ORIGINAL ARTICLE

Predicting aquifer characteristics to enhance hydrogeophysical model in fractured/karstified rocks of Dammam Formation at Bahr Al-Najaf Basin, Iraq

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Abstract

Groundwater represents a major water source in Bahr Al-Najaf basin. So, the knowledge of the aquifer parameters is an essential goal to assess and manage groundwater resources. A comprehensive view of the fractured and karstified aquifers within Dammam Formation at Bahr Al-Najaf basin is very important, because the karstified environments are very complex. This study is an attempt to extract mathematically empirical relationships between the hydraulic parameters and the geoelectrical properties, to improve the construction of a hydrogeophysical model, instead of using the conventional procedures of pumping tests or drill new well which need great effort and high cost. The enhanced hydrogeophysical model shows that the main aquifer has a uniform lithology of carbonate rocks, good water saturation and belongs to M. Dammam member. The correlation between hydraulic conductivity (K) m/day and aquifer resistivity (ρ_0) Ωm gave a logical relationship in such kind of aquifer, which has correlation coefficient (R^2) equals to 0.737. In addition, the correlation between transmissivity (T m^2/ day) and both of transverse resistance (T_r) Ωm^2 and longitudinal conductance (S_L) Ω^{-1} revealed the similarity in lithological characteristics of middle Dammam aquifer due to the approximately equal values of strong $R^2 = 0.862$ and 0.868, respectively. This may be due to the nature of the studied area as a discharge zone, which has a good porosity (φ) of 22% and a high water saturation (S_w) equals to 1 approximately. The extracted relationship of direct proportionality between T (m^2/day) and S_L (Ω^{-1}) is an important one. Therefore, this relationship can be used directly to calculate T (m^2/day) mathematically. In the present study, the relations between the hydraulic parameters and the geoelectrical properties are expressed as linear equations instead of nonlinear, because we believe that it is mathematically more acceptable and reliable for hard rock aquifers that the M. Dammam aquifer is confined with a fully saturated thickness. In addition, the comparison between R^2 of the linear and nonlinear relation of T (m^2/day) with T_r (Ωm^2) and T (m^2/day) with S_L (Ω^{-1}) appeared to have little divergence of R^2 equal to 0.028 and 0.001, respectively.

Keywords Hydraulic parameters · Fractured · Karstified rocks · Hydrogeophysical model · Dammam formation

Introduction

Bahr Al-Najaf suffers from the shortages in surface water quantities. This is due to its geographic location being near the southern semi-arid desert of Iraq, a way from surface water resources. So, the groundwater represents a major

water source such as the springs (most of them are dry) and tubular wells (self-flowing and artesian types). These are used as the major sources of water supply for domestic, agricultural and industrial uses.

Geophysicists have realized that a correlation between the hydraulic parameters and geoelectrical properties of an aquifer can provide a possible solution to reduce the spent costs and the consumed time associated with the conventional approach of pumping tests. So, selecting the hydrogeophysical methodology is considered as an optimal solution. Many relations between hydraulic and geoelectrical parameters of various aquifer types were studied and reviewed by several researchers (Kelly 1977; Niwas and Singhal 1981, 1985; Mazac et al. 1985; Huntley 1986; Frohlich et al. 1996; Chen

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et al. 2001; Niwas and de Lima 2003; Singh 2005; Hubbard and Rubin 2005; Pantelis et al. 2007; Ameen 2008; Chandra et al. 2008; Khalil and Santos 2009; Massoud et al. 2010; Sikandar et al. 2010; Niwas et al. 2011; Niwas and Celik 2012; Singh and Singh 2016).This relation can be used as a helpful tool to estimate the hydraulic parameters mathematically with acceptable degree of accuracy. There are recent literatures about contemporary real-life case studies of modeling techniques in water resource engineering (Wang et al. 2014; Gholami et al. 2015; Olyaie et al. 2015; Taormina et al. 2015; Chen and Chau 2016; Chau 2017).

All information obtained from the correlation between hydraulic and geoelectrical parameters is with respect to the granular aquifers, especially those of our country. Such aquifers consist of sand, gravel and/or sandy clay, with primary porosity to transmit groundwater due to the presence of inhered pores. All empirical relations extracted from those parameters described the prevailing conditions in such kind of aquifers.

But in the current study, there is another trend with respect to the fractured rock and karstified aquifers belonging to the Dammam Lst. Fn. This aquifer is characterized by an anisotropic property due to the presence of secondary porosity, which usually is associated with the fractures, bedding planes, and the limited occurrence of variable spaces.

Therefore, a complex underground drainage system will be constructed from an unorganized network of the water paths, which may enlarge due to the dissolution over time. So the agent control on the hydraulic behavior of such aquifers may vary, and create differences with those conditions governing the intergranular types.

This study is regarded as the first attempt in this discipline because it deals with a new subject that was not addressed by the previous studies in Iraq. Also to know more information about the correlation between hydraulic and geoelectrical parameters in such kind of aquifers, whole mathematical formulae of their empirical relationships are extracted.

Bahr Al-Najaf basin is located west and southwest of Najaf city and extends more than 40 km away (Fig. 1). It is a closed topographic depression at the eastern edge of the Western Desert, and has a total area of about 1200 km^2 with low hills (Al-Atia 2006). It generally occurs within two physiographic units, the first is the gypsiferious plain due to the presence of saline soils, and the second is the Pleistocene terraces as a result of occurrence of Tar Al-Najaf and the Mesas features (Al-Naqash 2002).The studied area covers 765 km^2 from this basin, and lies between longitudes 44°00ˉ–44°30ˉ East, and latitudes 31°40ˉ–32°05ˉ North (Fig. 2). The elevation ranges between 15 and 60 m above sea level and the gradient of the land is generally from
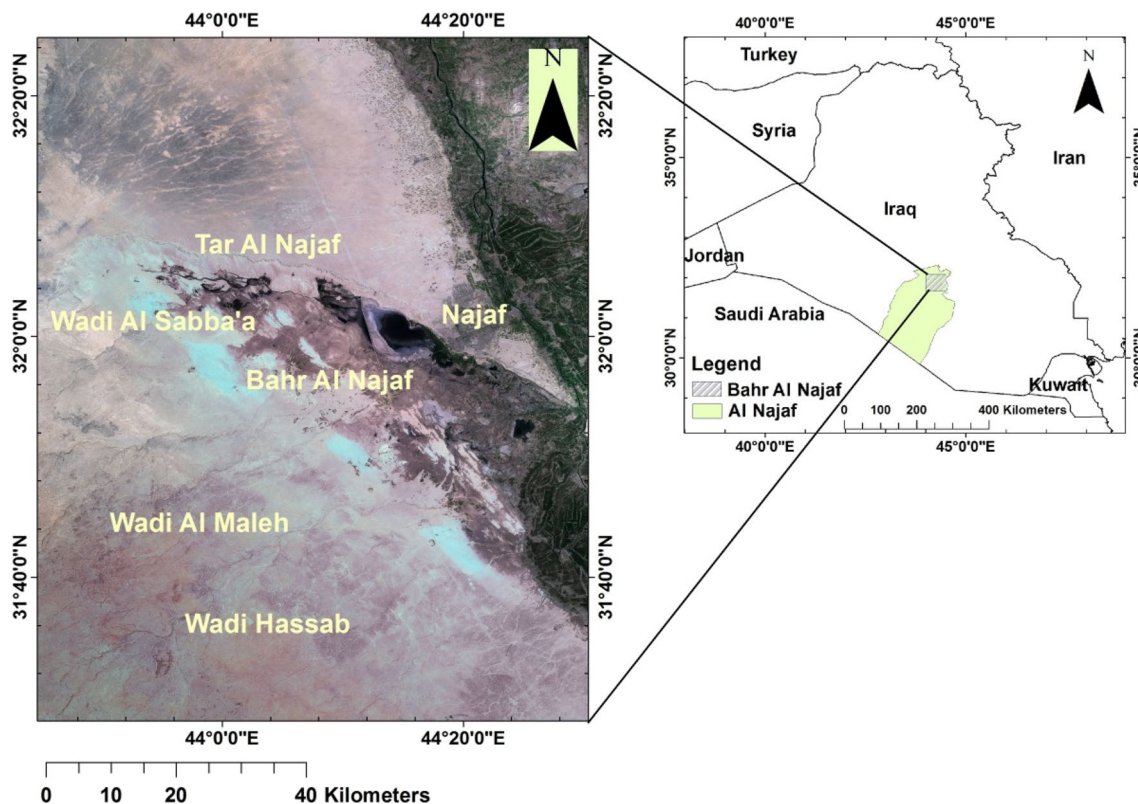

