

**Fractures Density Mapping Using Dc Resistivity and its
Effects on Water Accumulation in Tir'ah and Ad Dar'ah Areas,
Wadi Al'ays Quadrangle, Saudi Arabia**

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Abstract: Thirty Five vertical electrical sounding survey and correlation with hand-dug wells was carried out in the Tir'ah and Ad Dar'ah areas, for detecting and estimating the density of fractures and its effects on groundwater accumulation in basement rocks. These VESes were interpreted and subsurface layers ranging from five to six geoelectric units were delineated. The general recorded lithologies were the topsoil, alluvium, alluvial deposits, weathered basement and the fresh basement rocks. The weathered and fractured basement rocks in Tir'ah and fractured basement rocks in Ad Dar'ah areas were considered the main aquifers. The true resistivity values of these rocks, defined the fractures density and water content of the weathered rocks, were as higher than in the fractured rocks. The true resistivity maps reflected that, the parts of very low to low resistivity values of the weathered rocks in Tir'ah area suggest more groundwater accumulations, while the values of fractured rocks in the northwest parts depict more high water contents. In Ad Dar'ah area, the central parts are expected to be more fractured and of intermediate water content. The hydrogeological properties of these rocks were predicted and differentiated from these values. The thickness maps of these rocks revealed the high fractures density and high water amounts of the small thickness were more effective for current penetration than the large thickness. The depth to groundwater was generally shallow and its accumulation and flow direction were expected in the areas of low resistivity and high fractures density. The zonings of resistivities of the weathered, fractured and hard rocks are classified to low, medium and high values, respectively. Overlap of the resistivity ranges for the saturated rocks were observed in some locations. Furthermore, the calculated porosity and fractures density referred to the average values of the weathered rocks in Tir'ah area was found to be 4.57% and 3.32/m, for the fractured rocks, 3.3% and 2.38/m in Tir'ah area and 2.45% and 8.03/m in Ad Dar'ah area. These results confirmed that, the weathered rocks have the best good physical properties followed by the fractured rocks in Tir'ah area, then in Ad Dar'ah area. Consequently, this study which summarized the hydrogeological properties of the delineated aquifers are expected better in Tir'ah area than in Ad Dar'ah area. Deriving from this study, the resistivity values must be carefully used mapping groundwater aquifers and fracture densities.

Key words: VESes • Basement Rocks • Fractures Density • Water accumulation • Wadi Al'Ays • KSA

INTRODUCTION

The Wadi Al'Ays quadrangle is bounded by latitude 25° 00' and 26° 00' N and longitude 37°30' and 39°00' E and occupies 16360km² surface area in the northwestern part of the Arabian Shield (Fig. 1). It consists of deeply dissected mountainous country, in which the altitudes range from about 200 to 1600 m. The main ridge extends from Jabal Jufat Haja in the southwest, through Jabal Sharah, to Jabal Hammat Al Ambajah, where it is breached by Wadi Al Hamad and then continues through Jabal

juwam to the northwestern corner of the quadrangle. Drainage is dominated by Wadi Al Hamad, which crosses the quadrangle from the southeast to northwest, descending in altitude from about 500 to about 200 m. It is joined by the important tributaries of Wadi Al Jizl from the north, Wadi Khaybar from the northeast, Wadi Tir'ah, Wadi Al'Ays and Wadi Marmiyah from the south and by Wadi Amudan from the northwest.

The climate is arid, with only occasional rainfall brought by the prevalent northwesterly winds mainly in December. The winter diurnal temperature range is

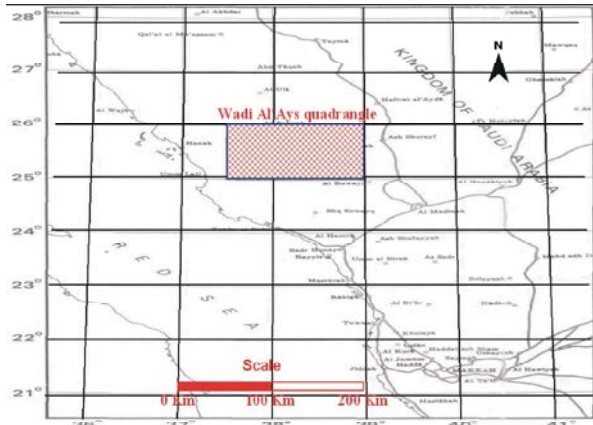


Fig. 1: Location map of the wadi Al'Ays quadrangle (Small Grid).

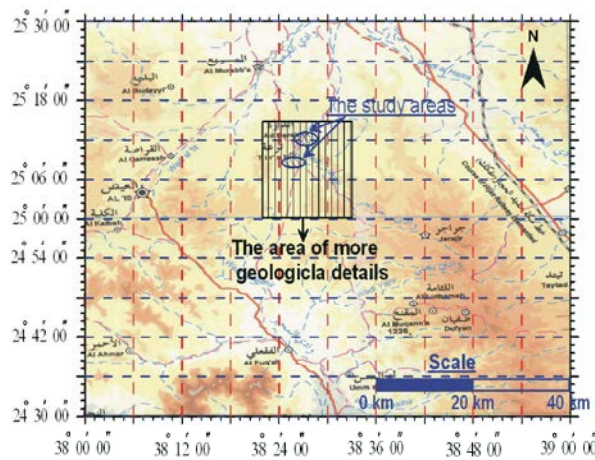


Fig. 2: General location map of Tir'ah and Ad Dar'ah study areas including limits of the area of more geological details.

10°C - 15°C, in the summer from June to September, temperature reaches daytime maxima of more than 40°C. The Tir'ah and Ad Dar'ah are the study areas included in quadrangle shown in Figure 2.

Various workers in the past have used the resistivity techniques, acoustic televiwers and core samples to map fracture densities. For example, Lukes *et al.* [1] studied the determination of the degree to which the very compacted granite is fractured and the hydraulic conductivity of the fracture system at Czech Republic by using the combination of neutron log, electrical resistivity logs, density log, fluid-resistivity log and acoustic log to test the function of the fracture system. Fractures were identified using the acoustic televiwer and the inspection of the core samples. They reported the density of the fractures varying with depth and it was 3 fractures per meter near the surface and dropped to 0.9 fractures per

meter at the depth of 80m. Between depths 80 and 300m, the density increased with depth to the maximum of 8.8 fractures per meter. The weathered zone to a depth of 25m had a permeability of 2×10^{-6} m/s. The zone of opened fractures reached to a depth of 95m with permeability varied from 2×10^{-9} to 2×10^{-7} m/s. The granite rocks below 95m have a dense network of fractures; however, the fractures were closed, so that the permeability was very low with values ranging from 2×10^{-12} to 4×10^{-9} m/s

Generally, Water availability in the Arabian Peninsula is governed by rainfall distribution, which is related in turn to topographic and geologic features. The main topographic features are the western, southwestern and southeastern mountain ridges, as well as the central plateau of the peninsula, which bring orographic rain. Surface runoff is more abundant in these regions than in the rest of the peninsula.

