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ESTIMATION OF HYDRAULIC PARAMETERS AND POROSITY FROM GEOELECTRICAL PROPERTIES FOR FRACTURED ROCK AQUIFER IN MIDDLE DAMMAM FORMATION AT BAHR AL-NAJAF BASIN, IRAQ

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ABSTRACT

This study tries to examine the correlation between the hydraulic and geoelectrical parameters in an appropriate way, to construct empirical relationship at sites in Bahr Al-Najaf basin in the middle part of Iraq. It is a first attempt of estimating mathematically the effective porosity, hydraulic conductivity, and transmissivity of a confined and anisotropic aquifer of Middle Dammam formation. This aquifer is distinguished with the presence of fractures and paleo karst features of Carbonate rocks. Sixteen of (VES) Schlumberger array using a maximum current electrode separation of (1000) m are conducted near existed wells and boreholes (with pumping test data). The field (VES) data is interpreted, and values of geoelectrical parameters as layer resistivity and thickness, in addition to Dar Zarrouk parameters are determined. Correlating Dar Zarrouk parameters with hydraulic conductivity and transmissivity (derived from pumping test analyses) at nine positions nearby selected boreholes is made. Then representing the results as several graphical relationships of nonlinear curves with polynomial equations of second order and show very good Reliability (R^2). Directly proportional relations between longitudinal conductance with both; the hydraulic conductivity of R^2 = 0.893 and the transmissivity of R^2 = 0.868 are more conformable for such aquifer of average resistivity (70) Ωm. Mathematically estimated values of hydraulic conductivity, transmissivity and those estimated by pumping test analyses are compared by means of histogram figures. The small error ratios (RMS %) as (5.53) and (6.32) between the average values respectively, verify the validity of this methodology to be applied in other sites of similar characteristics. Average effective porosity (secondary type) and water saturation of Middle Dammam aquifer are geophysically computed by Archie's equation as (22%) and (0.9) respectively. These results are close to the typical porosity of saturated carbonate rocks as (27%), and agree with the prevail knowledge that the studied area is a discharge zone for Al-Shbecha hydrogeological basin.

تخمين المعاملات الهيدروليكية والمسامية من الصفات الجيوكهربائية للخزان الجوفي الحجري المتكسر لتكوين الدمام في حوض بحر النجف، وسط العراق

جاسم محمد ثابت، أمين إبراهيم الياسي و علاء ناصر الشمري

المستخلص

هذه الدراسة تمثل محاولة لاختيار المضاهاة بين المعاملات الهايدروليكية والجيوكهربائية بطريقة مناسبة من أجل استنباط علاقات تجريبية بينهما في مناطق من حوض بحر النجف في الجزء الأوسط من العراق. إنها المحاولة الأولى لحساب قيم المسامية الفعالة، التوصيلية الهايدروليكية والناقلية رياضيا للخزان الجوفي المحصور والغير متجانس.

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إن هذا الخزان يتميز باحتوائه على الكسور والتكهفات القديمة العائدة لتكوين الدمام الكاربوناتي. تم إنجاز ستة عشر مسحا كهربائيا عموديا (VES) بترتيب شلمبرجر وبأقصى انفتاح مقداره (1000) م بين أقطاب التيار بالقرب من الآبار الموجودة وآبار الدلالة ذات معلومات الضخ الاختباري. تم تفسير المعلومات الحقلية العائدة للمسحح الكهربائي (VES)، وأن قيم المعاملات الجيوكهربائية كالمقاومية النوعية الحقيقية والسمك الطباقي، مضافا لمعاملات دار زاروك (Dar Zarrouk) قد حددت. إن المضاهاة لقيم معاملات دار زاروك مع قيم التوصيل الهايدروليكي والناقلية (المشتقة من تحاليل الضخ الاختباري) عند تسعة مواقع بالقرب من آبار الدلالة المختارة أجريت. لقد مثلت النتائج بشكل علاقات بيانية ذات منحنيات غير خطية ومعادلات متعددة الحدود للدرجة الثانية والتي تمتلك قيم ثقة (R^2) جيدة جدا. العلاقات الطردية المباشرة بين التوصيل الطولي مع كل من التوصيل الهايدروليكي ذي $R^2 = 0.893$ والناقلية ذي $R^2 = 0.868$ تعتبر أكثر ملائمة للاعتماد لمثل هذا الخزان والذي له مقاوميه نوعية تبلغ (70) أوم.متر. إن قيم التوصيل الهايدروليكي والناقلية المحسوبة رياضيا تمت مقارنتها مع تلك المحسوبة بواسطة الضخ الاختباري بهيئة أشكال إحصائية. إن صغر مقادير نسب الخطأ (RMS%) مثل (5.53) و (6.32) بين معدل القيم بالتعاقبي بين مشروعية هذه الطريقة للتطبيق في مناطق أخرى لها خصائص متشابهة. قيمة المسامية الفعالة (الثانوية) والتشبع المائي لخزان الدمام الأوسط قد حسبت جيوفيزيائيا بواسطة معادلة "آرجي" وكانت القيم (22%) و (0.9) بالتعاقب. إن هذه النتائج تقترب من المسامية المثالية للصخور الكاربوناتية المشبعة (27%)، وتتفق مع المعرفة السائدة بأن منطقة الدراسة هي منطقة تصريف لحوض شبچة الهايدروجيولوجي.

INTRODUCTION

Many investigators studied the relationships between geoelectrical and hydraulic parameters of the aquifers. Empirical and semi-empirical relations between them under different geological conditions have been studied by others (Chen *et al*., 2001).