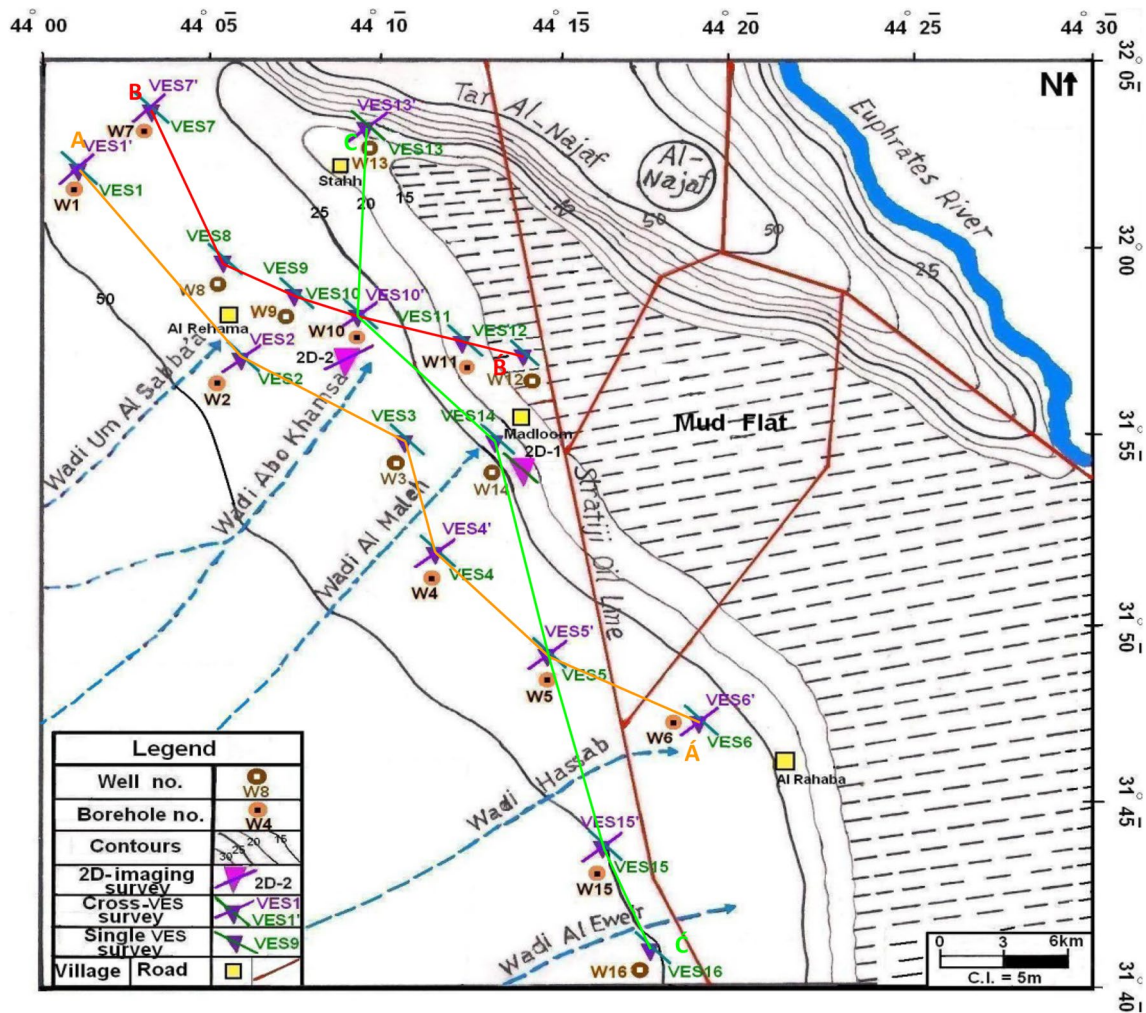**Fig. 1** Location view of the studied area by land sat imaging

Fig. 2 Shows the locations of VES,CVES,2D imaging stations, boreholes, wells, and three geoelectrical profiles (AA′, BB′, CC′) (Thabit et al. 2014)

SW towards NE, with a gentle slope as seen from the main direction of existing wadies. These wadies are running from the high regions in the desert to transport water towards Bahr Al-Najaf basin. This situation makes some eastern and northern parts of the studied area periodically contain amounts of water during numerous days of the year, and appear as marshes. These regions represent a low land covered with thick soil which is useful in growing certain plants. Otherwise, the western and southern parts of the studied area are stony, which is utilized as sources of building materials.

Bahr Al-Najaf basin has no results about its aquifer succession. However, there is some geoelectrical information and well-logging records in the surrounding regions made by GEOSURVY (1983), which helped to identify the lithological boundaries only, without any hydrogeophysical calculations.

The hydrogeological parameters of carbonate rocks and hard rocks, especially in karstified environments are very complicated, due to the nature of the hydrogeological system, as described for different regions throughout the world by many authors such as De Breuck (1991), Jones and Banner (2003), Vacher and Quinn (2004), Schneider and Kruse (2006), Kumar et al. (2014) and Thabit et al. (2014). So, this study is an attempt to extract empirical relationships between the hydraulic parameters and the geoelectrical properties of the fractured and karstified aquifers within Dammam Formation at Bahr Al-Najaf basin. To enhance the construction of a hydrogeophysical model, hydraulic parameters were calculated directly instead of using the conventional procedures of pumping tests, and most present wells are much far from each other and drilling new well needs great effort and high cost.

Geology of the studied area

Physiographically, the studied area lies within the gypsiferious plain and Pleistocene terraces units (Al-Naqash 2002). Several Formations of Tertiary period are exposed, but in some parts they are covered by the Gypcrete soils and other deposits. This study is concentrated on the Dammam Formation (M. and Up. Eocene), which is divided into three members of carbonate rocks (Buday 1980). An important part is the middle member consisting of fossiliferous dolomite and dolomitic limestone with interbedded layers of marl and cherty nodules in some depths (Al-Sayyab et al. 1982). It is characterized by fissures and paleokarst, so it becomes as a good groundwater-bearing layer of secondary porosity, with 4.77×10^{-5} storage coefficient (Al-Suhail 1996). The boundary of Euphrates Fault passes through the studied area (parallel to the Euphrates River approximately), and is regarded as part of Abu Jir Fault systems (Barazanji and Al-Yasi 1987).

Hydrology and hydrogeology

The study area is located within dry desert climate with little rainfall. The existing wells have artesian and self-flowing conditions with depths ranging between 60 and 200 m. The piezometric surface has an average depth of about 8 m below the ground surface. But, water level in the self-flowing type rises more than 1 m above the ground surface with high discharge during all days of the year. An important feature is the absence of mud content effect in this water, as observed from the purity of the groundwater (with no turbidity).

Topographic slope is usually coincident with the structural dip of the subsurface strata, which follows the normal stratigraphic column of Iraqi Desert, and Bahr Al-Najaf is a part of it (Lateef and Barwary 1984). Also, there is a subsurface pattern of flow due to infiltration of runoff water through near-surface fractures and joints at many areas. This is in addition to the underground drainage that comes from the huge regional aquifer.

Bahr Al-Najaf consists of a shallow poor aquifer of recent deposits and numerous confined aquifers of Miocene age. Electrical conductivity (EC) of shallow groundwater ranges between 5000 and 7000 μs/cm, with predominance of chloride water type, so it is an undesired source. The deep groundwater within the Dammam aquifer is of EC between 2500 and 3500 μs/cm with sulphatic water type, and regarded as desired one (Hassan 1973). Hard recrystallized Limestone forms the top of this aquifer and Rus Formation represents the bottom (Al-Rawi et al. 1983).

The hydraulic parameters of Dammam aquifer were calculated from pumping tests (Al-Suhail 1996; Al-Azawi 2009). The first found that the transmissivity is of an average value equals 870 m²/day, but the second found it with an average of 907.7 m²/day, in the deep penetrating wells. Obviously, these results seem high and close to each other. Also, this aquifer has a large thickness and the value of the storage coefficient reaches 4.77×10^{-5}, so it is hydrogeologically classified as confined type with relatively high piezometric pressure (Al-Suhail 1996). Its porosity is secondary due to highly fractured carbonate rocks with thr presence of paleokarst features (Jassim and Goff 2006).

Field work

Twenty five VES stations of 1D Schlumberger array are arranged along the three geoelectrical profiles (AA′, BB′, and CC′), to cover most parts of the studied area as much as possible (Fig. 2). The data are collected using SYSCAL pro+instrument. The VES stations are selected near productive wells. Maximum AB and MN spacing of array are 1000 and 160 m, respectively.

Schlumberger array is used because it is easy in the field measurements, and the measurements are more representative of the depth function (AB/2) as in Al-Ani (1998). In addition, several considerations may enhance the success of choosing Schlumberger array and VES technique in studying the deep aquifers: it can remove inhomogeneity effects from Schlumberger field curves, and the availability of many master curves to interpret those curves of VES.

Nine of the total numbers of the VES stations (1, 2, 4, 5, 6, 7, 10, 11, and 15) are measured as cross-vertical electrical sounding (CVES) surveys nearby the boreholes, to detect the heterogeneity of sediments. CVES is carried out in two perpendicular directions. The first one is in NW–SE direction, which is generally in the same direction of the strata. Whereas, the second is in SW–NE direction which represents the same direction of the strata dip as shown in Fig. 2. In this technique, resistivity measurements are taken along two perpendicular directions around fixed central point to determine the lateral variation of apparent resistivity values (Taylor and Fleming 1988). This variation may be caused by change in lithology (inhomogeneous sediments) and/or change in quantity and quality of the pore water (Steiench et al. 1997). In addition, if CVES survey is applied to homogenous and isotropic horizontal layers, the resulted curves will show no change in shape and type (Chandra et al. 2004). This method is accurate, easy and fast in detecting the heterogeneity of sediments.

Two stations of 2D imaging survey (2D-1 and 2D-2) are carried out using Wenner array along two profiles nearby stations VES10 and VES14 (Fig. 2). The profiles have lengths

of 390 m for each one, and electrode distances (a-spacing) equal to 10 m. Direction of the first profile is in NW towards SE, and the second is in NE towards SW.

2D survey is used because its measurements are very dense, so they gave a very approximate picture of geoelectrical zones. The results of 2D imaging display the lateral and vertical variations of resistivity and the thickness within each geoelectrical zone.

Wenner array was applied because of its sensitivity to vertical changes in resistivity. Also, it is (same as Schlumberger array) less affected by noise and has good strength in determining the investigation depth than the other electrode arrays. In addition, the Wenner array has better signal to noise ratio and easy in field measurements than Schlumberger array, although the latter has a better resolution (Dahlin and Loke 1998; Dahlin and Zhou 2001, 2004). It can use many types of electrode arrays such as Wenner–Schlumberger array but Wenner array is the best.

Data processing and interpretation

Data interpretation of VES survey

The field data of each VES station are interpreted by Ebert method (Orellana and Mooney 1966). We used this method because it is accurate and can interpret all type of field curves, and this method does not need large numbers of theoretical curves to interpret the field curves as in complete curve matching. Most field curves are of good quality types as shown in Fig. 3 of VES6. Also, the VES field curves were interpreted by IPI2win software (Moscow 2001) by application of forward calculation and inverse

modeling methods; this allowed us to accurately interpret the field curves. Its benefit is to calculate the values of the uncertainty in the resistivity and thickness for every layer of the field curve to draw the equivalent models, and then the values related with all processed curves that are used to calculate Dar-Zarrouk parameters and λ values.

There are many programs of interpretation, all have the same principle (theory) of interpretation, but we selected IPI2win because it is presumed that the user is an experienced interpreter in fitting the parts of the sounding curve to solve a geological problem. Targeting of geological result is a specific feature distinguishing IPI2win among other popular programs of automatic inversion (Bobachev et al. 2002). The program is also designed for presenting the interpreted results of several (VES) along unique geoelectrical profile in the form of pseudo-cross-section and resistivity cross-section.