The other major features that influence the availability of groundwater resources are the peninsula's igneous and metamorphic basement rocks known as the *Arabian Shield* and the sequences of sedimentary layers known as the *Arabian Shelf*. The shield consists of an outcrop of hard rocks that begins in the western part of Saudi Arabia and extends from the Gulf of Aqaba to the Gulf of Aden. The shield has limited groundwater stores in the alluvial deposits of wadi channels and geological joints and fracture zones [2].

Geology of Wadi Al'Ays Quadrangle: The Precambrian volcanic and sedimentary rocks of Wadi Al'Ays quadrangle are divided into three groups, the oldest of which is the Farri group. The lower half of the group consists of apparently sub-aqueous silicic volcanic rocks; the upper half begins with silicic andesitic and basaltic volcanic rocks intermixed with sedimentary rocks, some of which were of shallow-water origin and ends with thick pillow basalt.

Deposition of the succeeding Al'Ays group, that comprises a thick series of largely sedimentary rocks in the west and predominantly volcanic rocks in the east. Deposition of the Hadiyah Group that includes the Siqam Formation, consists mainly of basaltic to andesitic volcanic rocks, the Tir'ah Formation consists of distal submarine fan and trough-floor deposits and the Aghrad Formation comprises an alluvial fan conglomerate sequence overlain by thick sheet of sandstone deposits.

Four phases of tectonism and metamorphism have been recognized in the quadrangle. The first three events followed the deposition of the Farri, Al'Ays and Hadiyah groups, respectively and were accompanied and followed

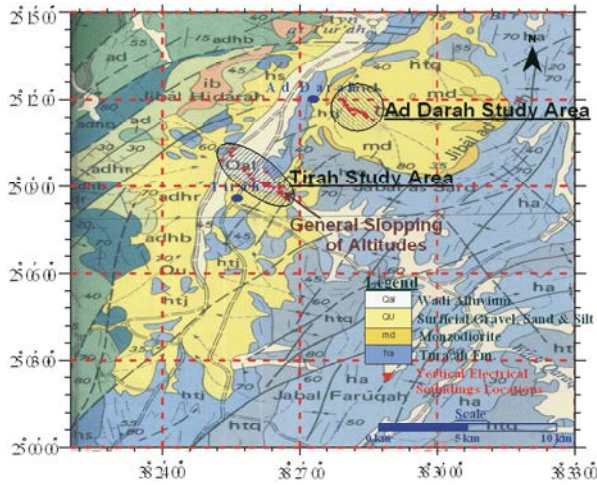


Fig. 3: General geologic map involving the two study areas and VESes locations.

by intrusive activities. The fourth phase, by analogy with structures in the Nuqrah quadrangle, is believed to have followed the deposition of the Jibalah Group elsewhere, although the group is not represented in the Wadi Al'Ays quadrangle.

Unconsolidated deposits, ranging from silt to boulders, occur throughout the area. From near Jabal Al Jaziyah to the north of the quadrangle, the central part of the trough floor is occupied by wadi sand and silt, hummocky and channeled, through which the main water courses pass. The pediment slopes at the sides of the trough and at the southeast are occupied mainly by gravelly to sandy braided stream deposits. Rejuvenation of drainage in the upper parts of the pediment slopes by

late minor uplift, probably apart of continuing movement related to the opening of the Red Sea, had resulted in the formation of Terraces in places.

Wadi alluvium and broad lateral braided stream deposits occur in the major wadis with feldspathic sand, being well developed in the area occupied by Jabal Ad Darah monzoniorite (Fig. 3). Windblown sand occurs mainly on the eastern side of the Jizl trough, deposited where the prevailing north-westerly wind, carrying alluvium from the trough floor and strikes the mountains to its northeast. A small area of windblown sand also occurs in the extreme southwest of Wadi Al'Ays quadrangle [3].

Geoelectric Surveying

Field Measurements: Thirty five vertical electrical soundings (VESes) data were acquired using Schlumberger array in the selected area of study using maximum electrode spacing $[AB/2]$ of 200m using CAMPUS OHMEGA (Ω) instrument. Through this study, four and three geoelectric cross sections were constructed in Tir'ah and Ad Dar'ah study areas (Fig. 4), respectively. Also, lithologic logging of some of the well encountered was carried out for correlation purposes with the VES data.

Quantitative Interpretation of the Field Data: Generally, the quantitative interpretation of the field data means the determination of the thicknesses and true resistivities of the individual layers. From the interpretation, it can detect the lithologies encountered within these layers in the vicinity of the analyzed VESes and between them.

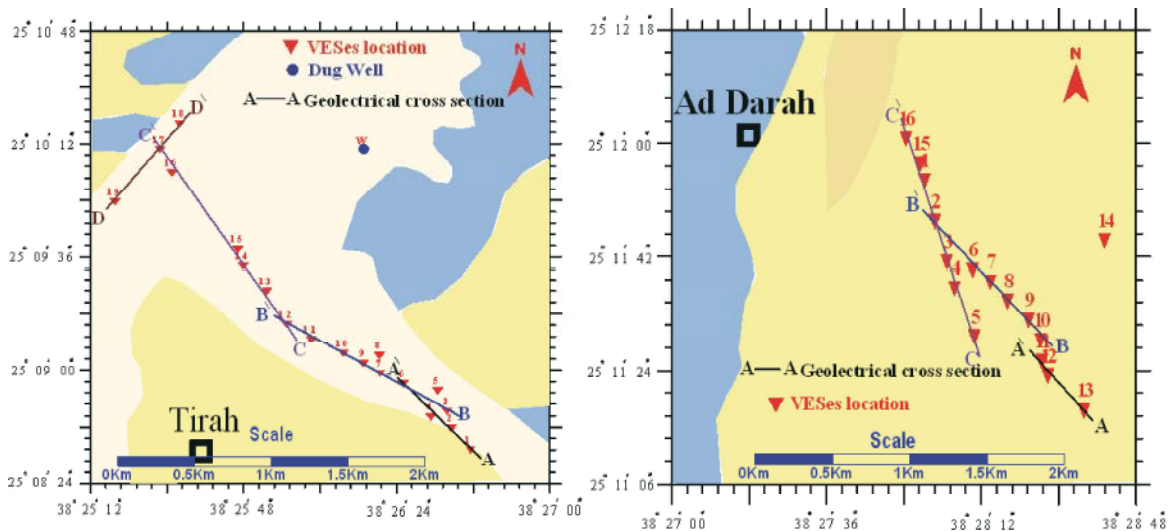


Fig. 4: Vertical Electrical Soundings (VESes) and geoelectric cross sections distribution map in Tir'ah (left) and Ad Dar'ah (right) study areas.