Application of surface geophysical methods in combination with pumping test analyses at a few sites provides efficient alternative to estimate aquifer parameters mathematically (Mazac *et al*., 1985).

These methods are comparatively cheaper than the conventional hydrogeological ones, and spatially provide distributed physical properties in regions that are difficult to sample (Kosinski and Kelly, 1981).

Determination of aquifer parameters by geophysical methods in fractured and karstified rocks can be a very difficult task, because the groundwater flow is very complicated one. Also, the accuracy in estimating data depends on the hydraulic behavior of the particular fractures in specific sites (Singh, 2005).

The aim of our study is to estimate simply the aquifer parameters and using them for the purpose of water extraction at Bahr Al-Najaf basin. Use of (VES) Schlumberger techniques has become very common in groundwater exploration and in evaluating the geophysical characters of the aquifer zone in several locations. The variation of apparent resistivity with change in electrode spacing and position gives information about the variation in subsurface layering, while increasing the spacing between the current electrodes, leads to the increasing in depth of investigation. Also many standard publishing of direct and indirect interpretation techniques are specifically for VES data (Koefoed, 1979).

The investigated area comprises (765) Km² from Bahr Al-Najaf basin, and is considered as one of the most developed agricultural area. It lies between the geographic longitudes (44° 00' – 44° 30') east, and latitudes (31° 40' – 32° 05') north, at the eastern edge of Iraqi Western Desert. The climatic conditions are arid to semi-arid with averages of (5 – 50)° C as minimum and maximum temperature.

Figure (1) shows the topographic setting of the studied area, and the presence of ephemeral wadies with (NE) and (E) trends, also existing wells and boreholes of pumping test records.

From the point of hydrogeology, this area is regarded as a discharge zone of Al-Shbecha hydrogeological basin towards Euphrates River. The topographic slope is gentle and coincide with strata structural dip (Lateef and Barwary, 1984).

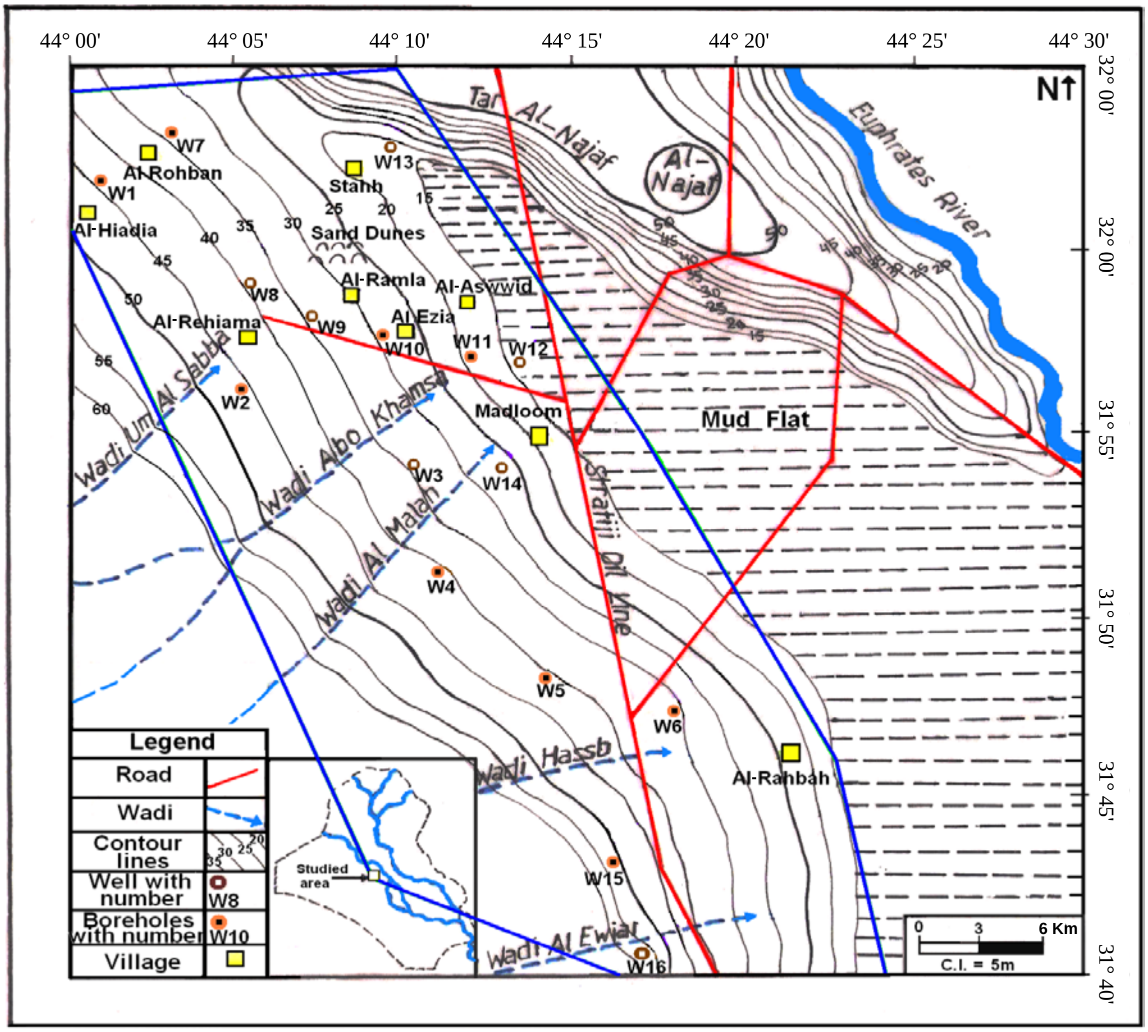


Fig.1: Map shows the topographic characteristics of the studied area and the distribution of available wells and boreholes (adapted from M.A.O., 1986)

GEOLOGY OF THE STUDIED AREA

The studied area lies within the gypsoferious plain and Pleistocene river terraces (Al-Naqash, 2002).