Results of VES interpretation are used to construct three geoelectrical sections (AA′, BB′, and CC′). All these geoelectrical sections are calibrated with:

- Lithological sections of the nearby wells from the drilling reports provided by GEOSURVY (1983) and General Commission for Groundwater, G.C.G.W. (2010) with the well-log recordings about the surrounding regions of the studied area.
- Hydrogeological information from Al-Suhail (1996), Al-Azawi (2009), and water quality from Al-Hasnawi (2009).
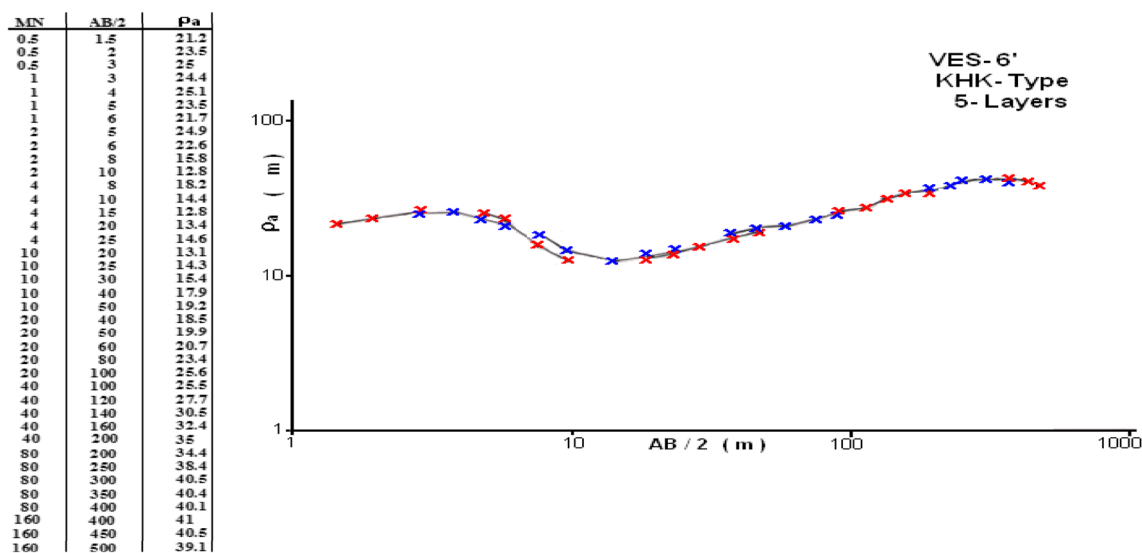- Structural characteristics concluded from Abdel Razak (1980) and Al-Saadi (2011) about the presence of local

Fig. 3 Field curve of VES6′ shows the good quality of field data

folding and faulting, as well as the extension of Abu-Jir fault system in the studied area.

- Current results of the inverse models of 2D-1 and 2D-2 imaging stations are also used to get more information about the karstified features, as cavities and sinkholes in upper part of Dammam Fn.

The geoelectrical sections with their geological sections are constructed in the same figure for every profile such as AA′ profile in Fig. 4; it shows four geoelectrical zones. The first represents the near-surface layers, that are made of caprock and/or the gypsiferious soil, which have thickness less than 10 m and resistivity values range between 20 and 300 Ωm due to obvious effect of the lateral heterogeneity in sediments. The second zone has an average value of resistivity equal to 14 Ωm, but differs beneath VES2 location (Rehaima region), where it reaches 31.8 Ωm; this region may be considered as a part of up-thrown block within Abu Jir faults zone (Abdel Razak 1980). This geoelectrical zone is correlated with Up. Dammam member mainly composed of marly and chalky limestone which is recrystallized in most parts. It

has cavities and sinkholes, which may be filled with saline groundwater with EC ranges between 5000 and 7000 µS/cm (Hassan 1973).This zone is separated from beneath geoelectrical zone by an impermeable thin layer of marl, which is clearly shown in inverted models of 2D-1 and 2D-2 stations (Fig. 4); this zone may be considered as aquitard unit as mentioned in Moore (2002).

The average value of resistivity within the third geoelectrical zone is 66.5 Ωm; this zone is located between two geoelectrical zones of low resistivities (Fig. 4). The lithological evidences of nearby wells 1, 4, and 6 indicate that the third zone is M. Dammam member that consists of fossiliferous dolomite and dolomitic limestone, and characterized by large paleokarst forming good groundwater paths (Jassim and Goff 2006). Therefore, this zone corresponds to the main aquifer. All artesian and self-flowing wells reach depths of more than 100 m generally, which agree with the detected depth of this zone.

The fourth zone represents the deeper geoelectrical zone in the section with average value of resistivity equal to 18.5 Ωm (Fig. 4). According to the drilling reports (Al-Suhail
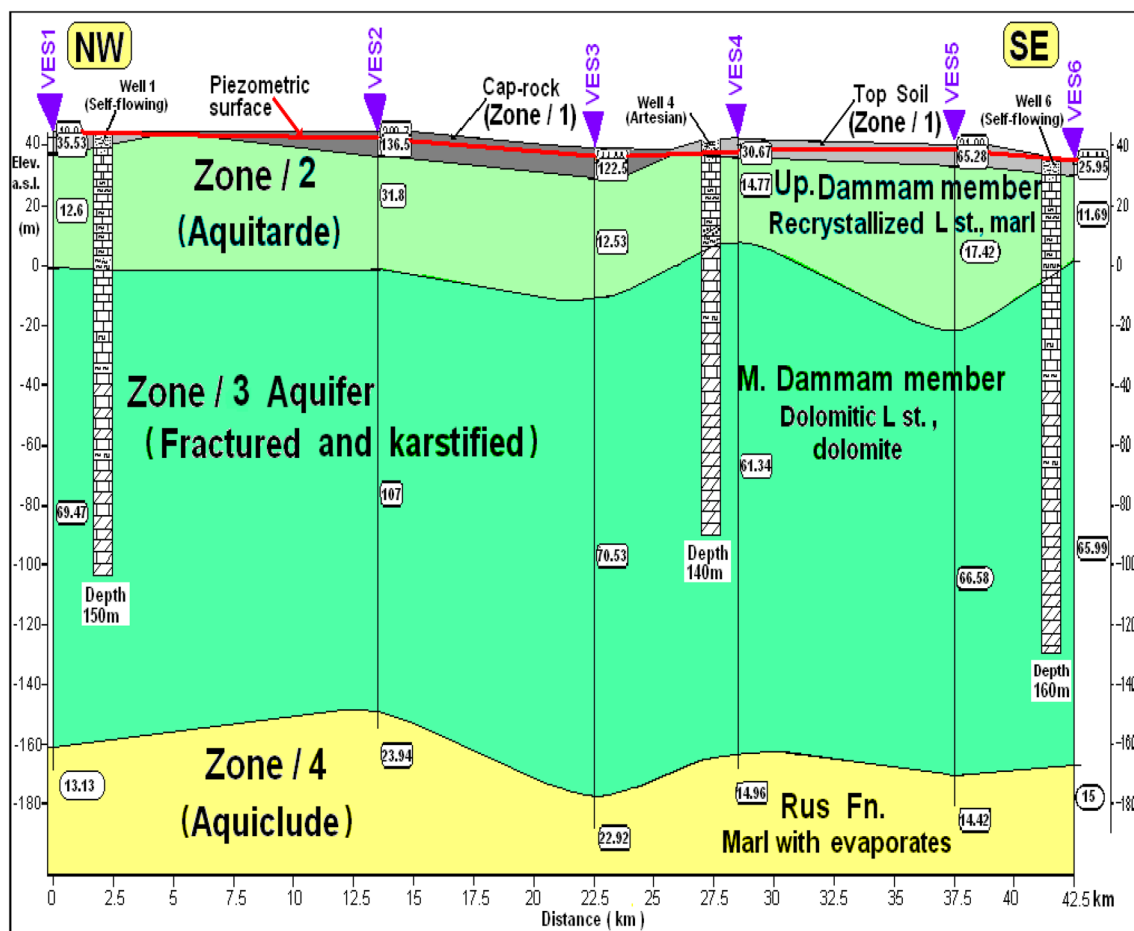

Fig. 4 Geoelectrical and geological sections along profile (AA′)

1996) and isopach map (Jassim and Goff 2006), the well of 200 m depth may totally penetrate Dammam Formation, depending on the appearance of grayish green shale, marl and evaporates. This refers to the end of Dammam Formation and the start of Rus Formation (Tamar Agha et al. 1997). Hence this zone acts as an aquiclude unit depending on its lithology, and constitutes a lower boundary of the main aquifer (zone three).

The other two geoelectrical and geological sections (BB′ and CC′) also show the same four zones with minor variations of thicknesses and resistivities. In addition, there are some variations in resistivity values due to the local up thrown causing increasing of resistivity more than the lowest parts (down thrown) as in the saturated regions. This area may be affected by many tectonic events which had led to form types of structural features such as the zone of Abu Jir faults with the up-thrown and down-thrown blocks (Abdel Razak 1980; Buday et al. 1987).

The results of nine CVES show that the sediments of the study area are homogeneous in properties (in vertical and horizontal distributions), because most of the field curves which belong to the same VES station have approximately similar shapes and types along two directions. But some of them are with less coincidence, especially in shallow parts, due to the presence of heterogeneity caused by cavities or variable salinity. Generally, the degree of similarity of the field curves reveals the similarity in lithology and thickness of aquifer. However, interpretation of CVES data is actually more complicated, as azimuthal variations in apparent resistivity are also produced by the presence of dipping stratigraphy and other lateral changes in Formation (Watson and Barker 1999).

Data interpretation of 2D imaging survey

The RES2DINV software (Geotomo software 2008) is used to interpret and create inverse models of measured data of the 2D stations. The purpose of this kind of survey is to know in detail the subsurface in the middle parts of the studied area, where there is an obvious emission of H_2S gas from some wells. Also, to determine the features which reflect the effects of deep subsurface structures performed by the tectonic events during a long time (Jassim and Goff 2006).

All the lithological sections of the drilled wells nearby 2D-1 and 2D-2 stations surveys are used as a reference for calibrating the results. The interpretations reveal the difference between two inverse models of the 2D imaging station as shown in Fig. 5. The high-resistivity layers over low-resistivity layers at lower section are reversed in the upper one. The reason is connected with the occurrence of surface water accumulations in Madloom location (upper section) due to its low topography relative to Ezia location (lower section).