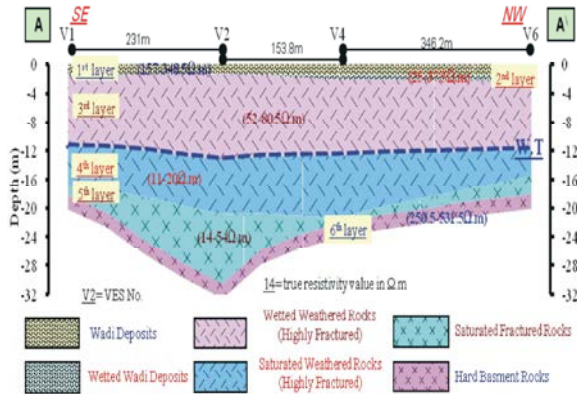


Fig. 5: Geoelectric cross section A-A' in Tir'ah study area.

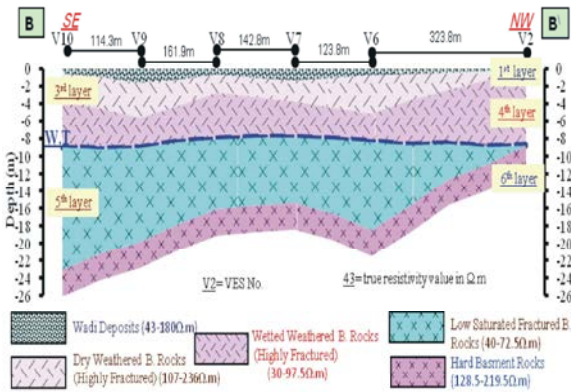


Fig. 6: Geoelectric cross section B-B' in Ad Dar'ah study area.

This may reflect the vertical and lateral changes in the rock constitution of the shallow section penetrated by the electric current. The determination of the true resistivities of the different subsurface layers can give good information about fractures and their density and groundwater accumulation, as well as their properties.

The quantitative interpretation of the geoelectric data obtained for the present study in the two areas includes the followings:

A- Interpretation of the vertical electrical sounding curves depends on Zohdy's technique [4] and Rinvert's technique [5] that was executed after the preliminary interpretation carried out according to Zohdy's technique in order to obtain the best picture of the true resistivities, which would assist in predicting the physical and hydrogeological properties of the recorded layers with depths. The results of VESes interpretation in Tir'ah area (such as Fig. 5) revealed that the number of the subsurface layers being varies from five, where the second layer is missed, to six layers, while in Ad Dar'ah area, they are generally five, because of missing of

the third layer instead of the second one (such as Fig. 6). Generally, from this interpretation and geological data, the reported lithologies of the recorded geoelectric layers ranges from alluvium (Wadi alluvium) to alluvial (gravel, sand and silt) deposits in the first and second layers (Quaternary age), while the layers from third to sixth are made up of basement rocks (Precambrian age). Accordingly, the estimated true resistivities of these layers reflect the following:

- The alluvium and alluvial deposits of the first and second layers are dry to wet at the two areas.
- The weathered rocks (highly fractured) of the third and fourth layers are wet to highly saturated in Tir'ah area and dry to wet in Ad Dar'ah area.
- The fractured rocks (low to moderately fractured) of the fifth layer are saturated in Tir'ah area to low saturated in Ad Dar'ah area.
- The rocks of the sixth layer at the two areas are compacted.

Geoelectric Outputs

Geoelectric Cross Sections: The VESes and cross sections distributed along Tir'ah area (Fig. 4) had been taken from the southeast-to the northwest direction. The VESes were measured in the locations of Wadi deposits (Fig. 3). On these cross sections (such as Fig. 5), the fourth and fifth layers were the predicted water-bearing layers at this area.

The first geoelectric layer was characterized by high to very high 92.5-445Ω.m resistivity values, but the second layer was distinguished by intermediate to high 25-164Ω.m resistivity values. The interpreted resistivity values classified the basement sequence to four geoelectric layers, the third, fourth, fifth and sixth, followed the Quaternary deposits. The low to high 15-131Ω.m, very low to low 7.5-21.5Ω.m, low to medium 14-72.5Ω.m and very high >205Ω.m resistivity values were the ranged values of these layers, respectively. These values indicated to these layers are composed of possibly mottled weathered rocks (highly fractured), saturated weathered rocks (highly fractured), saturated fractured rocks and compacted rocks, respectively.

The true resistivity values of the weathered and fractured rocks were compared with each other (Table 1) for revealing the expected effect of fractures density and their saturation on the conductivity. This comparison indicated low value for the saturated weathered layer 7.5Ω.m, while the low value 14Ω.m was interpreted to be saturated fractured layer. The high estimated values of the weathered and fractured rocks were 27.5Ω.m and 72.5Ω.m,

respectively. The calculated average of these values was 17.5Ω.m and 43.3Ω.m for the weathered and fractured rocks, respectively. The previous comparison concluded that, there is differentiation in the low, high and average values of these rocks and some overlapping between them (Fig. 13). This differentiation and overlapping gave a guide to the ability for separating between these rocks and expecting their hydrogeological properties.

Ad Dar'ah area, which was the second study area at Wadi Al'Ays, is located in the northeastern side of Tir'ah area (Fig. 2). Sixteen VESes were measured, distributed along the area (Fig. 4) and directed southeast-northwest. The area is characterized by alluvial deposits and bounded by Monzodiorite, then Tir'ah Formation (Figs. 3 and 4).

The interpretation of these VESes involved the construction of three geoelectric cross sections (such as Fig. 6). These cross sections showed the six recorded geoelectric layers. In comparison with the recorded layers in Tir'ah area, it is revealed that the same geoelectrical layers as with Ad Dar'ah area was obtained with slight differences in the subsurface geomorphology only. This comparison reflected that, the first and second layers are the same recorded layers in Tir'ah area and sometimes the second layer is not recorded in the two areas at some locations. The third layer in Tir'ah area is the third detected layer in Ad Dar'ah area, but it is dry and recorded only in the B-B cross section (Fig. 6). The fourth layer in Tir'ah area is the same recorded layer in Ad Dar'ah area, but it is wetted. The fractured basement rocks are the recorded constituents of the fifth layer in the two areas. These rocks are highly saturated in Tir'ah area and low to medium saturated in Ad Dar'ah area. The hard basement layer is recorded in the two areas and considered the six geoelectric layer (Figs. 5 and 6). Also, this comparison attained that, the groundwater in Tir'ah area is expected in the weathered and fractured layers, but in Ad Dar'ah area is contained in the fractured layer and its content is expected to be higher in Tir'ah area and lower to intermediate in Ad Dar'ah area.

