authors for the drilling of these wells.

ACKNOWLEDGEMENT

The authors would like to express their sincere appreciation to administration of University Campus, King Faisl University for their support of this study. Special thanks go to Mohamed Al Kulaib and Mohamed Al Farij for their assistance during the 2-D data acquisition. Thanks to the surveyors from Al Fawzaan and Al Khodary construction companies for their help in the setting up and the preparation of the resistivity profiles survey.

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