Also, there is a presence of a deep fractured zone at about 60 m depth in Ezia location (Fig. 5). It may be the source of gas emission in this region and it may be the cause of the water saturation in the surrounding layers. Also, there is a thin impermeable layer as marl rock of Up. Dammam member which is repeated in the same depth separating two kinds of aquifers. This interpretation is verified by calibrating them with the lithological sections of Up. and M. Dammam members and observing of large variation between water salinities related to shallow and deep aquifers.

Hydraulic parameters of Dammam aquifer

The results of pumping tests in the studied area had been recorded by Al-Suhail (1996) and Al-Azawi (2009). They calculated the hydraulic parameters of Dammam aquifer (Table 1), from the field measurements of EC related with water samples of the present wells and boreholes. There is a certain modification in using the values of saturated thicknesses (h), which are extracted from interpretations of VES curves. New recovery tests on two further wells (W4 and W15) are recorded from the researchers, and added to the present boreholes with pumping tests results. Consequently, the total number of boreholes becomes nine.

The Dammam aquifer was hydrogeologically proved to be of confined type from all previous studies, and currently confirmed by determining it between two confining layers as shown in Fig. 4. The water level in boreholes represents the piezometric surface instead of water table; consequently it is difficult to identify upper and lower aquifer boundaries by any field methods. But, it can be determined only from the interpretation results of VES field curves according to resistivity contrast between the successive layers. Also, calculation of hydraulic conductivity (K) by Eq. (1) may differ from that of the previous studies. Whereas, the identification of the lower boundary of Dammam Fn. in Bahr Al-Najaf Basin is from geoelectrical and geological sections, enabling us to easily calculate the saturated thickness of M. Dammam aquifer correctly and also its hydraulic conductivities at any borehole with reasonable accuracy (Table 1).

The prediction of Dammam lower boundary is at an average of 200 m depth from the resistivity survey results. It coincides with the lithological section of deep well in the studied area (Al-Suhail 1996). Also, it is conformable with the thickness of Dammam Formation in the surrounding regions of the studied area, as shown in the isopach map of Jassim and Goff (2006). The average value of K in Dammam aquifer is calculated using Eq. (1) of Hantush (1964), which equals to 6.14 m/day. This value coincides with moderate to high category of K (with clean sandstone and fractured rock aquifers), as pointed in Groundwater Manual of the United States Department of the interior (Brassington 2007).
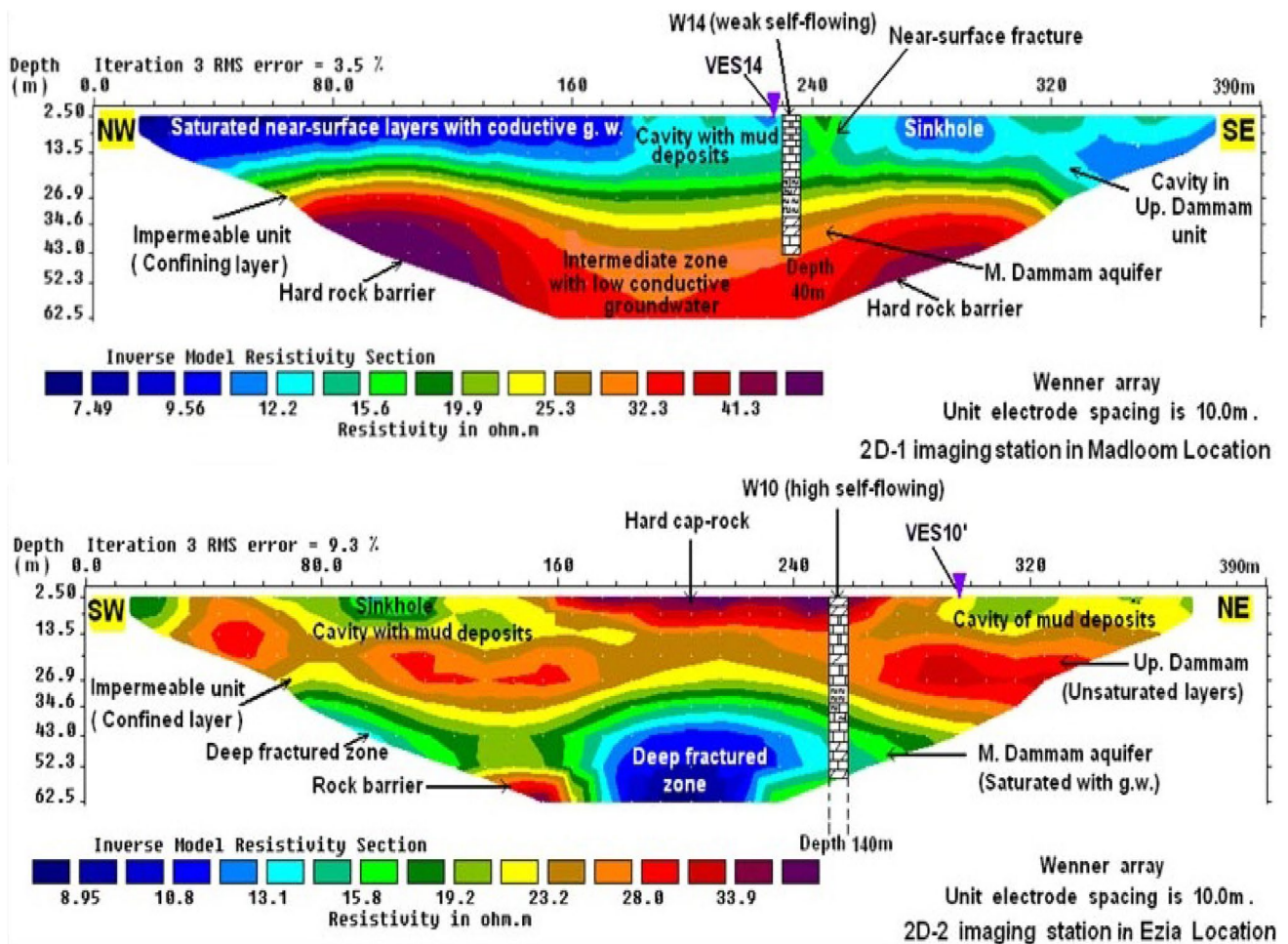
Fig. 5 Inverse models of 2D imaging stations at Madloom and Ezia locations

Table 1 Hydraulic parameters of Dammam aquifer obtained from the results of pumping tests of Boreholes

Bore hole no.	Depth (m)	Partial saturated thickness of Aquifer (m)	Transmissivity (T) m^2/day	Hydraulic conductivity (K) m/day	Electrical Conductivity (EC) µs/cm
W1	150	115	595	5.17	3000
W2	155	105	379	3.6	2750
W4	140	118	565.6	4.8	3000
W5	165	112	784	7.0	3250
W6	160	128.5	1092	8.5	2750
W7	150	119	600	5.0	3500
W10	140	112	995	8.65	3350
W11	150	115	1037	9.0	3700
W15	110	40	142	3.55	2750
Average	–	107.16	687.73	6.14	3116

$$T = K h, \tag{1}$$

where T is the transmissivity (m^2/day), K is the hydraulic conductivity (m /day) and h is the saturated thickness (m).

The concept of hydraulic conductivity (K) is a measure of aquifer ability to transmit the groundwater. It represents a quantitative expression and a function of both aquifer and water properties (Fetter 1980). As it is known that the mode

of electric conduction in this aquifer is essentially ionic one, so the electric current flows in same underground paths of the groundwater. This is due to their low resistance, so the observed resistivity values of an aquifer definitely refer to its water saturation and water quality.

Hydrogeophysical model of the main aquifer

To give a comprehensive view about the succession of the interpreted layers and the extension of the main aquifer, eight VES stations presented on the three geoeleectrical profiles (AA′, BB′, and CC′) as shown in Fig. 2 are selected to construct a fence diagram of hydrogeophysical model of the main aquifer (Fig. 6). They show that the third geoelectrical zone seems to be the main aquifer, it has a uniform lithology of unchanged and saturated thickness equals nearly to 160 m for the large distances, with average resistivity equals to 70 Ωm approximately. This is confirmed from the drilling depth (more than 100 m) of the productive wells, which have high discharges.

This aquifer belongs to M. Dammam member which consists of fossiliferous dolomite and dolomitic limestone

verified from the correlation between the geoelectrical models of VES and lithological sections of the existed wells (in geoelectrical and geological sections). The aquifer is of confined type bounded from the upper side by impermeable marl layer, with a low average resistivity equals to 19 Ωm within Up. Dammam member. While the lower boundary of aquifer is limited by the top of Rus Fn. at depth 200 m approximately, with a low resistivity of 20 Ωm. Decreasing resistivity is due to the layers of gypsum and marl of Rus Formation. In addition, this figure shows Abu Jir faults, the main extensions of aquifer, and flow direction of the groundwater in M. Dammam member. The water quality is clean and slightly brackish with an average *EC* of about 3116 μs/cm or the average ground water resistivity (ρ_w) equals to 3.21 Ωm, as measured in most water samples of boreholes (Table 1).

