Effect of structure and lithological heterogeneity on the correlation coefficient between the electric–hydraulic parameters of the aquifer, Eastern Desert, Egypt

A. I. Ammar¹ · K. A. Kamal¹

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Abstract

Discovering, studying and determining the hydrogeoelectrical properties of the aquifer at the new area by using resistivity sounding parameters are difficult and need high accuracy in measurements and interpretation. The hydrogeological settings of the area of northwest Al Hurghada town are not studied on large scale by using the surface geophysical measurements before this study. So, for this aim, 24 vertical electrical soundings (VESs) were measured and interpreted. Discovering of groundwater aquifer along the main wadi called Wadi Om Dehas especially to the Far East, adds to determine the main lithology, shaly sandstone, sandstone and sandstone to limestone, of the aquifer and the complicated structural setting at form of inferred faults by using VESs curves, were the main tenets at this study for studying their effects on the correlation coefficient (R^2) between the electric and hydraulic parameters of the aquifer. Accordingly, the two suggested locations were chosen for drilling and their results were as expected from VESs interpretation. The interpretation results using the true resistivity values assisted in delineating the complicated facies, heterogeneity of aquifer rock units and in expecting the flow direction of groundwater along the area. The relationship between the resistivity with transverse resistance and longitudinal conductance was carried out and assisted strongly in separating aquifer rock units. The heterogeneity and water salinity at different directions affected the strong relationship between the resistivity and transverse resistance where in case of shaly sandstone and sandstone it was weak but strong in case of sandstone to limestone. The hydraulic conductivity of aquifer was calculated using the transverse resistance. The transverse resistance was used in calculating the transmissivity and concluded that there is complicating and changing in its values from depth to others and from location to other due to the effect of structure and heterogeneity. This confirmed that the geological and hydrogeological settings of the area are more complicated. So, according to the relationship between the hydraulic conductivity (K_h) and resistivity (ρ_t), it can be said that it is strongly controlled by the nature of the aquifer rock units either heterogeneous or homogeneous. Accordingly, it can only use the last creating empirical equation in calculating the expected transmissivity values of the recorded water-bearing sandstone to limestone rocks at this area with taking into account the calculated value of R^2 between both depending on the statistical analysis.

Keywords VESCs · Structure tectonics · Heterogeneity · Resistivity parameters · Hydraulic parameters · Statistical analysis · Correlation coefficient

Introduction

Generally, the groundwater is a very important source for industry, agriculture and domestic purposes, especially in arid and semiarid areas like the area under study. So, because

of the higher drilling costs at these areas, especially when the groundwater occurs in limestone or sandstone complicated aquifers, the indirect surface measurements (geoelectrical method) and direct subsurface measurements (borehole data) will be used for understanding the electrical and geological properties of these aquifers, respectively. Then, these properties will be assisting in the determination of the electrical and hydrogeological parameters of these aquifers. Additionally, the hydraulic parameters of the aquifer may be estimated using electrical methods as concluded by Mazac et al. (1985, 1990), Purvance and Andricevic (2000a,

✉ A. I. Ammar
abdallah_ammam_708@hotmail.com

¹ Research Institute for Groundwater (RIGW), National Water Research Center (NWRC), Cairo, Egypt

b). Accordingly, the electrical measurements may assist in detecting the heterogeneity, fractures and aquifer parameters (Herwanger et al. 2004; Niwas and de Lima 2003).

Generally, the recorded aquifers at this area are expected complex in nature and hydrogeological parameters because of these aquifers are normally traversed by faults and fractures zones distribution that makes the groundwater dynamics more complex. Accordingly, Lattman and Parizek (1964), Siddiqui and Parizek (1971), Parizek (1976), Frohlich et al. (1996), Chandra et al. (2006), Solomon and Ghebreab (2008) concluded that the detection of faults and their trends are interesting in detecting groundwater aquifers and their continuity and discontinuity and also in controlling its flowing. Also, these faults affect more the lateral resistivity variation of the subsurface layers. Accordingly, the surface data at this study, the surface data from resistivity method and subsurface data, geological and hydrogeological data, from boreholes, were used in understanding the expected geophysical, geological and hydrogeological properties of the recorded aquifer. Also, these data assisted in how to delineate the faults and the role of these faults in the creation and continuity of the recorded aquifer. According to geoelectrical, geological and hydrogeological properties of this aquifer, it is assumed that the saturated pores of the recorded aquifer are distributed horizontally and vertically and may be controlled or affected by structure tectonics such as faults. These features may be important in feeding this aquifer and controlling its groundwater quality added to determine the locations of low and high groundwater accumulation.

In arid regions, like the area of study, groundwater is recharged only from the local rainfall plus water that enters as streams or via artesian deep aquifer. Deep groundwater at this area may be very old and a relic of former times when evaporation rates were reduced. So, the recharge of groundwater must be controlled to avoid fast depletion.

Chandra et al. (2006) had reported that the geophysical outputs help in expecting the potentialities of the hard rocks. Accordingly, at this study, the surface data from resistivity method and subsurface data, geological and hydrogeological data, from boreholes, were used in understanding the expected geophysical, geological and hydrogeological properties of the recorded aquifer. Also, these data assisted in how to delineate the faults and the role of these faults in the creation and continuity of the recorded aquifer. According to geoelectrical, geological and hydrogeological properties of this aquifer, it is assumed that the saturated pores of the recorded aquifer distributed horizontally and vertically and may be controlled or affected by structure tectonics such as faults. These features may be important in feeding this aquifer and controlling its groundwater quality added to determine the locations of low and high groundwater accumulation. So, the geophysical methods are used to characterize aquifer features

(faults and fractures or another pore system) prior to any hydrogeological or geological studies.

As a rule, the more porous or fissured/fractured rocks and the larger its groundwater content, the higher is the conductivity and the lower is the resistivity and the rock units are more conductive if the clay content increases. Several processes such as dissolution, faulting, shearing, columnar jointing, weathering and hydrothermal alteration usually increase the rock porosity and fluid permeability and hence lower resistivity (Sharma 1997). It is believed that at this study the different in pores types in form of fractures, fissures, joints, as secondary porosity of the carbonate aquifer, and primary porosity of the sandstone aquifer. These processes are more abundant in the areas of low resistivity values which reflect the increase in pores.

Generally, the expected lithology of the aquifer under study consists of the sandstone and limestone with shale and clay intercalation and is similar to the recorded sediments toward the north locations, especially at Wadi Dara (Sewidan and Himida 1991) (Fig. 1), and may complicate and change from location to other. The chosen area for studying this aquifer is located at the eastern desert of Egypt to the west of Al Hurghada governorate, specifying in the northwest of Al Hurghada town, between longitudes 33°27'47" and 33°33'10.7"E, and latitudes 27°15' 3.4" and 27°16'59.7"N (Fig. 1).

This area is located between the eroded limestone plateau (Middle Miocene) characterized with several topographic features to the northeast and the basement complex to the southwest and west. These features around the area include hills, plateaus, mountains and dry wadis (streams). It was believed that these streams and their tributaries were generated from the rainfall or from the structure controlling and may consider the main source in recharging the groundwater aquifer in several areas. Wadi Om Dehas is one of the several wadis at the regional area and the wadi under study. The direction of this wadi is from northeast, where the limestone plateau of Abu Sha'r El Qibli Mountain is present, to southwest and west, where the basement rocks of Abu Dokhan Mountain are present (Fig. 1).