The true resistivity values of the fractured layer, which is the shared water-bearing layer, in the two areas were compared and summarized the minimum values of this layer were 14Ω.m and 38Ω.m in Tir'ah and Ad Dar'ah area, respectively. The maximum values were 72.5Ω.m in Tir'ah area and 76Ω.m in Ad Dar'ah area. The average of these values were 42Ω.m and 60Ω.m in the two areas, respectively (Tables 1 and 2). This comparison assisted in predicting the density of fractures and water content in Tir'ah area are expected more abundant than in Ad Dar'ah area.

Table 1: True resistivity values of the saturated weathered and fractured layers and their average in Tir'ah study area

True Resistivity Value (ρ_t)	For Saturated Weathered Layer	For Saturated Fractured Layer
Maximum ρ_t	27.5 Ω.m	72.5 Ω.m
Minimum ρ_t	7.5 Ω.m	14 Ω.m
Average ρ_t	17.5 Ω.m	43.3 Ω.m

Table 2: True resistivity values of the saturated and semi-saturated fractured layer and their average in Ad Dar'ah study area

True Resistivity Value (ρ_t)	For Saturated to Semi-Saturated Fractured Layer
Maximum ρ_t	76 Ω.m
Minimum ρ_t	38 Ω.m
Average ρ_t	57 Ω.m

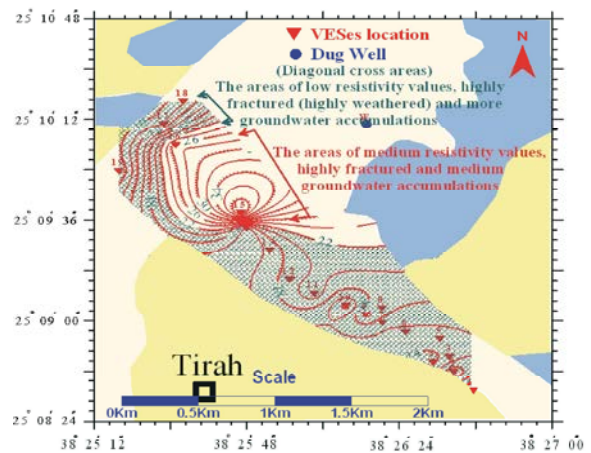


Fig. 7: True resistivity distribution map of the saturated weathered layer along Tir'ah study area.

True Resistivity and Thickness Maps of the Saturated Weathered and Fractured Layers

True Resistivity Maps: Generally, the true resistivity values of the weathered and fractured rocks were mapped for understanding their physical properties and for predicting the intensity of fracturing in rocks and the areas of more fracturing and groundwater accumulation. The distribution of these values of the weathered rocks across Tir'ah area (Fig. 7) suggest the differentiation in their values from very low in the southeastern parts to low in the northwestern parts. The parts having very low to low resistivity values <27Ω.m, through the diagonal cross parts (Fig.7) possibly suggest the probability for increase of fracture intensity and fractures density and therefore increasing in the water accumulation. The parts of intermediate values >27Ω.m, between VESes 15 and 16, may be referred to the relative decreasing in fractures density and water saturation percentage. Therefore, these rocks at these areas are sloped to the fractured rocks.

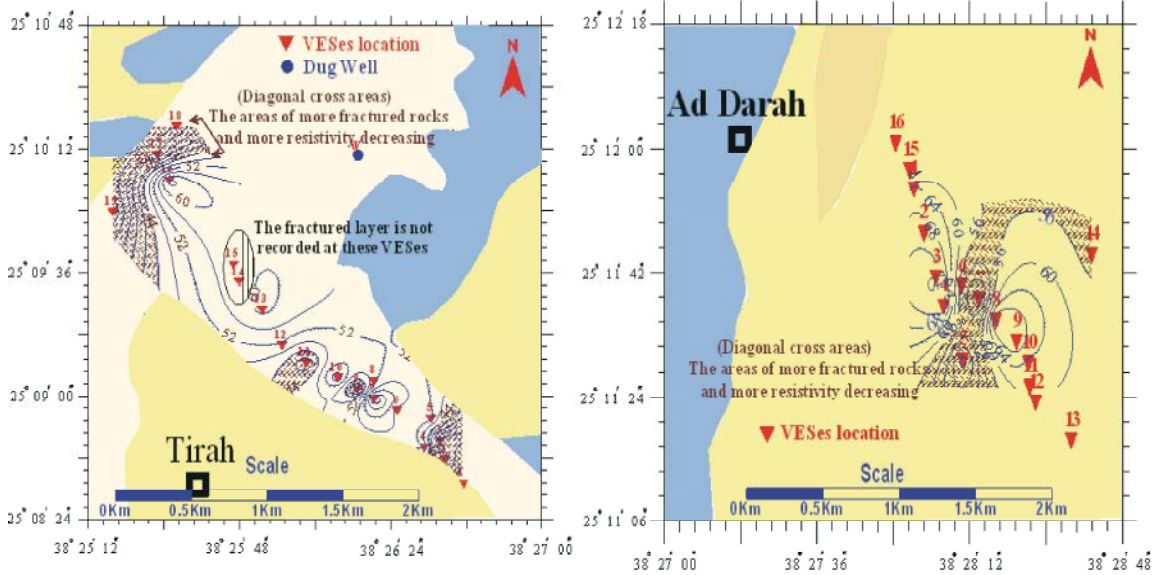


Fig. 8: True resistivity distribution map of the saturated fractured layer along Tir'ah (left) and Ad Dar'ah (right) study areas.

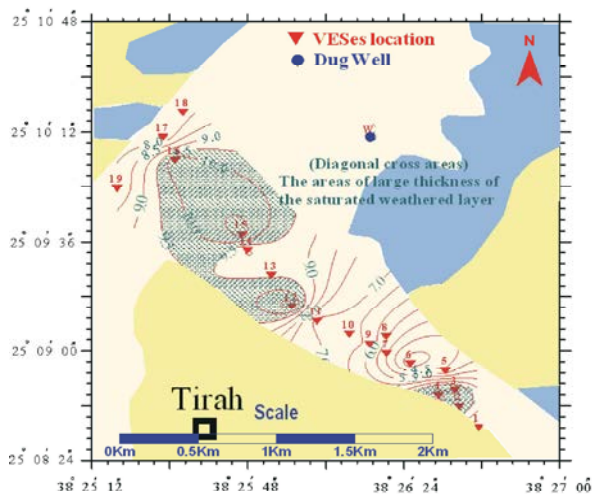


Fig. 9: Thickness distribution map of the saturated weathered layer along Tir'ah study area.

The true resistivity map of the fractured rocks, displayed different parts and characterized by values less than $44\Omega.m$ and more than $44\Omega.m$ ($<72.5\Omega.m$). The values less than $44\Omega.m$ of the diagonal cross areas (Fig. 8), considered these parts of more fractured and more water content. The large part from this area was recorded in the northwest.