Several formations of Tertiary period are exposed in the studied area, but in some parts are covered by the gypcrete and other sediments (Fig.2). This study is concentrated on the Dammam Formation, which may be divided into three members of carbonate rocks (Buday, 1980). An important part is the Middle Member, which consists fossiliferous dolomite and dolomitic limestone with interbedded layers of marl and cherty nodules in some depths (Al-Sayyab *et al.*, 1982). It is characterized by fissures and paleo karst becoming a good water bearing layers of confined type and secondary porosity, that has a storage coefficient of (4.77 E-05) (Al-Suhail, 1996). The geological cross-section along AA' profile, is shown in (Fig.3).

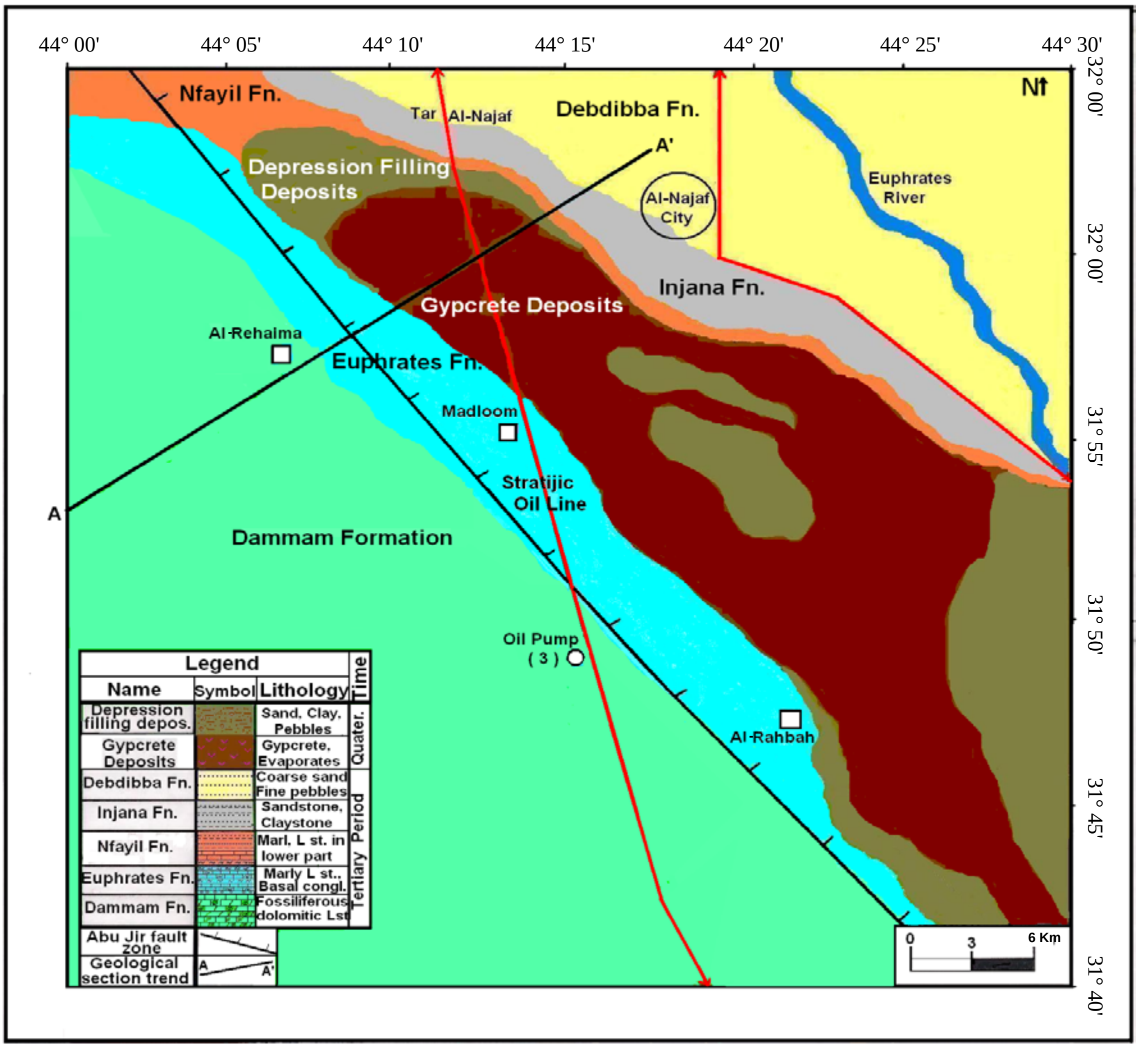


Fig.2: Map shows geological formations in the studied area, modified from geological map of Al-Najaf (NH-38-2), complied by Barwary and Nasira (1996)