The climatic conditions of the Red Sea are largely controlled by distribution of winds and change in atmospheric pressure over very wide area. During winter, the northern part of the Red Sea is subjected to a more variable weather than the southern part due to the influence of the nearby Mediterranean disturbances. The Red Sea region is hot and dry in summer but in winter the weather tends to be warm (Mabrouk 2009). Air temperature ranges between 23.04 and 37.66 °C in summer and 6.86 and 29.34 °C in winter. The humidity ranges between 46.15 and 55.73 and reaches highest values during the winter season and the lowest values during the summer. The evaporation ranges between 7.1

Fig. 1 General surface geological map including the study area of Wadi Om Dehas (Quadrangle Shape, dashed Line) (a, b) (after Conoco 1987, and Google Earth). The topographic map (c) including the distribution of the vertical electrical sounding stations (VESs),

drilled productive well, purple circle and the hydrogeoelectrical profiles (A–B, blue line, & C–D, red line) with the expected general dip direction along the study area. The below solid rectangle lay around the expected main recorded geological sediments at this area

and 14.06 mm/day. The rainfall average of all stations is 7.87 mm along the coast.

Topographically, the area under investigation is of relatively medium relief with respect to the surrounding areas. The ground elevation ranges between 100 m and more than 170 m in Sahl Hasheesh above sea level as measured at the area. Geomorphologically, the study area, including Wadi Om Dehas and wadi Dara to the north of Al Hurghada and Sahel Hasheesh in the southern raft of Al Hurghada, displays several major and minor geomorphological features. The highlands (Red Sea Mountains) extend parallel to the Red Sea coast composed of granitic rocks. The lowland is represented by both Gharib sector to the east and Esh El Mellaha sector to the west in Wadi Dara and represented by the loose sands and gravel. Also, it is dissected by different drainage basins controlled by local structures, lithological and erosion features. The coastal plain occupies the eastern part of the study area with a low topographic feature of an irregular longitudinal strip of land running parallel to the Gulf of Suez and the Red Sea coastal.

Geological settings

These settings were reported in more detail by several authors such as Egyptian General Petroleum Corporation Stratigraphic Committee (1964), Hantar (1965), Ghorab and Marzouk (1967), National Stratigraphic Subcommittee of the Geological Sciences of Egypt (1974), Garfunkel and Bartov (1977), Sellwood and Netherwood (1984), Beleity (1984), Scott and Govean (1985), Saoudi and Khalil (1986), Fawzy and Abdel Aal (1986), James et al. (1988), Darwish and El-Azabi (1993), Bosworth and Taviani (1996), Plaziat et al. (1998), McClay et al. (1998), Bosworth et al. (1998), Orszag-Sperber et al. (1998). In general, along the western margin of the Red Sea, South of Al Hurghada, reddish siltstones, sandstones and conglomerates are interpreted to be of probable late Oligocene–earliest Miocene age. Other exposures are composed of massive or horizontally stratified gravelly, coarse calcareous sandstones with angular chert fragments, pebbles of white Thebes limestones. In the southern Gulf of Suez subsurface, there is Member consisting of sandstone with intercalated red shale and occasional carbonaceous material. Also, there are gray shales and limestones immediately overlying the interbedded reddish siltstone, sandstones and shales. All these constituents represent the Nukhul Formation. Also, there is another formation is called Rudies are mainly Eocene and upper Cretaceous limestone, whereas Paleozoic and Mesozoic sandstones, followed by pre-Cambrian basement. And, also, there are Belayim Formation in the southern Gulf of Suez, middle Miocene

carbonate platforms and reefs developed directly on top of tilted basement fault.

Adding the previous formations, the Pliocene deposits occurred and are characterized by gravels and sands while the Quaternary deposits cover flat and topographically low areas as well as the coastal plains surrounding the present-day marine gulf. Quaternary alluvium and wind-blown sands cover the wadi floors. On the coastal plains, these deposits include loose to moderately consolidated coarse clastics, derived from the older pre-rift rocks that form the surrounding topographic highs.

Structurally, El Tarabili and Adawy (1972), Garfunkel and Bartov (1977), Jarrige et al. (1986), El Wazeer et al. (1992), Patton et al. (1994), Youness and McClay (1998), McClay and Khalil (1998) concluded that the basement gneisses and the granitoids are cut by N–S fault systems. All of the pre-Cambrian fabrics were reactivated during the late Cenozoic rifting of the Gulf of Suez. In particular, the zigzag pattern of the rift border fault and intra-rift fault systems results from reactivation and hard linkage of the NW-trending shear zones and foliation fabrics via the N–S and NNE–SSW fault fabrics. At Gebel El Zeit and Esh El Mellaha, main basement joint sets predate deposition of basal Paleozoic sandstones and themselves are locally intruded by Pan-African dike material.

At the onset of rifting, the main border fault or breakaway for the southern Gulf half-graben was positioned at the present basement scarp of the Red Sea Hills. In addition to the thick evaporitic sequences, the Serravallian in the southern Gulf of Suez is also noted for carbonate reefs and platforms located at the crests of fault blocks and along the western rift margin (e.g., at Esh El Mellaha; Cross et al. 1998; Fig. 2). Bosworth et al. (1998) suggested that the extensive development of carbonate platforms, where the study area is present, reflects a waning of tectonic activity, linkage of small fault blocks into larger, stable blocks and correspondingly a decrease in siliciclastic input for topographic highs.

Methods

In terms of electrical resistivity, one can expect that saturated porous zones (primary porosity like shaly sandstone and sandstone and secondary porosity like fractured limestone) contrast strongly with basement bedrock. Generally, the apparent resistivity data of the 24 VESs (Fig. 3), one-dimensional DC resistivity method (1D VES), by Schlumberger array, with max and min AB/2 ranged between 500 and 700 m, respectively, were carried out by RIGW staff using SAS1000 resistivity meter and collected during 2015 (Fig. 1c). The goals of this surveying were for groundwater exploration and discovering the different hydrogeological

Fig. 2 Fault activity maps for the southwestern margin of the Gulf of Suez based on interpretation of the plate tectonic setting of the Gulf of Suez. Fault movement and associated basin subsidence were progressively focused toward the axis of the rift through time, culminat-

ing in the present-day, narrow Gulf of Suez marine basin. The study area was labeled by the quadrangle shape (red color) (after Bosworth and McClay 2001)

conditions of the expected aquifer. All the VESs locations were chosen according to the geological and topographic features, which are very important in expecting the groundwater aquifer. Through this study, two main hydrogeoelectrical profiles, the first is transverse and the second is longitudinal, were constructed passing through a number of VESs and the available hydrogeological data of one productive well before carrying out the measurements and two productive

wells after carrying out the measurements (vertical electrical sounding curves (VESC)s), and recording the aquifer, for showing the terrain continuity and discontinuity picture of the subsurface rock units added to hydrogeological and structural settings of the subsurface recorded layers.

Fig. 3 Apparent resistivity curves of the measured VESs (VESCs)

Results and discussion

Geoelectrical Analysis

Generally, the quantitative interpretation of the field data, (VESC), depended on Zohdy's technique (1989), for initial model, and the Rinvert's software (1999) for forward and inverse model to estimate the electrical parameters, which are assisting in predicting the hydrogeological properties of the recorded water-bearing layers with depths. From this inversion (Forward and Inverse models as reported on Figs. 4 and 5, respectively, for VES6) it can detect the lithologies encountered within these layers and confirming of the expected faults. All these results may reflect the vertical and lateral changes in the rock constitution of the shallow section penetrated by the electric current. At this study, it was supposed that considerable resistivity contrasts between the basement rocks, the saturated limestone, shaly sandstone and sandstone can be detected.