On these maps, the general decrease of these values is from the southeast to the northwest. Because of depending the electrical current penetrating the considered section on the density of pore system (fractures) and its saturation percentages, it can be

concluded that the fracturing intensity and fractures density and their saturation are increased from the southeast to northwest. Consequently, the groundwater is expected more accumulated and its flow direction at the same direction along the area.

The true resistivity distribution map of the fractured layer in Ad Dar'ah area (Fig. 8) displayed a conductive axis at the central part of the area in the northeast-southwest direction. This axis is characterized by less resistivity values ranged from $38\Omega.m$ to $56\Omega.m$, but the other resistivity values are more than $56\Omega.m$. These values classified this layer into two parts; the first part, which recorded at the center of the area, is more fractured and it may include intermediate contents of groundwater. The second part, which includes the other locations, is predicted to be less fractured and of low groundwater content. At the end, these values predicted that, the amounts of groundwater at this layer are low to medium and less than the amounts of water implied within the same layer at Tir'ah area.

Thickness Maps: The thickness maps of the saturated rocks were constructed for delineating the horizontal and vertical variation in the thickness and determining the effect of aquifer thickness on rock resistivities (Figs. 9 and 10). The thickness map of the weathered layer (Fig. 9) summarizes some recorded parts characterized by large thickness, along diagonal cross parts. These thicknesses are comparable to the parts of low resistivity values (Fig. 7) and considered more efficient in lowering their resistivity.

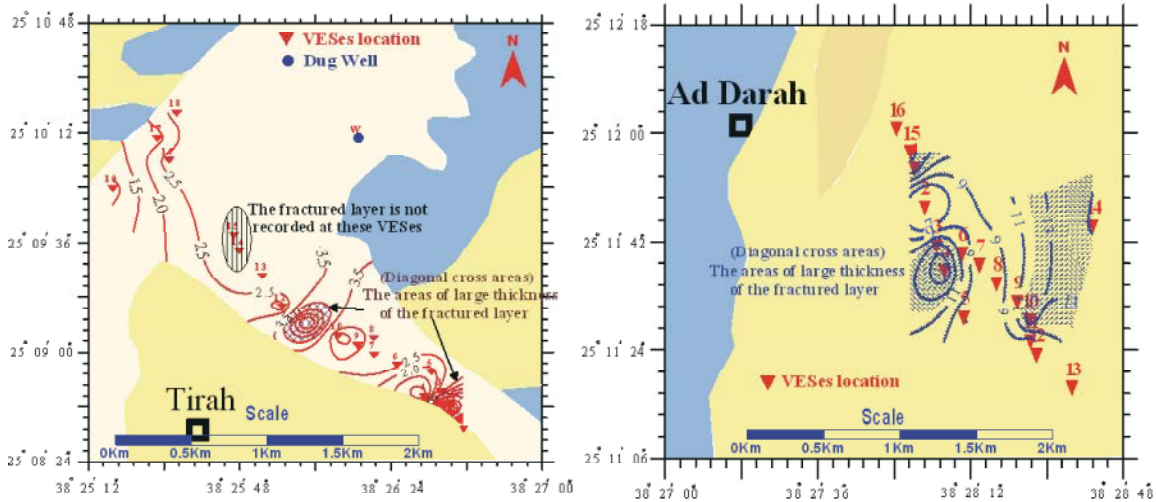


Fig. 10: Thickness distribution map of the saturated fractured layer along Tir'ah (left) and Ad Dar'ah (right) study areas.

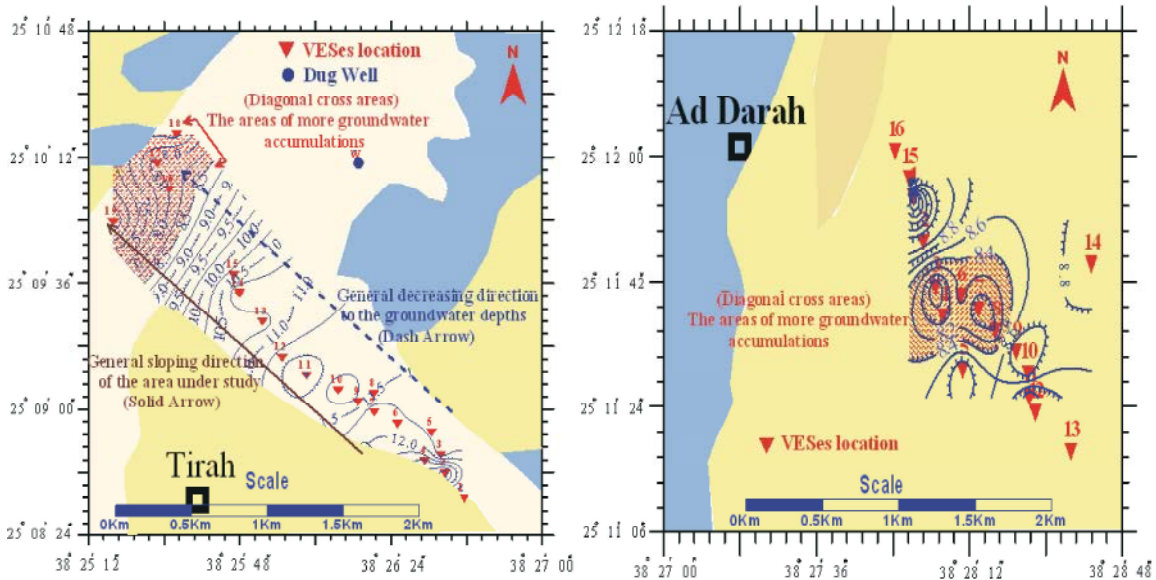


Fig. 11: Depth to groundwater distribution map along Tir'ah (left) and Ad Dar'ah (right) study areas.

The thickness map of the fractured rocks in Tir'ah area (Fig. 10) reflected a considerable thickness at the diagonal cross parts. These parts are comparable to the recorded areas of low resistivity (Fig. 8) and expected more fractured and water content.

The thickness maps of the fractured rocks in Ad Dar'ah area (Fig. 10) revealed that the thickness increases in some parts and decrease in the other parts as well as its missing in some other parts. On this map, the parts of increasing thickness (>11m) are the diagonal cross parts, while the parts of decreasing thickness (<11m) are the middle parts of the area, but it is not recorded under VESes 2, 12 and 13. However, the parts of less thickness are corresponding to the parts of low resistivity (Fig. 8).

This refers to the penetration of electric current that might have influenced the density of fractures and the increase of water amounts, while the parts of large thickness are corresponding to the parts of high resistivity (Fig. 8) except in some parts.

Depth to Groundwater Maps: These maps were constructed (Fig. 11) to delineate the configuration of groundwater depths along the area for determining their expected flow direction and its relation with the general sloping of area altitudes and groundwater accumulation. The distribution of these depths in Tir'ah area showed that, the depth to water in the southeastern part was 13m, while in the northwestern part was 6.5m.