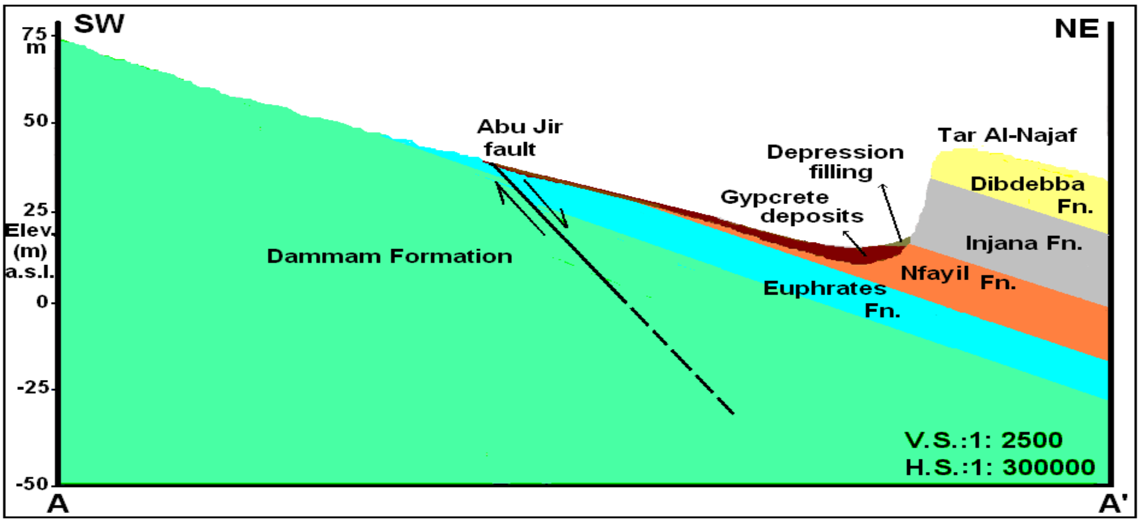


Fig.3: Geological cross-section along AA' profile, adapted from Barwary and Nasira (1996)

The studied area is located precisely within the separating zone between the Unstable Shelf (Mesopotamia Plain) and stable shelf (Western Desert), as shown in (Fig.4). Euphrates boundary fault passes through the studied area (approximately parallel to the Euphrates River), and is regarded as a part of Abu Jir Fault systems, which have deep depths and trend towards (NW – SE) direction (Barazanji and Al-Yasi, 1987). This zone and all surrounding regions are affected by the reactive uplifting of the blocks of the Western Desert during the Tertiary period (Al-Mubarak, 1996).

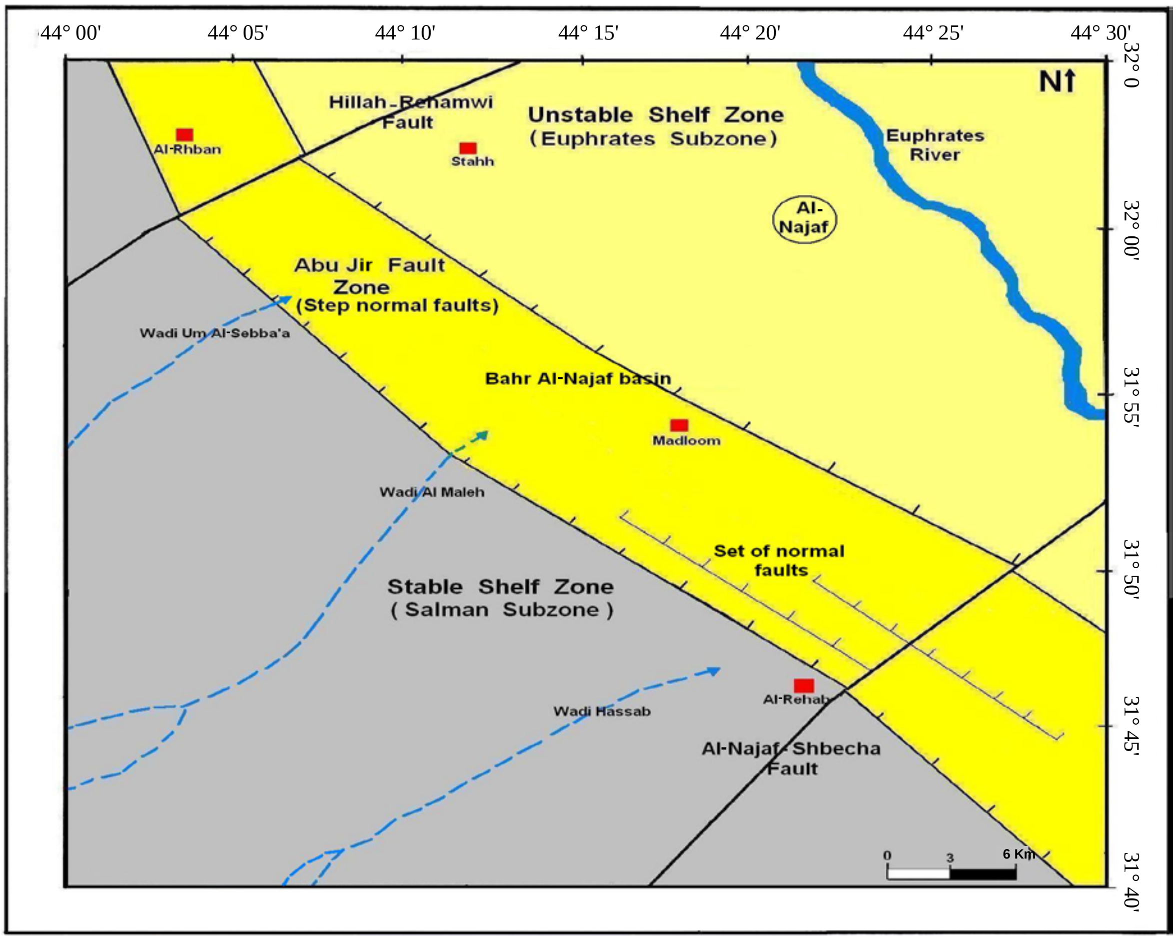


Fig.4: Map shows the structural features in the studied area, modified from Iraqi Tectonic Map (Buday and Jassim, 1984)