The results of VESs assisted in building of two 2D hydrogeoelectrical profiles along the study area (Fig. 1) and the general hydrogeoelectrical imagination to the recorded subsurface layers were reported on the profile A–B (Fig. 6) which reveal that the number of layers was five. These results are confirmed by the geological and available hydrogeological data of three wells before and after drilling with concentration on the saturated layers. These results confirmed that the area was subjected to high structure movements. Accordingly, the lithologies of the recorded geoelectrical layers, comparing with the subsurface data from the drilled wells, are composed of (wadi deposits at the top, sand and gravel, clay and sandy clay to clayey sand, increased the clay after 35 m, limestone with more fractures at depths from 85 to 90 m, sandstone and shaly sandstone then hard sandstone with claystone and siltstone at the base with increasing the shale content) and outcrops were formed, in general, from recent Pliocene and Pleistocene which are composed of wadi deposits, sandstone, limestone and sandstone with shale and

Fig. 4 Forward modeling (Tables a, b and Charts) for model VES6 model in comparison with data VES6 data-Schlumberger array at VES6

Fig. 5 Inverse modeling (Tables a, b and Charts) for sounding VES6 data-Schlumberger array at VES6

Fig. 6 Hydrogeoelectrical profile (A–B). First geoelectrical layer: dry wadi deposits (124–998 Ω m). Second geoelectrical layer: sand and gravel with minor content of clay (28–435 Ω m). Third geoelectrical layer: clay and sandy clay to clayey sand (1.5–30 Ω m). Fourth geoelectrical layer: sandstone, shaly sandstone (27–65 Ω m) to frac-

tured limestone (73–93 Ω m) (main aquifer). Fifth geoelectrical layer: massive limestone rocks, to the east, hard sandstone with shale and/or claystone and siltstone at the center, and basement rocks, to the west (451–3500 Ω m)

are called El-Tor Group. To the east of the area, recording the Middle Miocene carbonate complex of Abu Sha'r platform is expected. The electrical properties of these layers (resistivities and thicknesses) and their expected hydrogeological characteristics as shown on the hydrogeoelectrical profile A–B (Fig. 6) are:

First geoelectrical layer is composed of resistive wadi deposits and considered as the surface layer. Its resistivity values ranged from 124 to 998 Ω m, and its thickness ranged from 1 to 11.5 m.

Second geoelectrical layer is made up of resistive sand and gravel with minor content of clay. Its resistivity values ranged from 28 to 435 Ω m, and its thickness ranged from 2 to 48 m.

Third geoelectrical layer is made up of very conductive clay/shale and sandy clay/shale to clayey/shaly sand. Its resistivity values ranged from 1.5 to 30 Ω m, where the low value of resistivity gives indication about the pure wetted clay/shale while the medium resistivity value reflects the increase of sand with the clay/shale content and the expected sediments are composed of wetted sandy clay/shale to clayey/shaly sand. Its thickness ranges from 4 m to 51 m and sometimes reaches 104 m when there is increase in sand.

Fourth geoelectrical layer is made up of very conductive saturated sandstone and shaly sandstone, with resistivity values ranging from 27 to 65 Ω m, to fractured limestone with resistivity values ranging from 73 to 93 Ω m, and its thickness ranged between 5 m, to the west of the study area, and 93 m, to the east, especially at the central parts. Accordingly, this layer is considered the main groundwater aquifer at the study area. This lowering in resistivity resulted from increase in the shale content and salinity of water in pores while the intermediate resistivity depends on the occurrence of water content as main conductor to current through the pores or fractures. So, after drilling the suggested productive wells, it found increase in the shale content at the sandstone especially at the first depths of the aquifer after recording the fractured limestone (Figs. 6, 8b) and increase in the salinity from $\approx$ 1500 to 3200 in ppm.

Fifth geoelectrical layer is made up of resistive dry massive limestone rocks to the east, hard sandstone with shale and/or claystone and siltstone at the center, and basement rocks to the west with resistivity values ranging from 451 to 3500 Ω m. This layer considered the base of the recorded aquifer, and its depths may begin from 35 m, at the west parts, to 173 m, at the central parts to the east of the study area.

Along this profile (Fig. 6), there are inferred and detected faults between different VESs. The existence of these faults

was confirmed after inverting of the apparent resistivity curves, also confirming the previous assumption which concentrated on intersecting between the two adjacent VESs curves reflects the existence of faults.

Hydrogeological settings estimation

The hydrogeological setting at this area was not studied accurately before carrying out this study. So, at this study, the geoelectrical method adds to the previous geological and little hydrogeological data for studying and discovering the groundwater aquifer and its condition. All the previous studies at the limited subareas along this area had confirmed that the groundwater aquifer recorded at the shaly sandstone, sandstone to fractured carbonate rocks, especially at the first depths of aquifer. The shale content increases vertically with depth and horizontally at some locations and may transform at the deep depths to pure claystone or siltstone with minor contents of sandstone. After the recommendations of the geoelectrical studies, two production wells were drilled at VES 6 location to depth 170 m (W1) and VES 2 location to depth 190 m (W2) add to well (W) was drilled before carrying out the surveying with depth 150 m as located in Figs. 1, 6 and 7c. VES 1 was measured next to the drilled well (W) for calibration. The recorded lithology was wadi deposits at the top, sand and gravel, clay and sandy clay to clayey sand, increased the clay after 35 m, limestone with more fractures at depths from 85 to 90 m, sandstone and shaly sandstone and then hard sandstone with claystone and siltstone at the base with increasing shale content. The depth to groundwater was recorded at 63 m and in general after 60 m from the surface, especially to the west and east from the central parts of the study area, to 80 m and in maximum to 105 m especially at the center of the area to the north–south direction, and its salinity (T.D.S) is ≈ 1500 to 3200 in ppm. The screen depths were designed from 120 to 160 m at W1 and from 110 to 160 m at W2 and successfully yielded (Q) ≈ 90 m³/h. All the previous results of drilling confirmed the recorded and resulted outputs from the geoelectrical surveying interpretation. The extracted groundwater was used in water supplying such as for agriculture and other domestic means. These outputs will assist in studying and understanding a lot of hydrogeophysical characteristics of the recorded aquifer.

3-D maps of the geoelectrical results

3-D maps of the structure and engineering characteristics of aquifer

The depth to the top of aquifer and groundwater map was mapped to show the distribution depths to the top of aquifer and groundwater detection along the area and the expected flow direction of the groundwater (Fig. 7a). The recorded

maximum depth to the aquifer or groundwater was 111 m to the east at VES 16, and the minimum depth was 19 m at VES 18 to the southwest. Along this map, the shallow depths to the top of aquifer were recorded at the west but the deep depths were recorded at the east where Abu Sha'r Limestone Mountain is present. The expected flow direction of the groundwater was from the west to the east and from the southeast and southwest, to the northwest, at the east parts of the study area.

The minimum depth to the base of aquifer was 35 m and recorded at the southwest especially at VES 18 but the maximum depth was 220 m at VES 6 to the east as shown on map 7-B. The high changing at the depths to the base of aquifer reflects occurrence of major basin and subjects the area to the structure movements (faults) as reported at the previous studies (Fig. 2) and estimated or/and confirmed depending on applying Ammar and Kamal (2018) assumptions by using the apparent resistivity curves (VESC) of the measured VESs (Fig. 7), where these assumptions deduced that there is no fault between the coinciding and diverging measured VESs curves (VESC) and there is fault between the intersecting measured VESs curves and the intersect point of the two curves is the peak of this fault. Accordingly, it can predict the down-throw and up-throw of this fault as show on the measured VESs (Fig. 7c) because of the delineation of faults and how to expect and determine these faults is very complicated and very interesting in studying the aquifer hydrogeological properties.

These assumptions concluded that there are several sub-surface inferred faults (dashed lines) (Figs. 6, 7c). They were recorded at different locations and confirmed by the field observations and geological maps (Fig. 2) and from inversion of the resistivity field data as shown on the 2D hydrogeoelectrical model (Fig. 6). So, these faults were shown as extension to the observed and mapped geological faults (solid line), especially along the profile C–D or at the region of VESs 1, 2, 3, 4 and 5 (Fig. 1a, c). These delineated and mapped faults are connected with each other (Fig. 7c). Therefore, these faults showed that the hydrogeological conditions of the recorded aquifer seem very complicated because of their effect on the lateral homogeneity of the recorded layers.