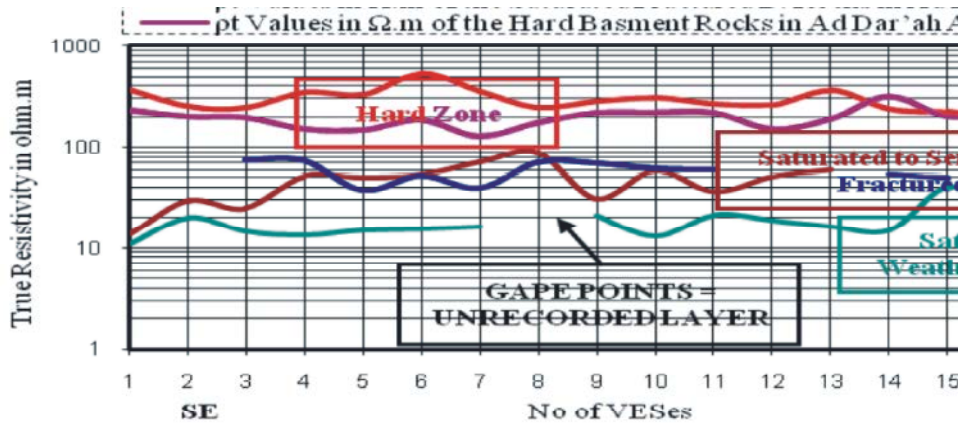


Fig. 12: True resistivity values zonations of the basement rocks in the two study areas.

These values referred to the groundwater are expected to accumulate in the northwest than the southeast; while the general flow direction of groundwater is expected to be the northwest. Also, because of the general sloping of the area, the observed altitudes from the southeast to the northwest (Figs. 3 and 11), thus, the groundwater is expected to accumulate more in the northwest part.

In Ad Dar'ah area, the depth to water range from 7.5m to 10.5m (Fig. 11). The shallow depths are recorded in VESes 3, 4, 6, 7 and 8, through the diagonal cross parts. These parts are comparable to the parts of low resistivities (Fig. 8) and the parts of large thickness (Fig. 10). Suggest high fractures density. Consequently, the main conditions for accumulating water, at the diagonal cross parts, are due to the condensation of fractures along these parts.

Zoning of the True Resistivity Values of the Dry and Saturated Basement Rocks: According to the true resistivity values of the recorded basement rocks, either the weathered or the fractured or the hard rocks at the two study areas, the zonings of these rocks for understanding their electrical and hydrogeological properties was carried out. These areas are classified to high zoning, medium zoning and low zoning. The high zoning characterizes the hard rocks, which have high electrical impedance and therefore they are compacted. The medium zoning characterizes the fractured rocks, which have medium electrical impedance and therefore they are fractured and have medium water content. The low zoning area characterizes the weathered rocks that have low electrical impedance and consequently they are highly fractured and have high water content (Fig. 12).

Generally, these zonings referred to the hard rocks at the two study areas have the same zoning and also the saturated fractured rocks, while the saturated weathered rocks in Tir'ah area have different zoning that lies beneath the zonings of hard and fractured basement rocks (Fig. 12). These levels referred to that having fresh hard rocks in Tir'ah area are relatively higher than in Ad Dar'ah area, while the zoning of the fractured rocks in the two areas is relatively at the same level. The previous conclusions indicated that, the fracture density and groundwater amounts in Tir'ah area are higher than in Ad Dar'ah area.

True Resistivity Ranges of the Saturated Weathered and Fractured Basement Rocks: Generally speaking, hard rocks are bad conductors of electricity, but many geological processes and/or weathered rocks and significantly have lower resistivity values. For instance, dissolution, faulting, shearing, columnar jointing, weathering and hydrothermal alteration usually increase the rock porosity and fluid permeability and hence lower resistivity. In contrast to the above processes, precipitation of calcium carbonate or silica reduces porosity and hence increases resistivity. Hardening of rock by compaction and/or metamorphism will reduce porosity and permeability and hence increase resistivity [6].

Resistivity is, therefore, an extremely variable parameter, not only from formation to formation, but even within a particular formation. There is no general correlation of lithology with resistivity. Nevertheless, a broad classification is possible according to which clays, shales, sands and gravel, compact sandstones and limestones and unaltered crystalline rocks stand in order to increase resistivity [6].

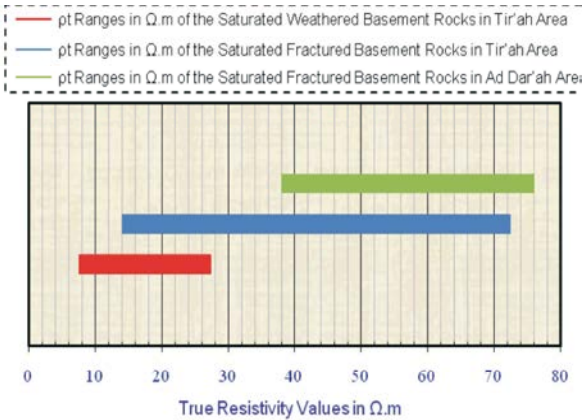


Fig. 13: Ranges of interpreted electrical resistivity of the weathered and fractured rocks in Tir'ah and Ad Dar'ah study areas.

Figure (13) shows the approximate resistivity ranges of saturated weathered and fractured rocks in Tir'ah and Ad Dar'ah areas. From this figure, it is evident that there is overlap between the resistivity values of the weathered and fractured rocks in Tir'ah area. This is because the resistivity ranges of the weathered rocks are between 7.5Ω.m and 27.5Ω.m and of the fractured rocks are between 14Ω.m and 72.5Ω.m. This overlapping refers to the assumption that, the two rocks are shared in some physical properties in some locations. While the resistivity ranges of the fractured rocks in Ad Dar'ah area are between 38Ω.m and 76Ω.m. The general resistivity ranges of the fractured rocks in the two areas are between 14Ω.m and 76Ω.m. These ranges confirms that, these rocks in some locations at Tir'ah area may include the same physical properties in Ad Dar'ah area such as their fracture density and water saturation, whereas the most locations in Tir'ah area are highly fractured and abundant in water content.

Calculating the Expected Porosity and Fractures Density of the Saturated Weathered and Fractured Rocks:

Generally, the secondary porosity includes vuggy porosity that acquired as a result of dissolution, fracture porosity and intergranular produced due to weathering. These secondary porosities are developed after the processes of deposition, compaction and sedimentation. Unweathered igneous and metamorphic rocks rarely have water potential, because their primary porosity is very low. These rocks cannot form aquifers unless they are highly weathered or fractured. Weathered rocks are often good aquifers, provided they have low clay content [7].

Quantity and Nature Distribution of the Electrolyte:

Ohm's law stated that, the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-section.

$$\text{Resistance in ohms} = \rho \frac{L}{S} \tag{1}$$

where: ρ is the resistivity of the conductor.