In addition, from the hydrogeophysical model (Fig. 6), there is an exception in determining the aquifer saturated thickness and the depth to the Rus Fn., exactly under the location of VES13. This may be due to the main dip of water-bearing layers from the SW towards the NE and E. This conclusion is coincident with the known direction of strata dip in this area, as mentioned in the geologic
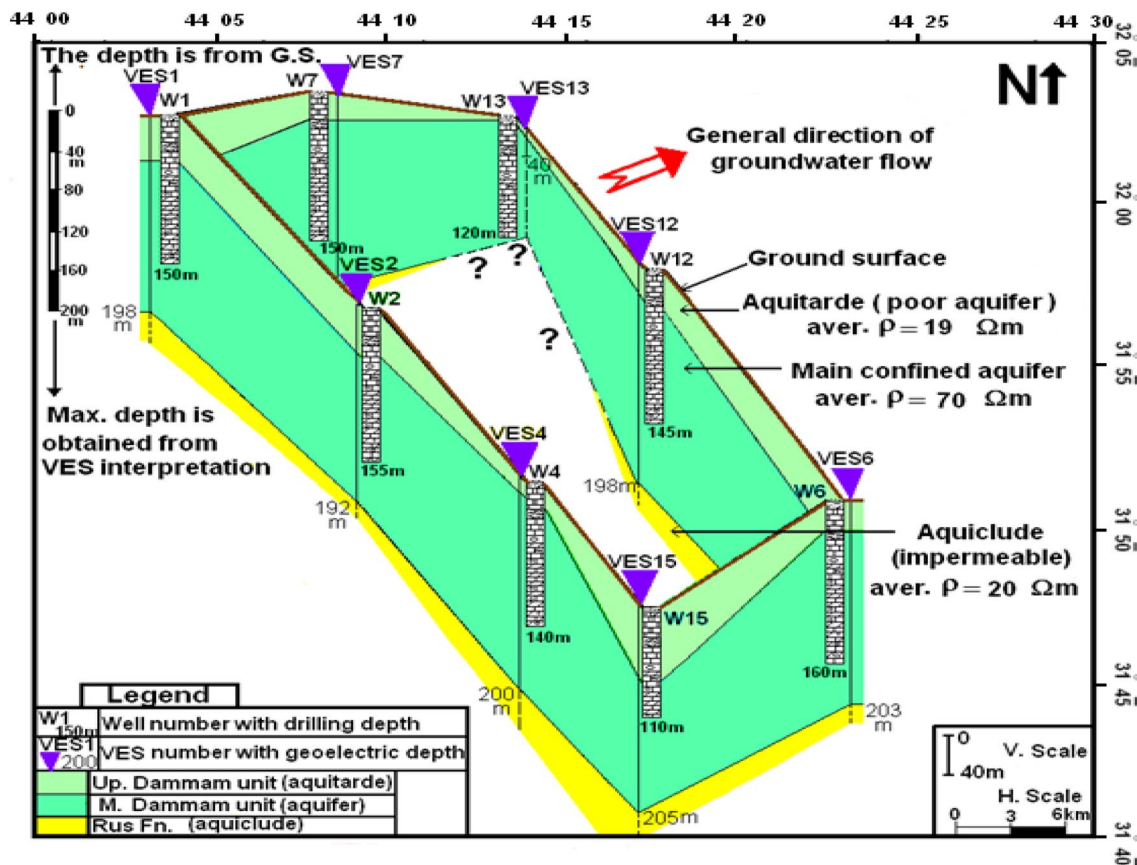

Fig. 6 Fence diagram constructed from the results of eight VES stations shows a hydrogeophysical model of the main aquifer

cross-section (Barwary and Nasira 1996). Topographically, the location of VES13 represents the lowest portion to accumulate the surface saline waters. Hence there is a clear corresponding between the surface slope and the structural dip of strata, which makes the flow of surface wadies and groundwater almost in the same direction, from the SW towards the NE and E.

Geoelectrical properties of Dammam aquifer

The geoelectrical properties of each geoelectrical zone may be described by five parameters that represent the most important of Dar-Zarrouk Parameters (Maillet 1947). They were derived on the bases of resistivity (ρ_i) and thickness (h_i) of the geoelectrical zone. Therefore, the Dar-Zarrouk parameters related to the nine VES stations are calculated and listed in Table 2.

Dammam aquifer porosity

The ground water resistivity (ρ_w) Ωm represents the reciprocal of the measured electrical conductivity (EC) μs/cm of the water samples from boreholes, which are listed in Table 1.

The aquifer resistivity (ρ_o) Ωm is estimated from the interpreted results of nine VES stations and shown in Table 2. The Formation factors (F) of Dammam aquifer are calculated according to the equation of Archie's law (1942) and listed in Table 3.

$$F = \rho_o / \rho_w. \tag{2}$$

The advantage of the above calculations is to find an average value for the effective porosity in M. Dammam aquifer by applying Archie's equation. The reason is to evaluate the water storage for the purpose of the water management. Most common requirements to apply the above equation are available:

Table 2 Geoelectrical characteristics with Dar-Zarrouk parameters of Dammam aquifer extracted from data of nine VES

VES no.	Aquifer resistivity (ρ_o) Ωm	Aquifer saturated thickness (H) m	Transvers resistance (T_r) Ωm^2	Longitudinal conductance (S_L) Ω^{-1}	Transverse resistivity (ρ_t) Ωm	Longitudinal resistivity (ρ_l) Ωm	Anisotropic factor (λ)
VES1	69.47	152.6	11323.90	5.41	57.19	36.30	1.25
VES2	107.0	141.8	17892.38	2.69	93.14	71.41	1.58
VES4	61.34	178.3	11278.67	4.23	56.39	47.82	1.08
VES5	66.58	145.0	11447.45	5.00	55.30	41.40	1.15
VES6	65.99	171.6	11742.92	5.00	57.84	40.60	1.19
VES7	64.46	168.9	11182.56	4.00	56.00	50.00	1.05
VES10	45.21	182.7	8570.86	6.92	40.81	30.34	1.15
VSE11	40.25	163.2	7100.03	6.65	35.75	30.00	1.09
VES15	111.1	135.3	18289.74	2.80	88.95	73.42	1.10
Average	70.15	160.93	12092.16	4.75	60.15	46.81	1.18

Table 3 Porosity values of M. Dammam aquifer, which are calculated using Archie's law

VES no.	Electrical conductivity (EC) μs/cm	Aquifer resistivity (ρ_o) Ωm	Ground water resistivity (ρ_w) Ωm	Formation factor (F)	Porosity ($\varphi\%$)
VES1	3000	69.47	3.33	20.86	22.0
VES2	2750	107.0	3.63	29.47	18.5
VES4	3000	61.34	3.33	18.58	23.0
VES5	3250	66.58	3.07	21.68	21.5
VES6	2750	65.99	3.63	18.17	23.5
VES7	3500	64.46	2.85	22.61	21.0
VES10	3350	45.21	2.98	15.17	25.7
VSE11	3700	40.25	2.70	14.90	25.9
VES15	2750	111.1	3.63	30.60	18.0
Average	3116	70.15	3.21	21.34	22.0

1. The saturated thickness of confined aquifer as seen by most existing wells of self-flowing and artesian types with high discharges.
2. The absence or very little clay content (Al-Hasnawi 2009), which is confirmed by the purity (without or with very low turbidity) of the water samples related to most wells in the studied area. In addition, the Dammam aquifer mainly consists of dolomitic limestone. So, the effect of clay content in the Dammam aquifer is neglected.
3. Little mineralization of the water of the Dammam aquifer depending on the EC (an average value equal to 3116 μs/cm or the average ρw equals to 3.21 Ωm) of groundwater of the existing boreholes due to their slightly brackish water type, according to Todd (1980).

So the porosity ($\varphi\%$) is calculated using an empirical relationship of Archie (1942, 1950) as follows:

$$\emptyset^m = \frac{a}{F} \ \text{ or } \ \emptyset = \sqrt[m]{\frac{a}{F}} \ \text{ and } \ \emptyset\% = \sqrt[2]{\frac{1}{F}} \times 100, \tag{3}$$

where a and m are constants related to the lithology (m is the cementation factor and a is a function of pore geometry), and assumed as (1) and (2), respectively, for most types of carbonates, depending on the types of carbonate rocks (Hill and Milburn 1956; Carothers 1968; Schon 1983).

The calculated average porosity value in Dammam aquifer by applying Archie's equation is 22.00% (Table 3). It is close to the $\varphi\%$ values of fractured dolomite and limestone that equal to 25 and 30%, respectively, which are pointed out in Younger (1993).

The calculated value of average electrical conductivity (EC) of the groundwater is 3116.6 μs/cm (Table 3) and it represents groundwater of slightly brackish quality (the final EC value represents average of all water samples of the presented wells and boreholes in the studied area). This value is corresponding to the average value 3265 μs/cm of maximum range of dry period (Al-Hasnawi 2009). In addition, the average value of aquifer resistivity that equals to 70.15 Ωm is conformable with typical average of the saturated limestone.

The water saturation (S_w) of the Dammam aquifer is calculated using the average values listed in Table 3, and by applying the following expression:

$$S_w = \sqrt[2]{\frac{F\rho_w}{\rho_o}} = \sqrt[2]{\frac{\rho_o}{\rho_w} \times \frac{\rho_w}{\rho_o}} = 1 \text{(approximately)}. \tag{4}$$

The S_w of this aquifer may be used to evaluate the aquifer realistic storage for the future water management in this area due to the permanent need of the groundwater. Also, Table 2 shows the average value of λ which equals to 1.18. This may reflect uniform condition in both; the main lithological sequence of dolomitic limestone and the main aquifer of comprehensive water saturation is confirmed by occurrence of many wells of high discharge. This visibility is due to the effects of the presence of the bedding planes and the random fracture networks which play as good water paths in such aquifer.

Relation between the hydraulic parameters and geoelectrical properties

Generally, the study of water-bearing layers indicates that the ρo (Ωm) is controlled by the porosity and ρ_w (Ωm) more than the resistivity of the rock matrix (Archie's law). So, ρ_o (Ωm) should reflect the nature of the K (m/day) of water-bearing layers, and the EC through the water content and along the interfaces between different layers (Niwas and Singhal 1985). The shape of the relation in most types of aquifers is nonlinear (exponential, logarithmic, polynomial, or hyperbolic) and rarely is linear (Chandra et al. 2008). The reason is related to the common effect of heterogeneity (variation of composition with directions) and the anisotropy (variation of hydraulic conductivity with directions) which may govern most aquifers. Singh and Singh (2016) found a linear relationship of three geological formations of different lithology.

In addition, in the current study, the Dammam aquifer is distinguished by low effect of clay content, because it mainly consists of dolomitic limestone. Also the presence of purity with all water samples may verify the leaching dissolution canals by the underground drainage along a large time. Because of these reasons and other field evidences, the effect of clay content in the Dammam aquifer is neglected here.