So, from the previous results, the occurring of these faults will affect on the topographic features (elevations and slope of these features (Fig. 1), groundwater occurrences, depths and flowing (Figs. 6, 7a). These faults were very important in expecting their effects on occurrence and mapping of the locations of high saturated thickness and their direction. So, according to the effect of these faults, the shallow depths of groundwater occurred in general to the SW and increased to the NE with increase in the thickness of the aquifer or the depth to the base of the recorded aquifer (Fig. 7). Also, these faults will complicate the groundwater flowing and it will

Fig. 7 3-D distribution maps of the depth to the aquifer and groundwater with the expected flow direction of groundwater (a), of the depth to the base of the aquifer (b), and the thickness of aquifer and the estimated inferred major faults (c) with example for delineating the expected fault zones at shallow and deep depths between the different VESCs using the apparent resistivity values according to

Ammar and Kamal assumptions (2018), the dashed lines with the expected down- and up-throwing and also, showing the location of the drilled production well (W) (pink circle) next to VES 1, and the suggested production wells, W1 and W2, (blue circles) next to VES 6 and VES 2, respectively. The cyan rectangle area is the recommended area for drilling production wells

be in general from southwest to northeast and from the southeast to the northwest especially to the right parts of the center of the area taking the direction from southeast to northeast as shown in Fig. 7a.

Also, these assumptions were confirmed after building the thickness map of the aquifer (Fig. 7c). From this map, the location of basin and its geometry form and the location of the major faults which assisted in building this basin and its direction can be expected. This basin was recorded to the east parts where VESs 1–7 and 12–15 are present and its direction was to the northwest. Most of the resulted inferred faults direction was NW–SE while some of these faults were directed to the N–S. Therefore, this map assisted in drawing the area and locations of the expected high groundwater potential. Accordingly, it decided that the best locations of the productive wells are close to the expected basin especially at VESs 1–7 and 12–15 as shown in map (Fig. 7c) with cyan rectangle. So, at this area the two wells W1 and W2 were drilled and confirmed that these locations were the high productive locations for groundwater along the study area. So, it can expect and confirm that the tectonic movements at form of faults were interesting in building and constructing of major basin of porous sediments have high groundwater amounts with more effect on the homogeneity of the recorded rock units of the subsurface with focusing on the aquifer rock unit.

3-D maps of the bed rocks resistivity, aquifer resistivity and aquifer transverse resistance (T_R)

The resistivity maps of the bed rocks and aquifer were designated for appearing the resistivity relief of the subsurface massive rocks with their types and the resistivity of the main water-bearing layer with expectation of their facies distribution along the area as shown in Fig. 8a, b, where map A showed that the expected massive limestone and sandstone rocks were deposited to the east and to the west of the central parts while the massive basement rocks were recorded to the far west and at the central parts along the area. Also, this map appeared that the bed rocks conditions were more complicated with expectation that the massive limestone and sandstone rocks have minor joints. The map B showed that the distribution of the sedimentary facies of the water-bearing layers was more complicated along the area and gave indication about the heterogeneity of the aquifer rock units.

Where the fractured basement was recorded at some locations to the west, the shaly sandstone and sandstone at the central parts, especially to the south and to the west at the contact with basement and to the east. While the sandstone to fractured limestone was recorded at the locations to the north and northeast and close to Abu Sha'r Limestone Mountain. All the previous observations confirmed that the

hydrogeological settings of the recorded water-bearing rocks are complicated and will assist in managing and dealing with the recorded aquifer with abrupt change in the hydrogeological parameters from location to other. Accordingly, the transverse resistance was calculated by using the equation $T_R = \rho_t * h$ where ρ_t is the true resistivity and h is the thickness and mapped as shown in Fig. 8c. This map reflected that the increase in the transverse resistance was to Abu Sha'r Limestone Mountain where the expected rock type of the aquifer is fractured limestone with sandstone. On this map, the low calculated value was smaller than $500 \Omega \text{ m}^2$, especially from the center to the far west of the study area, and the high calculated value was greater than $8000 \Omega \text{ m}^2$, especially at the parts close to Abu Sha'r Limestone Mountain and to the east.

Estimating the correlation coefficient (R^2) between the electrical parameters and electrical-hydraulic parameters

Niwas and Singhal (1981, 1985) developed two theoretical equations, for estimating transmissivity using transverse resistance and longitudinal conductance, by using the equation $L_C = h/\rho_t$ where ρ_t is the true resistivity and h is the thickness, derived from surface geoelectrical measurement under several conditions. Also, Soupios et al. (2007) were expected to give reliable results if relevant geological information of the area is available. However, this technique needs validation in a well-studied area. Niwas and Lima (2003), Niwas et al. (2011) stated that conceptually, the resistivity method is based on the equation of conservation of charges and Ohm's law; likewise, the flow fluid is based on the equation of conservation of mass and Darcy's law. Hence, an interrelationship between resistivity and hydraulic conductivity is expected to exist if the medium is the same. The electrical behavior of a rock can be quite different with difference in saturation by brine and by fresh groundwater. At fresh water, the dominant contribution is from the interfacial conductivity operating at the solid–liquid contacts. At saline water, the dominant effect is from the bulk pore electrolyte conductivity. This may cause some differences in the interrelationship between K_h and ρ_t , at those limiting conditions. (2) At the dimension corresponding to the depth of investigations of VESs, the relationship between K_h and ρ_t can be strongly controlled by the nature of the aquifer substratum. If the layer is resistive, both the current and the hydraulic flows are dominantly horizontal in a typical unit column of the aquifer, and the relationship between K_h and ρ_t is inverse. If the layer is conductive, the hydraulic flow is still horizontal, but the current flow in a characteristic unit column is dominantly vertical and for this conduction, K_h and ρ_t show a direct relationship.

Fig. 8 3-D distribution maps of the resistivity of the bed rocks for showing the relief of the bed rocks (a), of the resistivity of the aquifer (b) with the distribution of the sediments and rocks, and the transverse resistance of aquifer sediments (c)

At this study, the transverse resistance and longitudinal conductance of the aquifer were calculated as reported in Table 1. The highest calculated value of the transverse resistance was $8556 \Omega \text{ m}^2$ at VES 2 and its rock type is sandstone to limestone while the lowest calculated value was $311 \Omega \text{ m}^2$ at VES 22 and its rock type is sandstone with shale. The highest calculated value of the longitudinal conductance was $2.44 \Omega^{-1}$ at VES 12 and its rock type is sandstone while the lowest calculated value was $0.05 \Omega^{-1}$ at VES 23 and its rock type is sandstone with shale (Table 1).

The relationship between the resistivity (ρ_t) and transverse resistance (T_R) and that between the resistivity (ρ_t) and the longitudinal conductance (L_C) were carried out and indicated, in general, that the transverse resistance increases with increasing resistivity and the longitudinal conductance decreases with increasing resistivity (Fig. 9). These relationships were linear and assisted in separating the types of sediments of the aquifer as shown in Fig. 10.

In case of the relationship between the resistivity and transverse resistance [Figs. 9, 10(left)], the shale content with sandstone was more effecting on this relationship as estimated from the weak R^2 , Coefficient of Determination

or Square of Coefficient of Correlation, value which was $\sim 0.18\%$. This value reflects around $\sim 0.82\%$ of the transverse resistance which cannot be interpreted by the resistivity values because of the effect of shale content, types of the shale and salinity of the included water, while in case of the sandstone of the main rock type of aquifer, the R^2 value was also weak $\sim 0.24\%$. This value indicated that around 0.76% of the transverse resistance cannot be interpreted by the resistivity. This may be resulted from occurring some of the shale types in minor content added to the limestone thin beds and water salinity. Therefore, in general, it can be said that the heterogeneity or the variation of lithological composition and water salinity with different directions affected the strength of this relationship. So, the previous two relationships were weak. But the R^2 value in case of sandstone to limestone was $\sim 0.98\%$. So, the relationship between both at this case is very strong and this may result from the effect of pore system at this sediment with absence of the shale content.