DATA ACQUISION AND INTERPRETATION

Most of the selected wells and boreholes in the studied area have depths of more than (100) m, and of artesian self-flowing types, but few are of artesian only (non-flowing).They are numbered from (W1) to (W16), and signed with (sW) for the wells without results of pumping test, and (bW) for the boreholes with pumping test results, as shown in (Fig.1). The information about the selected wells and boreholes obtained from the drilling reports of Al-Furat Center for Irrigation Projects, 1994 and General Commission for Groundwater, (2010) are listed in (Table 1).

Table 1: Information about the selected wells (sW) and the boreholes (bW) from (F.C.I.P) and (G.C.G.W) reports, at or near (VES) locations

Well No.	Well locations	Coordinates		Well Depths (m)	Elevation a.s.l. (m)	Well types	Static water a.s.l. (m)	Discharge Liter/sec
		Latitudes	Longitudes					
bW1	Al-Hiadyia	32 02 04.9	44 01 15.7	150	45	Flowing	45	15
bW2	Al-Rehaima	31 65 05.5	44 05 10.3	155	45	Artesian	40	12
sW3	Al-hiadariya	31 5401.6	44 10 51.3	75	35	–	30	10
bW4	Al-Maamai	31 51 01.1	44 11 22.1	140	40	–	37	15
bW5	Al-Eimam	31 48 34.4	44 15 29.7	165	40	Flowing	40	15
bW6	Al-Rahbha	31 47 09.9	44 18 35.8	160	35	–	35	20
bW7	Al-Rohban	32 03 11.5	44 03 42.7	150	35	–	36	12
sW8	Al-Rehama	31 56 06.5	44 05 08.4	145	40	–	40.5	12
sW9	Al-Ramia	31 58 33.6	44 08 38.7	110	35	–	35	12
bW10	Al-Ezia	31 57 36.4	44 09 49.9	140	30	–	31	15
bW11	Al-Aswwid	31 57 06.8	44 12 33.9	150	19	–	20	20
sW12	Al-Aswwid	31 57 57.3	44 13 06.4	135	14	–	14	15
sW13	Stahh	32 03 08.2	44 10 10.9	125	20	–	21	30
sW14	Madloom	31 54 06.5	44 13 23.1	40	26	–	26	12
bW15	Al-Mahmia	31 43 01.7	44 17 25.5	110	50	Artesian	40	10
sW16	Al-Ewir	31 41 37.2	44 17 31.1	110	55	–	43	10

Sixteen (VES) with Schlumberger array are conducted with maximum spacing of (1000) m and (180) m between the current electrodes and potential electrodes, respectively. Positions of the measurements of (VES) techniques are arranged along three geoelectrical profiles, two of them extend parallel to each other's at (NW – SE) trend approximately. While the third one is almost perpendicular to the former profiles at (N – S) direction, as shown in (Fig.5). VES field data are measured with the help of Syscal R2 resistivity-meter and recorded accurately on the field charts.

The observed data of apparent resistivity are represented as curves of several types, which are smoothed and quantitatively interpreted by partial curve matching (Ebert sub method). Using sets of the theoretical master curves of two and three layers with the help of the auxiliary graph of A, Q, H and K types (Orellana and Moonley, 1968). The results of manual interpretation are improved and supported by the help of computer with the inverse modeling of IPI2 Win program (Moscow, 2001). All values of the quantitative interpretation are treated by the equivalence option to determine the uncertainty ranges of resistivity and thickness values for every layer. The geoelectrical results are listed in (Table 2).