In all established relationships between pumping test results and Dar-Zarrouk parameters, the interested goal is in extracting some empirical formulae to estimate unknown hydraulic parameters directly. Numerous authors such as Niwas and Singhal (1981, 1985) and Mazac et al. (1985) tried to derive the mathematical relations from hydraulic and geoelectrical parameters, using Ohm's law of current flow and Darcy's law of horizontal fluid flow in a medium. Frohlich and Kelly (1985) showed a direct empirical relation between K (m /day) and T_r (Ωm²). Mazac et al. (1985) studied the factors influencing the relations between electrical and hydraulic prosperities of aquifers and aquifer lithology. Frohlich et al. (1996) studied the relationship between K (m /day) and ρ_o (Ωm) in fractured crystalline bedrock of Rhode Island. A reverse proportionality between them has been found. This result coincides with the theoretical calculations of Heigold et al. (1979), Brown (1989) and Mazac et al. (1990).

These relations represent inverse and direct relationships between electrical resistivity and hydraulic conductivity. Niwas et al. (2011) solved the contradiction between direct and inverse relationships of electrical resistivity and hydraulic conductivity. Niwas and Celik (2012) concluded that the estimation of hydraulic conductivity values from VES data and those determined from pumping test are strongly correlated.

Relations of material properties between hydraulic and geoelectrical parameters

The first relation is drawn between the calculated $\varphi\%$ using Archie's empirical formula, and the ρ_o (Ωm) obtained from quantitative interpretation of VES as shown in Fig. 7. The resultant relation is an inverse proportionality and has a linear correlation with a strong reliability or correlation coefficient ($R^2 = 0.902$). The mathematical formula of this linear equation is written as:

$$\varphi = -0.104\rho o + 29.41. \tag{5}$$

Therefore, $\varphi\%$ of M. Dammam aquifer can be directly calculated from the surface measurements of resistivity values. The inverse proportional relation between $\varphi\%$ and ρ_o (Ωm) is considered as a logical resultant in such kind of aquifers. The secondary porosity (formed by fissuring and/or the solution processes) develops with time, and the final case is the saturated fractures. In other words, increasing of secondary porosity implies a further S_w in the aquifer, which equals to 1 approximately with decreasing of the ρ_o (Ωm) and vice versa. The present results are conformable with those of previous researchers such as Mazac et al. (1990) and Frohlich et al. (1996). There is an inverse relationship between $\varphi\%$ and ρ_o (Ωm) of the consolidated aquifers, which are always controlled by occurrence of fractures.

The second relation is constructed between the ρ_o (Ωm) and the hydraulic conductivity (K_p m/day) estimated from the pumping test (Fig. 8). The relation is an inverse proportionality and has a linear correlation with a good reliability (R^2) equals to 0.737. The negative slope confirms the prediction of condition in M. Dammam aquifer that the presence of a lot of saturated fractures leads to decrease the values of ρ_o (Ωm) and consequently increase K_p (m/day) values. This relation is mathematically expressed as a linear equation of first order, and can be used to calculate K of aquifer directly using the following formula:
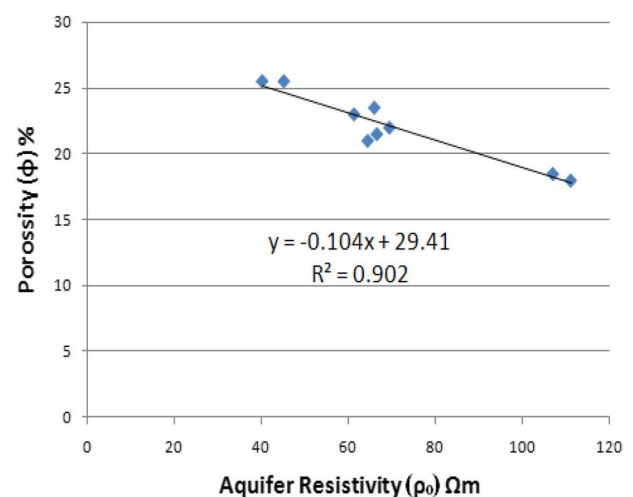
$$K = -0.070(\rho_o) + 10.84. \tag{6}$$

The physical relation between K and ρ_o has a direct correlation in some studies and inverse in others. Khalil and Santos (2009) studied the effect of degree of groundwater saturation in the relation between K and ρ_o. They found that the relation is generally nonlinear of inverse or direct polynomial relation between them depending on the degree of saturation of aquifer. An inverse relation when the degree of saturation of aquifers is higher than 50%. But, in this study the relation assumed a linear one and it seems to be mathematically more reliable. Because, we could easily fit a linear equation to the data instead of nonlinear that will give misleading results for high ρ_o, especially for hard rocks.

The necessary task is to test the results of the graphical presentation to get more confidence on the use of such approach in acquiring acceptable precision. To fulfill this purpose, a comparative process is done between the field measurements of the pumping tests with that of theoretical estimation by the mathematical (correlated) equations. Values of hydraulic conductivity estimated by the pumping tests are compared with that calculated directly by Eq. (6). The average values of them are also calculated with their ratio of root mean square error (RMS %), which equals to 4.5%

Fig. 7 Relation between the calculated porosity ($\varphi\%$) using Archie's law and aquifer resistivity (ρ_o) Ωm of M. Dammam aquifer

Well no.	$\varphi\%$	ρ_o (Ωm)
W 1	22.0	69.47
W 2	18.5	107.00
W 4	23.0	61.34
W 5	21.5	66.58
W 6	23.5	65.99
W 7	21.0	64.46
W10	25.5	45.21
W11	25.5	40.25
W15	18.0	111.10

y = -0.104x + 29.41
$R^2 = 0.902$

Aquifer Resistivity (ρ_0) Ωm

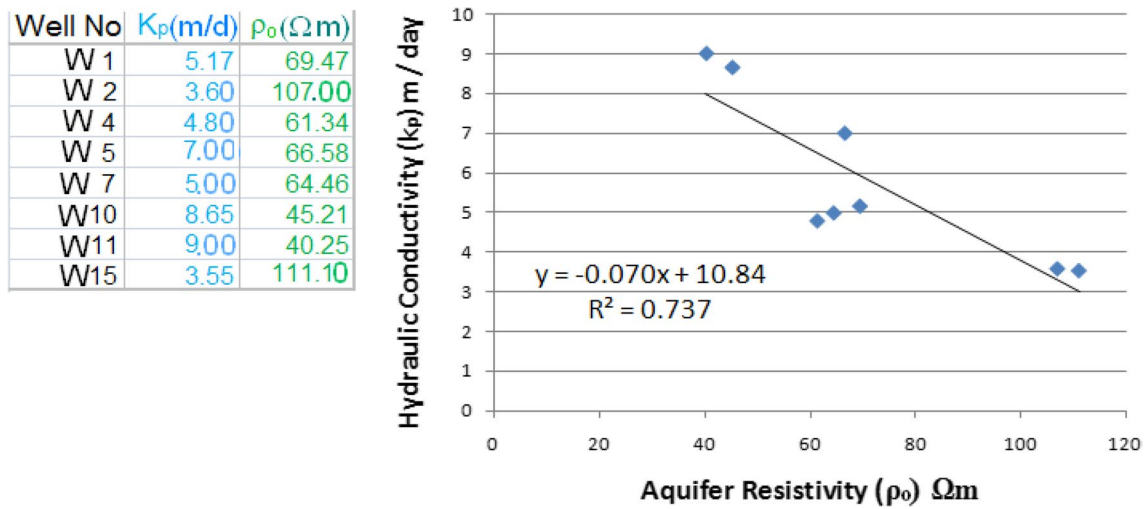| Well No	K_P (m/d)	ρ_o (Ωm)
W 1	5.17	69.47
W 2	3.60	107.00
W 4	4.80	61.34
W 5	7.00	66.58
W 7	5.00	64.46
W10	8.65	45.21
W11	9.00	40.25
W15	3.55	111.10

$y = -0.070x + 10.84$
$R^2 = 0.737$

Fig. 8 Relation between the hydraulic conductivity (K_p) m/day and aquifer resistivity (ρ_o) Ωm of M. Dammam aquifer

that means there is a large agreement between them and may emphasize the potential of this approach.

Relations of layer properties between hydraulic and geoelectrical parameters

Two relations are constructed between transmissivity (T) m²/day estimated by pumping test and Dar-Zarrouk parameters as transverse resistance (T_r) Ωm² and longitudinal conductance (S_L) Ω^{-1} obtained from the interpretation results of VES data.

First relation between T (m²/ day) and T_r (Ωm²) is shown in Fig. 9. It shows a relation of an inverse proportionality and a linear correlation with the correlated equation of first order and a strong reliability ($R^2 = 0.862$) as written below:

$$T = -0.069 \left(T_r\right) + 1482 . \tag{7}$$

This relation of R^2 (0.862) approximately equals to $R^2 = 0.890$ of a nonlinear equation for the same data calculated in Thabit et al. (2014). Also, the results of Singh and Singh (2016) show a linear relationship between T (m²/ day) and T_r (Ωm²).

The second relation is between T (m²/day) and S_L (Ω^{-1}). Figure 10 shows a direct proportionality and a linear correlation with the correlated Eq. (8) of first order and a strong reliability ($R^2 = 0.868$). This R^2 equals nearly to $R^2 = 0.867$ of a nonlinear equation which is also calculated in Thabit et al. (2014). In addition, this is consistent with linear
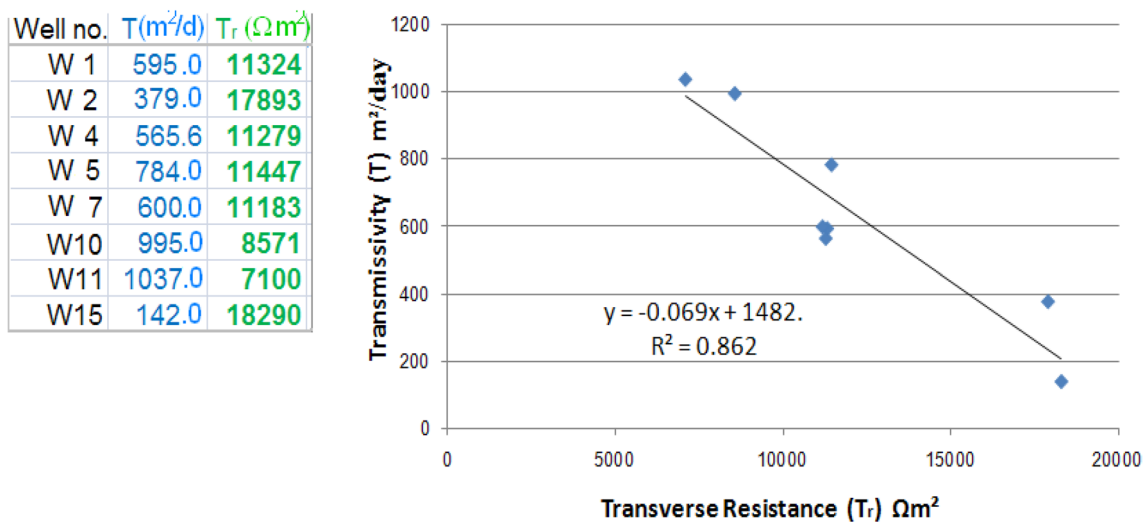
Well no.	T (m²/d)	T_r (Ωm²)
W 1	595.0	11324
W 2	379.0	17893
W 4	565.6	11279
W 5	784.0	11447
W 7	600.0	11183
W10	995.0	8571
W11	1037.0	7100
W15	142.0	18290