All the previous cases gave indication the transverse resistance was more affected by the increasing shale content and salinity and also by the type of sediments and their pore types. Also, this relationship will assist in understanding

Table 1 Resistivity (ρ_t) in $\Omega \text{ m}$ with rock type, thickness (h) in m, the transverse resistance (T_R) in $\Omega \text{ m}^2$ and the longitudinal conductance (L_C) in Ω^{-1} of aquifer

Vertical electrical sounding station (VESs)	True resistivity of aquifer (ρ_t) in $\Omega \text{ m}$	Thickness of aquifer (h) in m	Transverse resistance of aquifer ($T_R = \rho_t * h$) in $\Omega \text{ m}^2$	Longitudinal conductance of aquifer ($L_C = h/\rho_t$) in Ω^{-1}
VES 1	49 (sandstone, S.S)	86	4257	1.74
VES 2	92 (S.S to limestone)	93	8556	1.01
VES 3	45 (sandstone, S.S)	85.5	3890	1.88
VES 4	50 (sandstone, S.S)	70	3500	1.40
VES 5	47 (sandstone, S.S)	66	3102	1.40
VES 6	73 (S.S to limestone)	85	6205	1.16
VES 7	40 (sandstone, S.S)	84.5	3380	2.11
VES 8	30 (S.S with shale)	36	1080	1.20
VES 9	47 (S.S with shale)	33	1551	0.70
VES 10	39 (S.S with shale)	41.5	1618	1.06
VES 11	43 (S.S with shale)	11	473	0.26
VES 12	34 (sandstone, S.S)	83	2822	2.44
VES 13	73 (S.S to limestone)	89	6497	1.22
VES 14	77 (S.S to limestone)	91	7007	1.18
VES 15	84 (S.S to Limestone)	90	7560	1.07
VES 16	53 (sandstone, S.S)	62	3286	1.17
VES 17	54 (S.S with shale)	17.5	954	0.32
VES 18	65 (S.S with shale)	16	1040	0.25
VES 19	35 (S.S with shale)	19.5	683	0.56
VES 20	42 (S.S with shale)	21	882	0.50
VES 21	60 (S.S with shale)	26	1560	0.43
VES 22	27 (S.S with shale)	11.5	311	0.43
VES 23	93 (S.S with shale)	5	465	0.05
VES 24	85 (S.S with shale)	11.5	978	0.14

Fig. 9 General relationship between the resistivity (ρ_t) in $\Omega \cdot m$ and the transverse resistance (T_R) in $\Omega \cdot m^2$ (left) and the longitudinal conductance (L_C) in Ω^{-1} (right) of the recorded aquifer

Fig. 10 Relationship between the resistivity (ρ_t) in $\Omega \cdot m$ and the transverse resistance (T_R) in $\Omega \cdot m^2$ (left) and the longitudinal conductance (L_C) in Ω^{-1} (right) of the main different sediments (sandstone with shale, sandstone and sandstone to limestone) of aquifer

and calculating the expected transmissivity of the three main types of aquifer sediments and confirming there is difference in facies in two dimensions, vertically and horizontally, along the area of study as reported from the geological data. These results confirmed that the geological setting of the area was more complicated and, accordingly, it is difficult in understanding the hydrogeological setting.

On the same manner, the relationship between the resistivity and longitudinal conductance was carried out and gave indication the longitudinal conductance decreases with increasing resistivity [Figs. 9, 10(right)]. This relationship also assisted in the separation of the different sediments of the aquifer. Accordingly, in case of the sandstone with shale, the R^2 value was $\sim 0.47\%$, moderate, opposite to the resulted value $\sim 0.18\%$, weak, in case of the relationship between the resistivity and transverse resistance. This reflects that around 0.53% of the longitudinal conductance cannot be interpreted by the resistivity and the relationship is linear that may result from the effect of shale content and salinity increasing on the resistivity. This effect was smaller than in case of the transverse resistance.

The correlation between the resistivity and longitudinal conductance of the sandstone and sandstone to limestone was linear and strong as estimated from the R^2 values of both, which were $\sim 0.87\%$ and $\sim 0.92\%$, respectively [Figs. 9, 10(right)]. So, around $\sim 0.13\%$ and $\sim 0.08\%$ of the longitudinal conductance cannot be interpreted by the resistivity values in case of the sandstone and sandstone to limestone, respectively. This conclusion reflects that the effect of the shale content and salinity distribution on the resistivity was lower than in case of their effect on the transverse resistance. This relationship revealed that the value of the longitudinal conductance in case of the sandstone to limestone was smaller than in case of the sandstone. This may be resulted from the effect of pores distribution and their difference according to difference and change in sediments and their facies. Also, it may be the fractures into the limestone are distributed in different directions.

Sewidan and Himida (1991) evaluated of the hydraulic parameters for Dara area located to the north of the study area. Wadi Dara is the main wadi at Dara area and located at the western side of the Gulf of Suez and bordered by Wadi Shagar from the north and Esh El Mellaha Range from the south while

from the east and west is bounded by the Gulf of Suez and the Red Sea hills, respectively. The water-bearing formations consist mainly of fine to coarse sandstone, limestone overlaid by evaporite, gravel and wadi alluvium. These formations are intercalated with clays and shales, which give the whole formation at the semiconfined condition, and overlaid by the pre-Cambrian basement complex. These formations look like the recorded formations at the area under study, where the analysis of pumping and recovery tests performed at this wadi had been done by six methods manually and three methods using computer program. The data of both methods showed close similarity. The results showed that the aquifer in the area is of the semiconfined type and is dissected by several barriers (faults) which were not identified by the methods of investigations but they are identified by the current study using the resistivity method and calibrated with the geological studies. The weighted average values of the hydraulic parameters furnish reliable bases for further investigation and computation of groundwater potentialities within the study area using the relevant computer simulation programs.

Niwas and Singhal (1981, 1985) theoretically derived two equations using Ohm's law of current flow and Darcy's law for fluid flow in a medium as

$$T_h = \alpha T_R; K_h = \alpha \rho \quad (1)$$

$$T_h = \beta L_C; K_h = \beta / \rho \quad (2)$$

where T_h is the transmissivity, K_h is the hydraulic conductivity, ρ is the electrical resistivity, T_R is the transverse unit resistance, L_C is the longitudinal unit conductance of the aquifer and α and β are the constants of proportionality. In case of variation, the statistical average or mean value may be obtained and that may be used for estimating T_h from computed values of T_R in an area. In a geological sequence where resistivity, $\rho(z)$, or electrical conductivity, $\sigma(z)$, is a continuous function of depth z , one can consider the integrals termed as transverse unit resistance (Eq. 3) and termed as longitudinal unit conductance (Eq. 4).

$$T_R(z) = \int_0^z \rho(z) dz \approx \sum_i \rho_i d_i = T_{R_i} \quad (3)$$

$$L_C(z) = \int_0^z \sigma(z) dz \approx \sum_i \sigma_i d_i = L_{C_i} \quad (4)$$

Obviously T_R and L_C in Eqs. 1 and 2, respectively, are written for a homogeneous aquifer of average resistivity ($\rho = \sigma^{-1}$) and average thickness d or h . While dealing with basic equations of direct current prospecting, It was observed that if one considers a geological column built on a square unit, T_R is the resistance to the lines of current perpendicular to

the strata and L_C is the conductance offered to the lines of current parallel to it. It is thus obvious that Eq. 1 is derived by considering a vertical flow of the electric current indicating a direct correlation between hydraulic conductivity and electrical resistivity, whereas Eq. 2 is derived by considering a lateral flow of the current showing an inverse correlation. In hydrogeological investigations, transverse resistance (T_R) has been found to be functionally analogous to transmissivity (T_h) (Cassiani and Medina 1997; Niwas and Singhal 1985).

$$T_h = K_h h \quad (5)$$

Then, according to Eq. 3,

$$T_h = K_h T_R / \rho_t \quad (6)$$

and

$$T_h \rho_t = K_h T_R \quad (7)$$

Then,

$$K_h = T_h \rho_t / T_R \quad (8)$$

will be used in calculating the hydraulic conductivity.