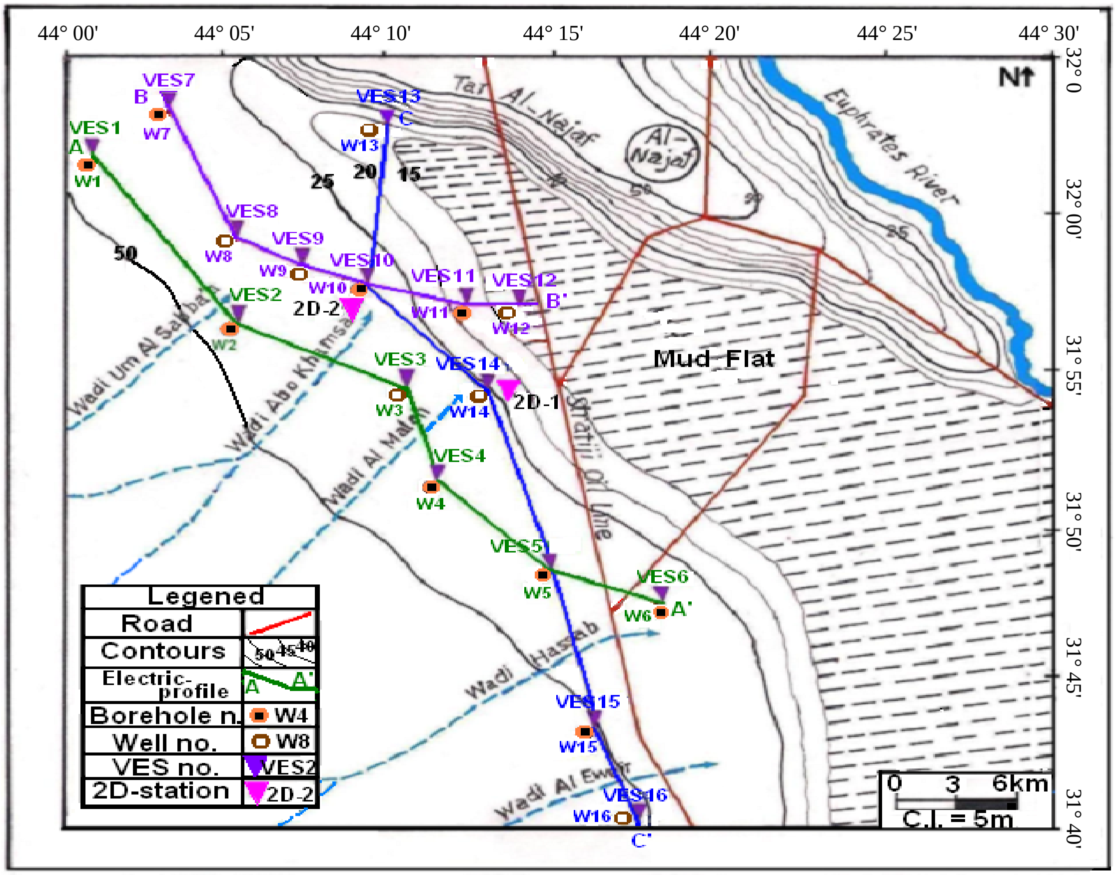


Fig.5: Three geoelectrical profiles (AA', BB' and CC'), with their intersections sites

Table 2: Quantitative interpretation of VES curves by the manual inverse modeling of IPI2W in Program

VES No.	ρ1 (Ωρ)	h1 (m)	ρ2 (Ωρ)	h2 (m)	ρ3 (Ωρ)	h3 (m)	ρ4 (Ωρ)	h4 (m)	ρ5 (Ωρ)	Total depth (m)
VES1	18.9	1.5	35,55	6.37	12.6	37.75	69.47	152.6	13.13	198
VES2	298.7	1.64	136.5	6.65	31.8	42.1	107	141.8	23.94	192
VES3	44.22	0.62	122.5	5.18	12.53	42.86	70.35	166.4	22,92	215
VES4	52.97	1.4	30.37	2.68	14.77	18.0	61.34	178.3	14.69	200.5
VES5	22.44	0.81	65.28	6.9	17.42	45.49	66.58	154	14.42	207
VES6	17.83	0.61	25.95	4.54	11.69	26.33	65.99	171.6	15.0	203
VES7	52.94	0,48	78.42	3.52	24.1	27.11	60.46	168.9	20.85	200
VES8	41.21	0.34	101.9	3.44	12.79	21.68	58.26	159.3	15.12	185
VES9	6.34	1.22	13.52	8.98	51.47	160.3	18.22	–	–	170.5
VES10	2.19	0.85	8.98	27.24	52.23	174	19.28	–	–	202
VES11	2.76	1.0	15.39	34.33	40.25	163.2	18.63	–	–	198.6
VES12	5.64	1.0	12.22	32.39	37.4	163.9	13.59	–	–	197.3
VES13	48.8	1.18	2.9	2.0	1.0	22.5	32.4	–	–	26.0
VES14	1.54	0.81	10.18	35.61	62.53	170	14.6	–	–	206.5
VES15	44.18	1.14	71.15	12.89	44.8	64.17	116.8	119	38.35	197
VES16	241	0.43	460.7	4.5	62	54.9	120.4	142.7	35.56	202.5

MATHEMATICAL FORMULATION BETWEEN DARCY'S AND OHM'S LAWS

Water in the fissures is the main factor controlling the flow of electric current in mineralized (electrolytic) water, by the ions which flow in same paths of water. If the flow of electric current is parallel to the geological layering and the hydraulic flow, an analogy between the electrical current flow and the groundwater flow in layered media may happen (Zhdanov and Keller, 1994). Since both; the hydraulic and electrical conductivity of the aquifer may be affected by similar variables, as they flow from the higher potential to the lower depending upon their potential gradients. The hydraulic potential gradient could naturally occur while carrying out the pumping test, whereas electric potential gradient could be imposed when carrying out the (VES) measurements (Lowrie, 1997).

Conceptually, the resistivity method is based on the equation of conservation of charges and Ohm's law; likewise, the hydrodynamics is based on the equation of conservation of mass and Darcy's law. Hence, an interrelationship between resistivity and permeability is expected to exist if the medium is the same. According to Darcy's law the specific discharge (q) in m/s between the opposite sides (in the aquifer) is proportional to hydraulic gradient (dh/t) and hydraulic conductivity (k) in m/s. The factor (k) is the proportionality constant in the following equation:

$$q = -k \frac{dh}{t} \quad \text{.............................. (1)}$$

The flow of water means movement of ions in the water; consequently, the electric current. According to Ohm's law, the flow of electric current in the medium (aquifer) is proportional to the potential gradient between the two points (source and sink). Hence mathematically, it cans be expressed as the equation below:

$$J = -\sigma \frac{dv}{t} \quad \text{.............................. (2)}$$

Where (dv), (J), (σ) and (t) are the potential difference, current density, electrical conductivity (reciprocal of resistivity), and thickness respectively. The factor (σ) is considered as the proportionality constant in the above equation.