In rocks, it is most often observed that water generally acts as a conductor. The more abundant the water, the wider the cross-section of the conductor; the quantity of water depends on porosity and saturation. On the other hand, the length of the conductor is proportionality reduced when the concentrations between pores are direct. From the foregoing, it is clear that the electrical resistivity of a rock essentially depends on its water content, the quality of this water, as well as the nature of its distribution.

These factors were taken into account in an extremely important experimental law established for saturated media.

Archie's Law: For a rock saturated with water, Archie established an experimental relationship linking the resistivity of the rock, porosity, the nature of distribution and the resistivity of the electrolyte:

$$\rho_{rock} = \rho_w a \varphi^{-m} \tag{2}$$

where:

- ρ_{rock} Is the bulk resistivity of the rock in Ω.m;
- ρ_w Is the resistivity of the formation water in Ω.m;
- ϕ Is the porosity in %;

m is the cementation factor, fairly constant for a given rock and in-dependent of the fluid, 'm' characterizes the distance travelled by the electric current; this is the equivalent of what we often call tortuosity. It depends on the shape of the pores and the interconnections between them; it generally varies between 1.3 and 2.2;

a is the a factor which depends on the lithology and varies between 0.6 and 2.

Generally, the parameters in the above equation characterizing the texture of the rock are known as the formation factor (F):

$$F = a \varphi^{-m} \tag{3}$$

Archie's expression for a saturated rock then becomes:

$$\rho_{rock} = F \rho_w \quad (4)$$

The following relationship is generally accepted for carbonates and formations that are well cemented and consolidated:

$$F = 1 \varphi^{-2} \quad (5)$$

Generally, the increase in permeability also increases the formation factor [7].

According to the longitudinal conductance (Siemens), which mean the product of average conductivity and thickness of a layer:

$$\text{Longitudinal conductance} = \frac{h}{\rho_t} \quad (6)$$

By applying and considering the low interpreted resistivity values which suggest that an existing relation between density of fractures and resistivity thus, we derived an equation relating Min. ρ_t , h and ρ_t , that was used to calculate the expected density of fractures as shown as follow:

$$\text{Density of fractures} = \text{Min. } \rho_t \frac{h}{\rho_t} \quad (7)$$

By applying the equations numbers 4, 5 and 7, the formation factor (F), porosity ($\varphi\%$) and density of fractures per meter to the saturated weathered and fractured basement rocks in the two areas were estimated (Tables 3, 4 and 5).

Tables 3 to 6 showed that the minimum calculated value of the formation factor of the weathered rocks in Tir'ah area as 3.52 and the maximum value as 6.88. The minimum and maximum calculated values of the porosity are 3.81% and 5.33%, respectively. While the calculated densities of fractures are 1.74/m as a minimum value and 4.89/m as a maximum value (Table 3).

The minimum calculated values of the formation factor, porosity and density of fractures of the fractured rocks in Tir'ah area are 4.48, 1.88% and 0.16/m, while the maximum values are 28.32, 4.72% and 4.6/m, respectively. Also, in Ad Dar'ah area, the minimum values are 12.16, 2.03% and 4.19/m and the maximum values are 24.32, 2.87% and 11.86/m, respectively (Tables 4 and 5). The maximum value of the fractures density (11.86/m), which calculated in Ad Dar'ah area, is expected, because these rocks are more fractured, but they have low to medium water contents.

Table 3: The calculated expected porosities and densities of fractures of the saturated weathered basement rocks in Tir'ah study area

No of VESes	ρ_t Values in $\Omega.m$ of the Saturated			ρ_w in $\Omega.m$	$F=\rho_t/\rho_w$	$(\varphi)^2=1/F$	$(\varphi)\%$	Density of Fractures =
	Weathered B.R. in Tir'ah Area	Thickness (h) in m						Min. $\rho_t^*(h/\rho_t)$
1	11	5.5	3.125	3.52	0.28	5.33	3.75	
2	20	7.6	3.125	6.4	0.16	3.95	2.85	
3	14.5	7.8	3.125	4.64	0.22	4.64	4.03	
4	13.5	8.8	3.125	4.32	0.23	4.81	4.89	
5	15	4.6	3.125	4.8	0.21	4.56	2.30	
6	15.5	3.6	3.125	4.96	0.20	4.49	1.74	
7	16.5	5	3.125	5.28	0.19	4.35	2.27	
8	The Weathered Rocks is not recorded							
9	21	6.4	3.125	6.72	0.15	3.86	2.29	
10	13	6.7	3.125	4.16	0.24	4.90	3.87	
11	21.5	6.6	3.125	6.88	0.15	3.81	2.30	
12	19	10.8	3.125	6.08	0.16	4.06	4.26	
13	16.5	9.4	3.125	5.28	0.19	4.35	4.27	
14	15	8.9	3.125	4.8	0.21	4.56	4.45	
15	40.5	10.7	3.125	12.96	0.08	2.78	1.98	
16	27.5	10.4	3.125	8.8	0.11	3.37	2.84	
17	12	7.5	3.125	3.84	0.26	5.10	4.69	
18	11.5	7.8	3.125	3.68	0.27	5.21	5.09	
19	7.5	8	3.125	2.4	0.42	6.45	8.00	

Table 4: The calculated porosities and densities of fractures of the saturated fractured basement rocks in Tir'ah study area

No of VESes	ρt Values in Ω.m of the Saturated						Density of Fractures =
	Fractured B.R. in Tir'ah Area	Thickness (h) in m	ρ _w in Ω.m	F=ρ _t /ρ _w	(φ) ² =1/F	(φ)%	Min.ρ _t *(h/ρ _t)
1	14	1.3	3.125	4.48	0.223	4.72	1.30
2	29.5	9.7	3.125	9.44	0.106	3.25	4.60
3	25	2.9	3.125	8	0.125	3.54	1.62
4	52	0.6	3.125	16.64	0.060	2.45	0.16
5	50	1.8	3.125	16	0.063	2.50	0.50
6	54	2.6	3.125	17.28	0.058	2.41	0.67
7	72.5	3.6	3.125	23.2	0.043	2.08	0.70
8	88.5	14.3	3.125	28.32	0.035	1.88	2.26
9	31	2.2	3.125	9.92	0.101	3.18	0.99
10	60	1.7	3.125	19.2	0.052	2.28	0.40
11	36	6.5	3.125	11.52	0.087	2.95	2.53
12	51.5	1.7	3.125	16.48	0.061	2.46	0.46
13	61	3.3	3.125	19.52	0.051	2.26	0.76
14	The Fractured Rocks is not recorded						
15	The Fractured Rocks is not recorded						
16	66	2.8	3.125	21.12	0.047	2.18	0.59
17	28.5	1.8	3.125	9.12	0.110	3.31	0.88
18	24	2.7	3.125	7.68	0.130	3.61	1.58
19	20	0.8	3.125	6.4	0.156	3.95	0.56