According to the analysis of the pumping test data which was carried out by Sewidan and Himida (1991) to the north of this area at Wadi Dara, the transmissivity in m^2/day had been calculated. The calculated minimum and maximum values were 143 m^2/day and 327 m^2/day , respectively. By applying Eq. 8, the hydraulic conductivity (K_h) will be calculated to the recorded aquifer by using the following equations as reported in Table 2:

$$K_h = 143 \rho_t / T_R \quad (9)$$

in case of using the minimum calculated value of T_h .

$$K_h = 327 \rho_t / T_R \quad (10)$$

in case of using the maximum calculated value of T_h .

$$K_h = 200 \rho_t / T_R \quad (11)$$

in case of using the average calculated value of T_h .

The resulted values of the hydraulic conductivity of the aquifer according to the application of Eqs. 9–11, as recorded at Table 2, gave indication the maximum values were calculated in case of the main water-bearing rocks which are shaly or sandstone with shale. These results reflect that rocks are highly porous and their pores are highly connected with each other, and accordingly, the expected permeability will be high. All the calculated hydraulic conductivity values were used in carrying out the relationship with the resistivity. This relationship was in general linear and the hydraulic conductivity may increase with increasing resistivity and/or decrease with increasing shale content at the recorded water-bearing rocks as shown in Fig. 11.

Table 2 Resistivity (ρ_t) in Ω m and the calculated minimum, maximum and average hydraulic conductivity (K_h) in m/day of the aquifer

Vertical electrical sounding station (VESs)	True resistivity of aquifer (ρ_t) in Ω m	Minimum hydraulic conductivity (K_h) of aquifer ($143 * \rho_t / T_R$) in m/day	Maximum hydraulic conductivity (K_h) of aquifer ($327 * \rho_t / T_R$) in m/day	Average hydraulic conductivity (K_h) of aquifer ($200 * \rho_t / T_R$) in m/day
VES 1	49 (sandstone, S.S)	1.7	3.8	2.3
VES 2	92 (S.S to limestone)	1.5	3.5	2.2
VES 3	45 (sandstone, S.S)	1.7	3.8	2.3
VES 4	50 (sandstone, S.S)	2	4.7	2.9
VES 5	47 (sandstone, S.S)	2.2	5	3
VES 6	73 (S.S to limestone)	1.7	3.8	2.4
VES 7	40 (sandstone, S.S)	1.7	3.9	2.4
VES 8	30 (S.S with shale)	4	9.1	5.6
VES 9	47 (S.S with shale)	4.3	9.9	6.1
VES 10	39 (S.S with shale)	3.4	7.9	4.8
VES 11	43 (S.S with shale)	13	29.7	18.2
VES 12	34 (sandstone, S.S)	1.7	3.9	2.4
VES 13	73 (S.S to limestone)	1.6	3.7	2.2
VES 14	77 (S.S to limestone)	1.6	3.6	2.2
VES 15	84 (S.S to limestone)	1.6	3.6	2.2
VES 16	53 (sandstone, S.S)	2.3	5.3	3.2
VES 17	54 (S.S with shale)	8.2	18.7	11.4
VES 18	65 (S.S with shale)	8.9	20.4	12.5
VES 19	35 (S.S with shale)	7.3	16.8	10.3
VES 20	42 (S.S with shale)	6.8	15.6	9.5
VES 21	60 (S.S with shale)	5.5	12.6	7.7
VES 22	27 (S.S with shale)	12.4	28.4	17.4
VES 23	93 (S.S with shale)	28.6	65.4	40
VES 24	85 (S.S with shale)	12.4	28.4	17.4

The resulted correlation (R^2) value of this relationship at the three cases during calculating the minimum, maximum and average hydraulic conductivity was $\sim 0.036\%$, very weak. This value confirms that the rocks of aquifer are different from location to another and also different vertically and horizontally in their pores and pores connection. Also, in Fig. 11, the resulted empirical formula from the relationship between the hydraulic conductivity and resistivity of the aquifer is as follows:

$$K_h = 0.098\rho_t \quad (12)$$

in case of using the minimum calculated transmissivity value of the aquifer ($143 \text{ m}^2/\text{day}$) by using the pumping test data.

$$K_h = 0.224\rho_t \quad (13)$$

in case of using the maximum calculated transmissivity value of the aquifer ($327 \text{ m}^2/\text{day}$) by using the pumping test data.

$$K_h = 0.137\rho_t \quad (14)$$

in case of using the average calculated transmissivity value of the aquifer ($200 \text{ m}^2/\text{day}$) by using the pumping test data.

Therefore, the previous empirical Eqs. 12–14 cannot be used in calculating the hydraulic conductivity of the aquifer from the resistivity values of this aquifer because of the very weak value of the coefficient of correlation (R^2) between both.

So, the results in Table 2 were used in creating a new relationship between the resistivity and the hydraulic conductivity of the expected different rock types of the aquifer. This relationship showed the relation between the both was linear in case of the different recorded rocks of the aquifer. It was weak in case of sandstone rocks but moderate in case of shaly sandstone and sandstone to limestone. This relation was inverse in case of the main rock type of the aquifer which was sandstone to limestone, and this will assist in reflecting the true conditions of the transmissivity and hydraulic conductivity at such rocks. It is expected that the inverse relation due to the impedance of the sandstone and limestone rocks to electric current was high. The saturated pores of these rocks will affect also the resistivity where it increases with decreasing saturated pores. So, the resistivity will increase with decreasing hydraulic conductivity and the transmissivity. The resulted values of the R^2

Fig. 11 Relationship between the resistivity (ρ_t) in $\Omega.m$ and the minimum hydraulic conductivity (K_h) in m/day of the aquifer (a), the maximum hydraulic conductivity (K_h) in m/day of the aquifer (b) and the average hydraulic conductivity (K_h) in m/day of the aquifer (c)

were $\sim 0.415\%$, moderate, $\sim 0.187\%$, weak, and $\sim 0.573\%$, moderate to strong, in case of shaly sandstone, sandstone and sandstone to limestone, respectively (Fig. 12a, b, c).

Then, the resulted empirical equations will be:

$$K_h = 0.189\rho_t \quad (15)$$

In case of shaly sandstone, ($R^2 = 0.415\%$)

$$K_h = 0.041\rho_t \quad (16)$$

In case of sandstone, ($R^2 = 0.187\%$)

$$K_h = 0.12576/\rho_t \quad (17)$$

In case of sandstone to limestone, ($R^2 = 0.573\%$).

At the end, the last Eq. 17 can be used in calculating the transmissivity in case of the main lithology of the aquifer which is sandstone to limestone because of the high value of R^2 as follows:

$$T_h = h(125.76/\rho_t) \quad (18)$$

for sandstone to limestone

Therefore, the calculated values of the transmissivity are reported in Table 3.

Conclusion and recommendations

The main aim of this paper is to show the effect of structure tectonics and heterogeneity of the rock units on the relationship between the electric parameters and electric and hydraulic parameters of the aquifer using the statistical analysis in the form of correlation coefficient value (R^2) by using resistivity sounding technique and hydraulic parameters, where the resistivity sounding technique was used in determining

Fig. 12 Relationship between the resistivity (ρ_t) in $\Omega.m$ and the minimum hydraulic conductivity (K_h) in m^2/day of the sandstone with shale (a), sandstone (b) and sandstone to limestone (c)

Table 3 Resistivity (ρ_t) in $\Omega.m$ and the minimum calculated transmissivity (T_h) in m^2/day of the sandstone to fractured limestone

Vertical electrical sounding station (VESs)	True resistivity of sandstone to limestone (ρ_t) in $\Omega.m$	Thickness of sandstone to limestone (h) in m	Transmissivity (T_h) of sandstone to limestone ($h * (125.76/\rho_t)$) in m^2/day
VES 2	92 (S.S to limestone)	93	127
VES 6	73 (S.S to limestone)	85	146
VES 13	73 (S.S to limestone)	89	153
VES 14	77 (S.S to limestone)	91	149
VES 15	84 (S.S to limestone)	90	135
Average	80	90	142

the complicated subsurface resistivity parameter values. In general, this technique assisted in discovering the groundwater aquifer and studying the structural and hydrogeoelectrical conditions of this aquifer. The resistivity measurements were carried out at 24 vertical electrical sounding stations (VESs) along wadi Om Dehas. The interpretation of these VESs assisted in detecting and discovering the water-bearing layers change in its thickness and lithological constituents along

the area. The shaly sandstone, sandstone, and sandstone to limestone were the main geological units of the recorded aquifer. This aquifer is thickening toward the east where Abu Sha'r Mountain in the form of graben takes NWN-SES direction. Therefore, the suggested locations for drilling the productive wells were chosen along this graben as shown on profile A–A. Accordingly, the resulted new data of drilling at two locations confirmed the expected results from the

geoelectrical outputs and assisted in studying the hydrogeological conditions of this aquifer.