$y = -0.069x + 1482.$
$R^2 = 0.862$

Fig. 9 Relation between transmissivity (T) m²/day and transverse resistance (T_r) Ωm²

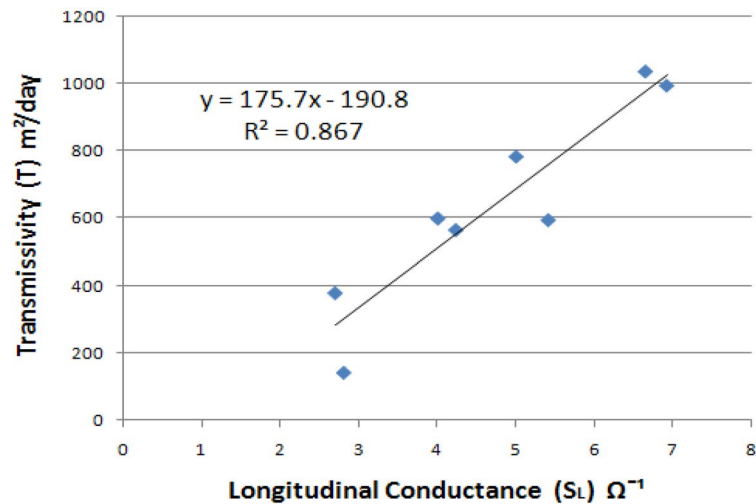| Well no.	T(m^2/d)	S$_L$(Ω^{-1})
W 1	595.0	5.41
W 2	379.0	2.69
W 4	565.6	4.23
W 5	784.0	5.00
W 7	600.0	4.00
W10	995.0	6.92
W11	1037.0	6.65
W15	142.0	2.80

Fig. 10 Relation between transmissivity (*T*) m^2/day and longitudinal conductance (*S*$_L$) Ω^{-1}

relationships of ρ_w (Ωm) with *K* (m/day) and S_L (Ω^{-1}) with *T* (m^2/day) of hard rocks aquifers (Chandra et al. 2008).

$$T = 175.7\,(S_L) - 190.8. \qquad (8)$$

In the current study, the relations between *T* (m^2/day) with both T_r (Ωm^2) and S_L (Ω^{-1}) are expressed as linear equations instead of nonlinear. Because we believe that the used second-order polynomial to fit the data is a poor choice. The slope of this function reverses at higher resistivity, and this will give an erroneous interpretation. It will predict that transmissivity increases at high resistivity, for example, which is unlikely. Most of the plots could be fit with a linear relationship nearly as well as the second-order polynomial, and it would be difficult to justify using the second-order polynomial based on R^2 if the uncertainty in the data was considered.

The correlation between the layer properties as between *T* (m^2/day) and both Tr (Ωm^2) and S_L (Ω^{-1}) reveals the similarity in lithological characteristics of Middle Dammam aquifer, since they have approximately the equal values of a strong reliability (R^2) of correlation in Eqs. (7 and 8) but with an inverse and a direct proportionality, respectively. So, the first relation supported the other. This may coincide with the nature of the studied area as a discharge zone, which has a good φ of 22% and a high S_w of 1 approximately. Therefore, the equations above can be used directly to calculate the *T* (m^2/day) value mathematically.

But, the extracted relationship between *T* (m^2/day) and S_L (Ω^{-1}) seems to be an important one (a relation of direct proportionality). So, this relationship can obviously reveal the realistic case about the correlation between the related parameters, while other relations can play an assistant role in supporting the final results. The principal concept is based on the fact that the easier travel of injected electric current

occurs through groundwater paths. Therefore, the relationship between S_L (Ω$^{-1)}$) and *T* (m^2/day) could be demonstrated relaying on the direct connection. That means the measure of low resistivity is due to the occurrence of high saturated fractures.

In addition, the comparative processes are done between the field measurements of the pumping tests with that of theoretical estimation by the mathematical (correlated) equations. Values of transmissivity estimated by the pumping tests are compared with that estimated by Eqs. (7) and (8). The average values of them are calculated with their RMS % errors which equal to 6 and 7%, respectively. Accordingly, they have a large agreement because of the small values of RMS % between them, which may also emphasize the potential of this approach.

Discussion

The authors have only one article in the same study area, the similarity between this study and the current study only in the relation between *T* (m^2/day) and both T_r (Ωm^2) and S_L (Ω^{-1}) was a nonlinear calculated with polynomial equation of second order, but in the current study the relations were linear between *T* (m^2/day) and both T_r (Ωm^2) and S_L (Ω^{-1}). Because we believe that the use of second-order polynomial to fit the data is a poor choice. The slope of this function reverses at higher resistivity, and this will give an erroneous interpretation. It will predict that transmissivity increases at high resistivity, for example, which is unlikely. Most of the plots could be fit with a linear relationship nearly as well as the second-order polynomial, and it would be difficult to justify using the second-order polynomial based on R^2 if the uncertainty in the data was considered. In addition, the

comparison between linear and nonlinear equations of T (m²/day) and T_r (Ωm²) and T (m²/day) with S_L (Ω⁻¹) appeared to have a little divergence of R^2 equal to 0.028 and 0.001, respectively.

As it is illustrated in many places, the main aim of such kind of studies is to estimate the aquifer's hydraulic parameters from the surface resistivity data, by means of graphical presentation that relates the hydraulic and geoelectrical parameters as several mathematical equations with strong reliability (R^2) extracted to calculate the hydraulic parameters (T and K) directly.

In this study, all relations are mathematically expressed as linear equations instead of nonlinear relations that will give misleading results for high ρ_o, although there is no significant difference between them in reliability (R^2). We found that it is more acceptable to apply mathematics for hard rocks of confined aquifer with a full saturation thickness of clean water. This is consistent with linear relationships of ρ_w (Ωm) with K (m/day) and S_L (Ω⁻¹) with T (m²/day) of hard rock aquifers (Chandra et al. 2008), and with the linearity result between T (m²/day) and T_r (Ωm²) of different formations in Singh and Singh (2016). In addition, the comparison of the relation between T (m²/day) and T_r (Ωm²), and the relation between T (m²/day) and S_L (Ω⁻¹) for both linear and nonlinear relationships appeared to have a little divergence of R^2 equal to 0.028 and 0.001, respectively; the nonlinear equations are calculated in Thabit et al. (2014). In the previous studies, the researchers attempted to find many correlations between these parameters, some of them are not logical when they are mathematically treated especially in full saturated aquifers.

This study indicates that the S_L (Ω⁻¹) is affected by the main aquifer thickness, which is regarded as unchanged factor against other variable factors such as the ρ_o (Ωm) and K (m/day). So, the relation between T (m²/day) and S_L (Ω⁻¹) is the better in the mathematical treatment for using to calculate the unknowns directly. Therefore, Eq. (8) is considered better to be used. Practically, T represents a rate of the horizontal groundwater flow through a vertical strip of aquifer, and the interest of this parameter is from its proportion with the production which is yielded by the pumping wells. So, the larger transmissivity (T) means the larger hydraulic conductivity (K) and the aquifer thickness (H).

The equality of strong reliability in values of the correlated Eqs. (7 and 8) may refer to the similarity between averages of the resistivities in the vertical and horizontal directions of Dammam aquifer. In addition, the average value of anisotropy factor (λ) which is calculated from the result of (9) VES stations nearby the boreholes is equal to 1.18, and the high degree of water saturation (S_w) is equal approximately to 1. These reasons may reflect the uniform conditions in both; the main lithological sequence of dolomitic limestone and the main aquifer of comprehensive water saturation which are confirmed by the occurrence of many wells of high discharge. This visibility is due to effects of the presence of the bedding planes and the random fracture networks which play as good water paths in such aquifer.

To give a total vision of the subsurface features and extension of the main aquifers, all results of VES, 2D imaging, hydrogeophysical model, lithological sections of the nearby wells and the types of the graphical relationships between hydraulic and geoelectrical parameters are used to give more knowledge about the subsurface structures and features from enhanced hydrogeophysical model (Fig. 11). It is showed that the extension of the main aquifers depends on the hydrogeophysical model in Fig. 6. Also, the main trend of groundwater flow in M. Dammam member is from SW towards NE, which is conformable with the slope direction of ground surface (in the strata dip direction which is determined by the continually decreasing of resistivity values). In addition, the increase in the occurrence of many self-flowing wells with high discharge and number of uninhabited springs are in the same direction. This may be affected by the expected Abu Jir fault which appears near VES4. The enhanced hydrogeophysical model has a great significance in managing the large aquifer of M. Dammam for better future water supply in Bahr Al-Najaf Basin.

The main aquifer has a uniform lithology of unchanged and saturated thickness for the large distances, with average resistivity of about 70 Ωm. This is confirmed from the drilling depth (more than 100 m) of the productive wells, which have high discharges. The water quality is of slightly brackish with average (EC) of about 3116 μs/cm), as calculated in most water samples collected from boreholes. This aquifer belongs to M. Dammam member, which is verified from the correlation between the geoelectrical models and lithological sections of the existed wells. The aquifer is of confined type bounded from the upper side by impermeable marl layer, with low average resistivity (19 Ωm) within Up. Dammam member while the lower boundary of aquifer is limited by the top of Rus Fn. at depth equal to 200 m approximately, with low resistivity of 20 Ωm. Decreasing resistivity is due to the layers of gypsum and marl of Rus formation. In addition, this figure shows Abu Jir faults, the main extensions of aquifer, and flow direction of the groundwater in M. Dammam member.