These two fundamental laws are analogy with each other and have a large ability for conforming in an aspect of theoretical consideration, when the electric current flow is simulated with the groundwater flow system (Kresnic, 2007). Thus, the equations (1) and (2) can be combined together via a subscriber factor, which is the aquifer thickness (t) here. It is also dealt with by Sri Niwas *et al*. (2003) as:

$$k = \frac{q}{dh} \frac{dv}{J} \sigma \quad \text{.............................. (3)}$$

Where (q/dh) and (dv/J) are only ratios, and the dependency exists between (q) and (dh) and also between (J) and (dv) remains as constants for the same aquifer, and can be written as (Aq) and (A_J):

$$k = Aq\, A_J\, \sigma \quad \text{.............................. (4)}$$

The constant Aq (q/dh) characterizes the flow of water and is dependent on the hydraulic conductivity (k) of formation (usually unchanged), whereas A_J (dv/J) relates with the flow of the electric current, hence it depends on hydraulic conductivity. There is electrolytic current conduction and deals with the ions.

Present in the mineralized groundwater as (charge carriers), so (A_J) could be considered depending on the salinity (also usually unchanged). When the groundwater quality remains fairly constant, and there is a horizontal groundwater flow with a steady state condition (as in the case of the studied area), the product of (Aq) and (A_J) will also be constant, and it can be replaced by the constant (A):

$$k = A\,\sigma \quad \text{or} \quad k = \frac{1}{A\rho} \quad \text{.............................. (5)}$$

The above relation indicates that the hydraulic conductivity (k) is inversely proportional to the aquifer resistivity (ρ). This relation seems to be logical because of the fact; low resistivity is an indication for presence of a highly fissured or a porous aquifer. Also the equation (5) can be transformed, when multiplying its both sides by the factor (t) (aquifer thickness) to become:

$$t\,k = \frac{t}{A\rho} \text{ by substituting will } \; T = AS \quad \text{............. (6)}$$

Where (T) and (S) are transmissivity (m^2/s) and longitudinal conductance (Ω^{-1} or mho) of the aquifer, respectively; also these properties carry the effect of aquifer thickness.

It is assumed, that the fissures are well connected, since this may not always occur in the real domain. So, the hydraulic parameters of the aquifer must be estimated from a long pumping duration to ensure the presence of interconnected fractures. This consideration is verified from the high discharge of most existing wells in the studied area and for long time and also by choosing a suitable geophysical method as (VES) technique with a Schlumberger array, to investigate successfully the deep fractured and karstified aquifers (Keller and Frischknecht, 1982 and Goldscheider and Drew, 2007). Froehlich, *et al*. (1996) and others observed that the transverse resistance is the dominant parameter within the layers, when the electric current tends to flow perpendicular to the bedding planes. So this case controls the K-shaped sounding type curve, because the middle layer is of a higher resistivity than the upper and lower layers. But, when the electric current flows parallel to the beddings as in H-shaped sounding type curve, then the longitudinal conductance is the dominant parameter.

ESTIMATION OF HYDRAULIC AND GEOELECTRICAL PARAMETERS

Results of pumping test analyses were conducted on seven boreholes of drilling depths that exceed (100) m, by Al-Suhail (1996) and Al-Azawi (2009).

There is a further contribution of another two boreholes (numbered W4 and W11) achieved by the researcher in the current study. Table (3) shows the values of hydraulic parameters of M. Dammam aquifer estimated on the mentioned boreholes, besides the field measurements of electrical conductivity (EC) of their waters in μS/cm. It is necessary to know, that Middle Dammam aquifer is identified as confined type from the results of the previous hydrogeological studies. Nevertheless, this charastification is currently confirmed by the qualitative interpretation of (VES) data, as being located between two confining layers of marl and evaporate rocks of low average resistivity; as (20) Ωm. Also the partially saturated thickness of this aquifer (at every borehole) depends on the depth of drilling, and the average value is about (107) m as recorded with other information (Table 3).

Table 3: Hydraulic parameters of Middle Dammam aquifer, obtained from the pumping test results

Bore Hole No.	**Depth (m)**	**Partial saturated thickness of Aquifer (m)**	**Transmissivity T (m^2/day)**	**Hydraulic Conductivity k (m/day)**	**Electrical Conductivity (µs/cm)**
bW1	150	115	595	5.17	3000
bW2	155	105	379	3.6	2750
bW4	140	118	565.6	4.8	3000
bW5	165	112	784	7.0	3250
bW6	160	128.5	1092	8.5	2750
bW7	150	119	600	5.0	3500
bW10	140	112	995	8.65	3350
bW11	150	115	1037	9.0	3700
bW15	110	40	142	3.55	2750
Average	–	107.16	687.73	6.14	3116

Also the magnitudes of all geoelectrical properties including the Dar Zarrouk parameters are calculated, which are related to the nine (VES) stations in the vicinity of the nine boreholes mentioned above. The counting applications are made using the following equations:

$$Tr = \sum \rho 1\ h1 + \rho 2\ h2 + \text{----} + \rho n\ hn \quad \text{and} \quad Tr = \frac{Tr}{H} \quad \text{………..} (7)$$