The outputs of the suggested assumptions according to Ammar and Kamal (2018) by using these curves in the form of inferred faults were confirmed with the previous geological and structural studies. These outputs concluded that several inferred faults at several directions affected the geological units and may contribute to creating the main water-bearing layer. So, the expected dip direction of the geological layers was from the west, where the basement rocks are present, to the east, where the central parts are present and from the east, where Abu Sha'r Mountain is present, to the west, where the central parts are present. Also, the resistivity values of this aquifer assisted in expecting the complicated flow direction of the groundwater which was from west to east and from southeast to the northwest. These values showed that the facies of the rock units are more complicated and changed vertically and horizontally with depth. Therefore, the expected hydrogeological settings will be more complicated. Also, the calculated transverse resistance showed its increase toward Abu Sha'r Mountain where the minimum value was less than $500 \Omega \text{ m}^2$ and the maximum value was $8000 \Omega \text{ m}^2$ close to Abu Sha'r Mountain.

The relationship of the resistivity with both the transverse resistance and the longitudinal conductance was carried out. These relationships were linear and assisted strongly in separating the types of sediments of the aquifer. In case of the relationship between the resistivity and transverse resistance of the shale content with sandstone, the correlation coefficient (R^2) was very weak ($\sim 0.18\%$) because the effect of shale content (shaly sandstone) and water salinity (1500–3200 ppm) in case of the sandstone R^2 was weak (0.24%) and it may be resulted from occurring minor of shale added to the limestone thin beds and water salinity. Therefore, in general, it can be believed that the heterogeneity and water salinity at different directions affected the strength of this relationship. But in case of sandstone to limestone, R^2 was very strong (0.98%) and may result from the effect of pore system with absence of the shale content. The transverse resistance was more affected by the shale content, salinity and rock units. Also, the relationships between the resistivity and longitudinal conductance of the sandstone and sandstone to limestone were linear and strong. The longitudinal conductance in case of the sandstone to limestone was smaller than in case of the sandstone.

The maximum calculated values of the hydraulic conductivity were in case of shaly sandstone. These results reflect that the rocks are highly porous and their pores are highly connected with each other and accordingly the expected permeability will be highly added to the effect of salinity on the real values of this parameter. The relationship between the hydraulic conductivity, as hydraulic parameters (conductivity and transmissivity), and resistivity, as electrical parameters,

was in general linear, and the hydraulic conductivity may increase with increasing resistivity and/or decrease with increasing shale content at the water-bearing rocks. This relation confirmed the occurrence of differences vertically and horizontally at the hydraulic conductivity. The maximum calculated values of the transmissivity were in case of sandstone to limestone, then the intermediate calculated values in case of sandstone and then the low calculated values were calculated in case of the shaly sandstone. The resulted relationship between the resistivity and the hydraulic conductivity of the expected different rock types of the aquifer was in general linear, and its R^2 was weak in case of sandstone rocks but it was moderate in case of shaly sandstone and sandstone to limestone. This relation was inverse in case of the main rock type of the aquifer which was sandstone to limestone and may be due to the high impedance of the sandstone and limestone rocks to electric current. So, the resistivity will increase with decrease in the hydraulic conductivity and transmissivity. The resulted values of R^2 were $\sim 0.415\%$, $\sim 0.187\%$ and $\sim 0.573\%$ in case of shaly sandstone, sandstone and sandstone to limestone, respectively.

Therefore, created Eq. 18 can be used in calculating the transmissivity from the resistivity at this area when the aquifer rocks are sandstone to limestone with taking into account the R^2 value that resulted from the statistical analysis. Finally, the heterogeneity of aquifer and the effect of structure movements of the geological layers were the main and interesting reasons for the non-deducing of the relationships for calculating the hydrogeological parameters, like hydraulic conductivity (K) and transmissivity (T) from the resistivity parameters, like true resistivity (ρ), transverse resistance (T_R) and longitudinal conductance (L_C) of the recorded rock units.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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References

Ammar AI, Kamal KA (2018) Resistivity method contribution in determining of fault zone and hydro-geophysical characteristics of