Table 5: The calculated porosities and densities of fractures of the saturated fractured basement rocks in Ad Dar'ah study area

No of VESes	ρt Values in Ω.m of the Saturated						Density of Fractures =
	Fractured B.R. in Ad Dar'ah Area	Thickness (h) in m	ρ _w in Ω.m	F=ρ _t /ρ _w	(φ) ² =1/F	(φ)%	Min.ρ _t *(h/ρ _t)
1	66	14.4	3.125	21.12	0.05	2.18	8.29
2	The Fractured Rocks is not recorded						
3	76	14.3	3.125	24.32	0.04	2.03	7.15
4	75	17.1	3.125	24	0.04	2.04	8.66
5	38	7	3.125	12.16	0.08	2.87	7.00
6	53	10.1	3.125	16.96	0.06	2.43	7.24
7	40	7.5	3.125	12.8	0.08	2.80	7.13
8	72.5	8	3.125	23.2	0.04	2.08	4.19
9	71	10.8	3.125	22.72	0.04	2.10	5.78
10	62.5	14.1	3.125	20	0.05	2.24	8.57
11	61	8	3.125	19.52	0.05	2.26	4.98
12	The Fractured Rocks is not recorded						
13	The Fractured Rocks is not recorded						
14	54.5	15.2	3.125	17.44	0.06	2.39	10.60
15	50	15.6	3.125	16	0.06	2.50	11.86
16	The Fractured Rocks is not recorded						

Table 6: Minimum and maximum values and their averages of the calculated physical parameters of the saturated rocks at the two areas.

Rock Type and Area	Calculated Parameter and its Average		
	Formation Factor (F)	Porosity (φ%)	Density of Fractures per meter
Weathered Rocks in Tir'ah Area	3.52-6.88 (5.2)	3.81-5.33 (4.57)	1.74-4.89 (3.32)
Fractured Rocks in Tir'ah Area	4.48-28.32 (16.4)	1.88-4.72 (3.3)	0.16-4.6 (2.38)
Fractured Rocks in Ad Dar'ah Area	12.16-24.32 (18.24)	2.03-2.87 (2.45)	4.19-11.86 (8.03)

For the various rock types encountered in the investigated area, the summary of the results obtained for the formation factors, porosity and fracture densities are shown in table 6:

The current work findings suggested that generally, the weathered rocks, in Tir'ah area, have good physical properties than the fractured rocks in the same area and in the Ad Dar'ah area. Consequently, we deduce that the hydrogeological properties of the mapped aquifers in Tir'ah area are better than in Ad Dar'ah area.

CONCLUSIONS

The Wadi Al'Ays quadrangle is bounded by lat 25° 00' and 26° 00' N and long 37°30' and 39°00' E and occupies 16360km² in the northwestern part of the Arabian Shield. The Arabian Shield of the peninsula's igneous and metamorphic basement rocks is one of the several major features that influence the availability of groundwater resources in these areas. This shield consists of an outcrop of fresh hard rocks and it has limited groundwater storage in the alluvial deposits of Wadi channels and geological joints and fracture zones. The Tir'ah and Ad Dar'ah sites are the two studied areas included at this quadrangle.

Nineteen and sixteen vertical electrical soundings (VESes) were carried out in Tir'ah, as well as dug well data and Ad Dar'ah areas, respectively, at Wadi Al'Ays quadrangle. These VESes were interpreted using Zohdy's technique [8] and Rinvert's technique [5]. The thicknesses, true resistivities and lithologies of the subsurface geological layers are the results of interpretation, that were used for constructing four and three geoelectrical cross sections along these areas, respectively. Generally, the geologic layers are classified into Quaternary sediments and Precambrian rocks. These layers were classified into five to six geoelectric units in Tir'ah area, but in Ad Dar'ah area, they were generally six. The lithologies of these layers are formed from Wadi alluvium and alluvial deposits in the first and second geoelectric units (Quaternary age), while the four remaining layers are made up of basement rocks (Precambrian age). The basement rocks were classified into weathered, fractured and compacted rocks.

The weathered and fractured layers in Tir'ah area and the fractured layers in Ad Dar'ah area are considered the main water-bearing layers. The true resistivity values of these layers, referred to the fractures density and water content, are higher in the weathered layers than in the fractured layers. Consequently, the groundwater is

expected to be more accumulating in Tir'ah area than in Ad Dar'ah area.

The true resistivity maps of the saturated rocks were constructed and concluded the parts of very low to low resistivity values of the weathered rocks, that were expected more fractured and more groundwater accumulations. The resistivity values of the fractured rocks in Tir'ah area, reflected locations in the northwestern part, were considered more fractured and more water content. In Ad Dar'ah area, these values delineated a conductive axis directed northeast-southwest and classified the rocks into two parts. The first part is expected to be more fractured and includes medium water content at the center of the area, but the second part characterizes by less fractured and low water content. The comparison between the resistivity values of these rocks was carried out and deduced overlapping between them. This overlapping assisted in differentiating between the hydrogeological properties of these rocks.

The thickness maps of the saturated layers were designed to reflect the high fractures density and high amounts of water of the small thickness were the more effective on the electrical current penetration than of the large thickness, which has lower fractures and lower water content. *The groundwater depth maps* were constructed as revealed the detection of groundwater depth was shallow and its accumulation and flow direction were expected more in the parts that characterized by low resistivity, large thickness and high fracture density.

The zonings of resistivity values of the weathered, fractured and hard basement rocks at the two areas were determined and classified to high, medium and low, respectively. Also, *the ranges* of these values to the saturated rocks were calculated and exhibited overlapping between them. This overlapping showed that, these rocks are shared in some physical properties, such as fractures density and water content in some locations and differ in the other ones.

The porosity and fracture density of the saturated rocks were calculated and defined as the minimum value of porosity of the weathered rocks in Tir'ah area was 3.81% but the maximum value was 5.33% and their average was 4.57%. The minimum porosity of the fractured rocks at the same area was 1.88%, but the maximum value was 4.72% and their average was 3.3%. In Ad Dar'ah area, the minimum porosity of the last rocks was 2.03%, but its maximum value was 2.87% and their average was 2.45%. The minimum calculated values of fractures densities of the weathered and fractured rocks in Tir'ah area were 1.74/m and 0.16/m, but the maximum values were 4.89/m

and 4.6/m and their averages were 3.32/m and 2.38/m, respectively. In Ad Dar'ah area, the minimum value was 4.19/m and the maximum value was 11.86/m and their average was 8.03/m. At the end, all the previous results reflected that, the weathered rocks in Tir'ah area are predicted including the good physical properties, then the fractured rocks at the same area, then the fractured rocks at Ad Dar'ah area. Consequently, the hydrogeological properties of the recorded aquifers are expected to be better in Tir'ah area than in Ad Dar'ah area.

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