Depending on the enhanced hydrogeophysical model (Fig. 11) and the types of the graphical relationships between hydraulic and geoelectrical parameters, the extracted relationship between S_L (Ω⁻¹) and T (m²/day) is the important one. So, this relationship can obviously reveal the realistic case about the correlation between the related parameters, while other relations can play an assistant role for supporting the final results. The principal concept is based on the fact that the easier travel of injected electric current occurs through groundwater paths. Therefore, the relationship
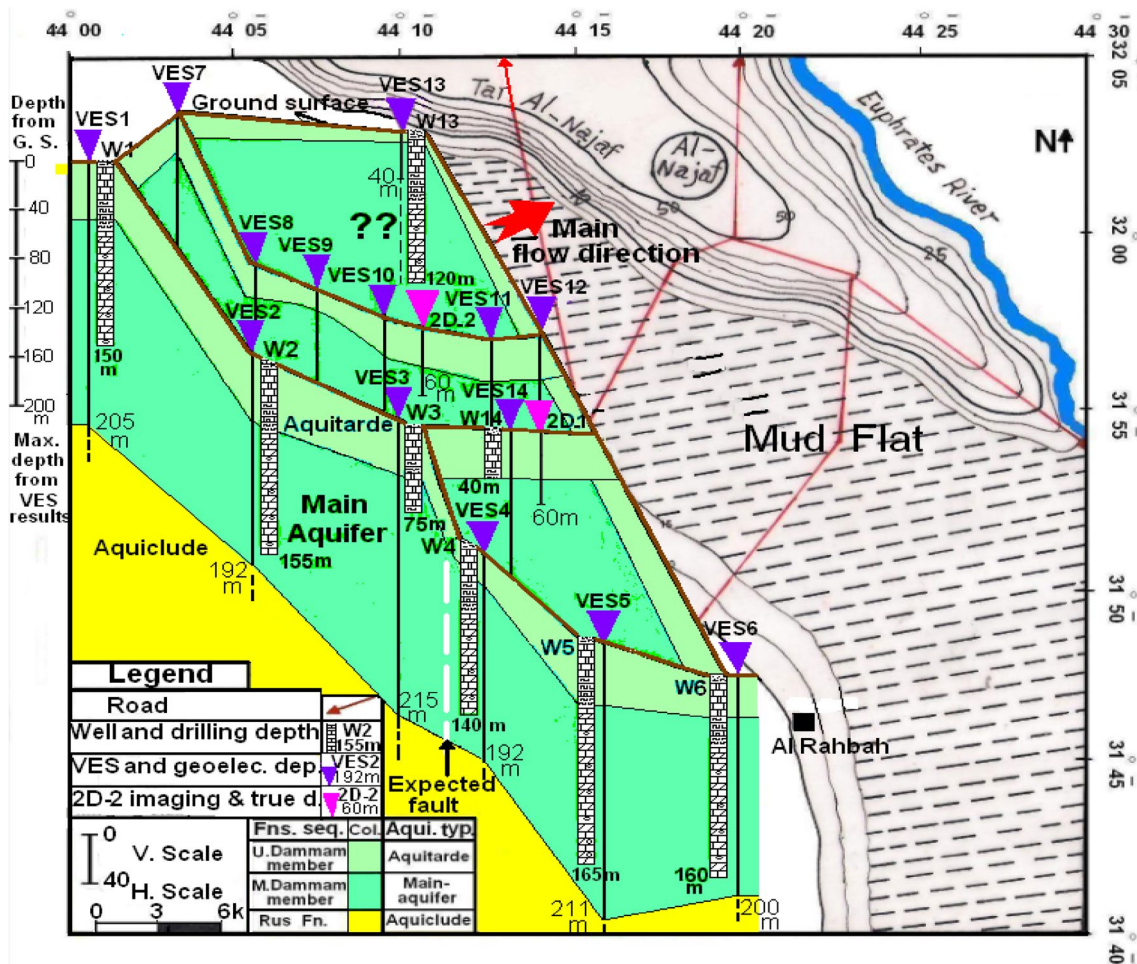
Fig. 11 Enhanced hydrogeophysical model with the map of the studied area shows the subsurface features and extension of the main aquifers; northern and eastern parts are considered as discharge regions of Maanyia hydrogeological basin

between S_L (Ω^{-1}) and T (m²/day) could be demonstrated relaying on the direct connection. That means the measure of low resistivity is due to the occurrence of high saturated fractures.

There is little or no effect of clay content in most parts of M. Dammam aquifer, which is clearly deduced from the high purity (almost without turbidity) in all water samples of the boreholes.

Depending on all considerations mentioned above, a wide validity is present for applying Archie's equation to calculate the porosity of M. Dammam aquifer. Therefore, a new estimation of the porosity is operated with an average value of 22%. The water saturation of aquifer is calculated as a value equal approximately to 1, which may be used for evaluating the aquifer realistic storage for the future water management, in this area of permanent need for the groundwater.

From the previous results, there is almost unchanged saturated thickness along the main M. Dammam aquifer. So that, the accepted assumption here corresponds with the second suggestion of Frohlich et al. (1996) which is related to unchanged thickness (H) of aquifer, but to variable ρ_o (mΩ) and K (m/day). Therefore, the theoretical case of the M. Dammam aquifer will be exhibited as the following equation:

$$S_L = \frac{H}{\rho_o} \quad \text{and} \quad T = K\,H, \tag{9}$$

when H is a constant thickness of M. Dammam aquifer in both the electric and hydraulic equations, and returning to Fig. 11 that shows a relation of direct proportionality and linear correlation between T (m²/day) and S_L (Ω^{-1}). Hence the decrease of ρ_o (mΩ) leads to increase of the magnitudes of other parameters such as S_L (Ω^{-1}), T (m²/day) and K (m/day). Exactly as what is found from the interpreted results at northern and eastern parts of the studied area, which are considered as discharge regions of Maanyia hydrogeological basin.

Conclusions

1. The main aquifer is located between two impermeable layers composed of marl rocks of low resistivity. So it seems as a confined type of 160 m average thickness with average resistivity of 70 Ωm approximately. It is located at depths extended to more than 100 m and the expected groundwater flow is towards NE. The results of geophysical interpretation are verified by the calibration with nearby lithological sections of the existed wells as confined aquifer of M. Dammam member, which consists of fossiliferous dolomite and dolomitic limestone. The upper layers are determined as marl of Up. Dammam member by the inverse model of 2D imaging and the lithological sections of nearby wells. While, the lower ones are detected as marl and gypsum of Rus Formation, by the geoelectrical and geological sections of the VES stations.

2. The correlation between the material properties of hydraulic and geoelectrical parameters as between K (m/day) with ρ_o (Ωm) gave logical relationship of aquifer ($R^2 = 0.737$). In addition, the correlation between the layer properties as between T (m²/day) and both T_r (Ωm²) and S_L (Ω^{-1}) revealed the symmetry in lithological characteristics of middle Dammam aquifer due to possessing the equality and strength of reliability ($R^2 = 0.862$ and $R^2 = 0.868$, respectively), but with opposite proportionality. So, they supported each other. This may coincide with the nature of the studied area as discharge regions of Maanyia hydrogeological basin. It has a good φ of 22% and a high degree of Sw of 1, especially in the northern and eastern parts of the studied area.

3. The extracted relationship between T (m²/day) and S_L (Ω^{-1}) is an important one. So, this relationship can obviously reveal the realistic case about the correlation between the related parameters, while other relations can play an assistant role for supporting the final results. Therefore, Eq. (8) can be used directly to calculate T (m²/day) mathematically.

4. Middle Dammam aquifer has a fully saturated thickness, which is identified from the results of the quantitative interpretation. The aquifer thickness is regarded as unchanged (constant) factor against other variable factors such as the ρ_o (Ωm) and K (m/day). Hence, the proposed condition of this aquifer must be conformable with the second suggestion of Frohlich et al. (1996) to apply for deducing the aquifer hydrogeophysical model correctly and calculate directly aquifer hydraulic parameters (T and K).

5. The empirical relationships between the hydraulic and geoelectrical parameters seem in fractured rock aquifer to have mathematical equations of a strong reliability (R^2). So, the relations are mathematically expressed as linear equations instead of nonlinear of polynomial relations that will give misleading results for high aquifer resistivity (ρ_o). This was done because it is believed that they are mathematically more acceptable due to the presence of confined hard rock aquifer with a fully saturation thickness of clean water and similarity in lithological characteristics, and the groundwater plays an important role in controlling the conductions of the electric current. Moreover, the comparison between linear and nonlinear equations of T (m²/day) and T_r (Ωm²) and T (m²/day) with S_L (Ω^{-1}) appeared to have a little divergence of R^2 equal to 0.028 and 0.001, respectively. Therefore, these relations are more logic in comparison with intergranular aquifer type due to the overlapping and interfering effects of different sediments in their deposits.

6. The empirical relationships related with the fractured rock aquifers have best reliability (R^2), than that of intergranular aquifer types. The reasons may be due to the more uniform in lithological characteristics, with the limited effect of mud content in the fractured rock aquifers (as verified in the current study). Whereas these considerations definitely lacked in alluvium, due to the overlapping effect of different sediments in their deposits.

7. The quantitative estimation of hydraulic parameters of aquifer reduces the additional expenditures of drilling and carrying out pumping tests of wells and offers an alternate approach of calculating the hydraulic parameters.

8. Generally, the correlation between the hydraulic and geoelectrical parameters usually leads to acceptable empirical relationships, when extracted from the accurate and correct field measurements with good understanding to the aquifer conditions. Therefore, selecting the hydrogeophysical methodology to calculate directly aquifer hydraulic parameters is considered as an optimal solution to reduce high costs and consumed time.

9. The current study may be taken as a preliminary basis for the further studies, using a longer spread of Schlumberger sounding technique. Especially for the purpose of hydrogeological requirements, in this area and the surrounding regions to detect the deeper bearing-water formations. In addition, to determine exactly the vertical and lateral extensions of Abu Jir faults zone which are considered an important feature and an active factor for many geological settings in the studied area. Because it has a large effect of creating good aquifers, or making a hydraulic connection and may mix various type of groundwater.

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