- carbonate aquifer, eastern desert, Egypt. *Appl Water Sci* 8(1):1–27. <https://doi.org/10.1007/s13201-017-0639-9>
- Beleily AM (1984) The composite standard and definition of paleo events in the Gulf of Suez. In: Proceedings of 6th exploration seminar, Cairo, March 1982. Volume 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo, pp 181–198
- Bosworth W, McClay K (2001) Structural and stratigraphic evolution of the Gulf of Suez Rift, Egypt: a synthesis. In: Ziegler PA, Cavazza W, Robertson AHF, Crasquin-Soleau S (eds) *Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins*, vol 186. Muséum National d'Histoire Naturelle, Paris, pp 567–606. ISBN: 2-85653-528-3
- Bosworth W, Taviani M (1996) Late Quaternary reorientation of stress field and extension direction in the southern Gulf of Suez, Egypt: evidence from uplifted coral terraces, mesoscopic fault arrays and borehole breakouts. *Tectonics* 15:791–802
- Bosworth W, Crevello P, Winn RD Jr, Steinmetz J (1998) Structure, sedimentation, and basin dynamics during rifting of the Gulf of Suez and northwestern Red Sea. In: Purser BH, Bosence DWJ (eds) *Sedimentation and tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London, pp 77–96
- Cassiani G, Medina MA Jr (1997) Incorporating auxiliary geophysical data into groundwater flow parameter estimation. *Groundwater* 35:79–91
- Chandra S, Rao VA, Krishnamurthy NS, Dutta S, Ahmed S (2006) Integrated studies for characterization of lineaments to locate groundwater potential zones in hard rock region of Karnataka, India. *Hydrogeol J* 14(5):767–776
- Conoco (1987) Geological map of Egypt 1:500000, NG 36 NE Quseir. The Egyptian General Petroleum Corporation, Cairo
- Cross NE, Purser BH, Bosence DWJ (1998) The tectono-sedimentary evaluation of a rift margin carbonate platform: Abu Sha'r, Gulf of Suez, Egypt. In: Purser BH, Bosence DWJ (eds) *Sedimentation and tectonics of Rift Basins: Red Sea-Gulf of Aden*. Chapman and Hall, London, pp 271–295
- Darwish M, El-Azabi M (1993) Contribution to the Miocene sequences along the western coast of the Gulf of Suez, Egypt. *Egypt J Geol* 37:21–47
- Egyptian General Petroleum Corporation Stratigraphic Committee (1964) Oligocene and Miocene rock stratigraphy of the Gulf of Suez region. Egyptian General Petroleum Corporation Consultative Stratigraphical Committee, Cairo, pp 1–142
- El Tarabili E, Adawy N (1972) Geologic history of the Nukhul-Baba area, Gulf of Suez, Egypt. *Am Assoc Pet Geol Bull* 56:882–902
- El Wazeer F, Ismail F, Standen E (1992) Fracture geometry and hydrocarbon productivity in the basement rocks of the Zeit Bay field-Gulf of Suez, Egypt. In: Proceedings of 10th petroleum exploration and production conference, Cairo, November, 1990. Volume 1. Egyptian General Petroleum Corporation, Cairo, pp 579–605
- Fawzy H, Abdel Aal A (1986) Regional study of Miocene evaporates and Pliocene-Recent sediments in the Gulf of Suez. In: Proceedings of 7th exploration seminar, Cairo, March, 1984. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo, pp 49–74
- Frohlich RK, Fisher JJ, Summerly E (1996) Electric-hydraulic conductivity correlation in fractured crystalline bedrock: central Landfill, Rhode Island, USA. *J Appl Geophys* 35:249–259
- Garfunkel Z, Bartov Y (1977) The tectonics of the Suez rift. *Isr Geol Surv Bull* 71:1–44
- Ghorab MA, Marzouk IM (1967) A summary report on the rock-stratigraphic classification of the Miocene non-marine and coastal facies in the Gulf of Suez and Red Sea coast. General Petroleum Company, Cairo, unpublished report, E. R. 601
- Hantar G (1965) Remarks on the distribution of Miocene sediments in the Gulf of Suez region. In: 5th Arabian petroleum congress, Cairo. Cairo University, Cairo, pp 1–13
- Herwanger JV, Worthington MH, Lubbe R, Binley A (2004) A comparison of cross-hole electrical and seismic data in fractured rock. *Geophys Prospect* 52:109–121
- James NP, Coniglio M, Aissaoui DM, Purser BH (1988) Facies and geological history of an exposed Miocene rift-margin carbonate platform; Gulf of Suez, Egypt. *AAPG Bull* 72(5):555–572
- Jarrige JJ, Ott d'Estevou P, Burolet PF, Thiriet JP, Icart JC, Richert JP, Sehans P, Montenat C, Prat P (1986) Inherited discontinuities and Neogene structure: the Gulf of Suez and northwestern edge of the Red Sea. *Philos Trans R Soc Lond* 317(A):129–139
- Lattman LH, Parizek RR (1964) Relationship between fracture traces and the occurrence of groundwater in carbonate rocks. *J Hydrol* 2:73–91. [https://doi.org/10.1016/0022-1694\(64\)90019-8](https://doi.org/10.1016/0022-1694(64)90019-8)
- Mabrouk WA (2009) The hydrogeological conditions of some selected wadis along the western coast of the Red Sea between longitudes 32°00'–34°00'E and latitudes 27°00'–29°00' N. Al-Azhar University, Cairo, M.Sc. thesis
- Mazac O, Kelly WE, Landa I (1985) A hydrogeophysical model for relation between electrical and hydraulic properties of aquifers. *J Hydrol* 79:1–19
- Mazac O, Cislérova M, Kelly WE, Landa I, Venhodova D (1990) Determination of hydraulic conductivities by surface geoelectrical methods. In: Ward SH (ed) *Geotechnical and environmental geophysics*, vol II. SEG, Tulsa, pp 125–131
- McClay K, Khalil S (1998) Extensional hard linkages, eastern Gulf of Suez, Egypt. *Geology* 26:563–566
- McClay KR, Nichols GJ, Khalil S, Darwish M, Bosworth W (1998) Extensional tectonics and sedimentation, eastern Gulf of Suez, Egypt. In: Purser BH, Bosence DWJ (eds) *Sedimentation and tectonics of rift basins: Red Sea-Gulf of Aden*. Chapman and Hall, London, pp 223–238
- National Stratigraphic Sub-Committee of the Geological Science of Egypt (1974) Miocene rock stratigraphy of Egypt. *Egypt J Geol* 18:1–69
- Niwas S, de Lima OAL (2003) Aquifer parameter estimation from surface resistivity data. *Groundwater* 41:94–99
- Niwas S, Singhal DC (1981) Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *J Hydrol* 50:393–399
- Niwas S, Singhal DC (1985) Aquifer transmissivity of porous media from resistivity data. *J Hydrol* 82:143–153
- Niwas S, Tezkan B, Israil M (2011) Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. *J Hydrol* 19:307–315
- Orszag-Sperber F, Harwood G, Kendall A, Purser BH (1998) A review of the evaporites of the Red Sea-Gulf of Suez rift. In: Purser BH, Bosence DWJ (eds) *Sedimentation and tectonics of rift basins: Red Sea-Gulf of Aden*. Chapman and Hall, London, pp 409–426
- Parizek RR (1976) Lineaments and groundwater. In: McMurty GT, Petersen GW (eds) *Interdisciplinary applications and interpretations of EREP (Skylab) data within the Susquehanna River Basin*. Skylab EREP Investing. #475 NASA Contributions Penn State University, Pennsylvania, pp 4-59–4-86
- Patton TL, Moustafa AR, Nelson RA, Abdine SA (1994) Tectonics evolution and structural setting of the Suez rift. In: London SM (ed) *Interior rift basins*. AAPG Memoir 59:7–55
- Plaziat JC, Montenat C, Barrier P, Janin MC, Orszag-Sperber F, Philobos E (1998) Stratigraphy of the Egyptian syn-rift deposits: correlations between axial and peripheral sequences of the northwestern Red Sea and Gulf of Suez and their relations with tectonics and eustasy. In: Purser BH, Bosence DWJ (eds) *Sedimentation and tectonics of rift basins: Red Sea-Gulf of Aden*. Chapman and Hall, London, pp 211–222

- Purvanca DT, Andricevic R (2000a) Geoelectric characterization of the hydraulic conductivity field and its spatial structure at variable scales. *Water Resour Res* 36:2915–2924
- Purvanca DT, Andricevic R (2000b) On the electrical–hydraulic conductivity correlation in aquifers. *Water Resour Res* 36:2905–2913
- Rinvert (1999) Geophysical software package: licensed to hydrogeology and engineering geology. Hochi Minh City-Vietnam., Reg., Number, RW 140032, February 03, 1999
- Saoudi A, Khalil B (1986) Distribution and hydrocarbon potential of Nukhul sediments in the Gulf of Suez. In: *Proceedings of 7th exploration seminar, Cairo, March, 1984. Volume 1. Egyptian General Petroleum Corporation and Egypt Petroleum Exploration Society, Cairo*, pp 75–96
- Scott RW, Govean FM (1985) Early depositional history of a rift basin: Miocene in the western Sinai. *Palaeogeogr Palaeoclimatol Palaeoecol* 52:143–158
- Sellwood BW, Netherwood RE (1984) Facies evolution in the Gulf of Suez area: sedimentation history as an indicator of rift initiation and development. *Mod Geol* 9:43–69
- Sewidan AS, Himida IH (1991) Evaluation of hydraulic parameters for Dara area (Gulf of Suez), Egypt. *Qatar Univ Sci J* 11:307–330
- Sharma PV (1997) *Environmental and engineering geophysics*. Cambridge University Press, Cambridge, pp 207–261. ISBN 0-521-57240-1
- Siddiqui SH, Parizek RR (1971) Hydrogeologic factors influencing well yields in folded and faulted carbonate rocks in Central Pennsylvania. *Water Resour Res* 7:1295–1312
- Solomon S, Ghebreab W (2008) Hard-rock hydrotectonics using geographic information system in the central high lands of Eritrea: implications for groundwater exploration. *J Hydrol* 349(1–2):147–155. <https://doi.org/10.1016/j.jhydrol.2007.10.032>
- Soupios PM, Kouli M, Vallianatos F, Vafidis A, Stavroulakis G (2007) Estimation of aquifer hydraulic parameters from surficial geophysical method: a case study of Keritis Basin in Chania (Crete-Greece). *J Hydrol* 338:122–131
- Youness AI, McClay KR (1998) Role of basement fabric on Miocene rifting in the Gulf of Suez-Red Sea. In: *Proceedings of 14th petroleum conference, Cairo, October, 1998. Volume 1. Egyptian General Petroleum Corporation, Cairo*, pp 35–50
- Zohdy AR, Bisdorf RJ (1989) Schlumberger sounding data processing and interpretation program. U.S., Geological Survey, Denver, Co

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