Where (ρ1 h1) and (ρ2 h2), (Tr), (ρt), and (H), are the bulk resistivities in (Ωm) and thicknesses in (m) of first and second layers, total transverse resistance of (n) layers perpendicular to the bedding planes in (Ωm^2), average transverse resistivity normal to the bedding planes in Ωm, and total thickness of (n) layers in (m) respectively.

$$S = \sum \frac{h1}{\rho 1} + \frac{h2}{\rho 2} + \text{----} + \frac{hn}{\rho n} \quad \text{and} \quad \rho 1 = \frac{H}{S} \quad \text{……….….. (8)}$$

Where (S) and (ρl), are the total longitudinal conductance of n layers along the trend of bedding planes in (Ω^{-1}), and average longitudinal resistivity in Ωm, respectively.

$$\text{Also} \quad \lambda = \sqrt{\rho t/\ \rho l} \;=\; \sqrt{Tr.S/\ H} \quad \text{…………………..…..….. (9)}$$

Where (λ) is an anisotropic factor due to the heterogeneity of the medium (aquifer), and always has average value between (1 – 2) (Habberjam, 1979). The average value of anisotropic factor (λ) within this aquifer is calculated about (1.18), across the two perpendicular directions as seen in (Table 4). This value seems small and may be close to the homogeneous condition, which may refer to the same lithology and a unique groundwater flow. Also the average of aquifer saturated thickness is computed as (160) m, and listed with all results extracted from the above equations in the (Table 4).

Table 4: Geoelectrical properties including Dar Zarrouk parameters of Middle Dammam aquifer extracted from (VES) data

VES No.	Aquifer resistivity ρo (mΩ)	Aquifer saturated thickness (m)	Transverse resistance Tr (Ωρ)	Longitudinal conductance S (Ω^{-1})	Transverse resistivity ρt (Ωm)	Longitudinal resistivity ρ1 (m)	Anisotropic factor (λ)
VES1	69.47	152.6	11323.90	5.41	57.19	36.30	1.25
VES2	107.0	141.8	17892.38	2.69	93.14	71.41	1.58
VES4	61.34	178.3	11278.67	4.23	56.39	47.82	1.08
VES5	66.58	145.0	11447.45	5.00	55.30	41.40	1.15
VES6	65.99	171.6	11742.92	5.00	57.84	40.60	1.19
VES7	64.46	168.9	11182.56	4.00	56.00	50.00	1.05
VES10	45.21	182.7	8570.86	6.92	40.81	30.34	1.15
VES11	40.25	163.2	7100.03	6.65	35.75	30.00	1.09
VES15	111.1	135.3	18289.74	2.80	88.95	73.42	1.10
Average	70.15	160.0	12092.16	4.75	60.15	46.81	1.18

The advantage of the above calculations is also to find the average value of Middle Dammam effective porosity and hence its storage ability for the purpose of the waters management. The most common requirements (as referred in many references) are available in the conditions of this area for applying Archie's equation such as; presence of uniform and confined saturated thickness, absence of clay content within its lithology, and a little mineralization of its waters. This information is obtained from the qualitative and quantitative interpretations of the field curves, in addition to observing properties of the groundwater samples. The formation factors (F) of Middle Dammam aquifer at selected locations is calculated according to the equation below:

$$F = \frac{\rho o}{\rho w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

Where (ρo) and (ρw) are; bulk resistivity of the saturated rocks and resistivity of the groundwater of existed boreholes in (Ωm). Hence, the porosity (φ) of Middle Dammam aquifer at the mentioned locations are calculated, using the equations as in below:

$$(\varphi)^{m} = \frac{a}{F} \quad \text{or} \quad \varphi = \sqrt[m]{a/F} \quad \text{and} \quad \varphi\% = \sqrt[2]{1/F} \times 100 \quad \ldots\ldots\ldots \text{(11)}$$

Where (φ) is effective porosity, and (a), (m) are constants related to the lithology that (a) is porosity coefficient and (m) is cementation index. They are assumed as (1) and (2) respectively, according to Humble formula in case of the carbonate rocks (like the Middle Dammam aquifer). All values of the hydraulic and geoelectrical parameters needed to calculate the porosity at every position are listed in (Table 5).

Table 5: Porosity values of Middle Dammam aquifer by applying Archie's equation

VES No.	**Electrical conductivity (μs/cm)**	**Aquifer resistivity ρo (Ωm)**	**Ground water resistivity ρw (Ωm)**	**Formation factor F**	**Porosity φ (%)**
VES1	3000	69.47	3.33	20.86	22.0
VES2	2750	107.0	3.63	29.47	18.5
VES4	3000	61.34	3.33	18.58	23.0
VES5	3250	66.58	3.07	21.68	21.5
VES6	2750	65.99	3.63	18.17	23.5
VES7	3500	64.46	2.85	22.61	21.0
VES10	3350	45.21	2.98	15.17	25.5
VES11	3700	40.25	2.70	15.00	25.5
VES15	2750	111.1	3.63	30.60	18.0
Average	3116.6	70.15	3.25	21.35	22.00

Estimated values of hydraulic and geoelectrical parameters in this study are conformable with that values of the previous studies of similar lithologies (Younger, 1993 and Hassan and Al-Kubaisi, 2002). Hence the water saturation (Sw) (the fraction of the pore volume filled with groundwater) of the Dammam aquifer is also calculated using the average values listed in (Table 5), and by Applying the following equation:

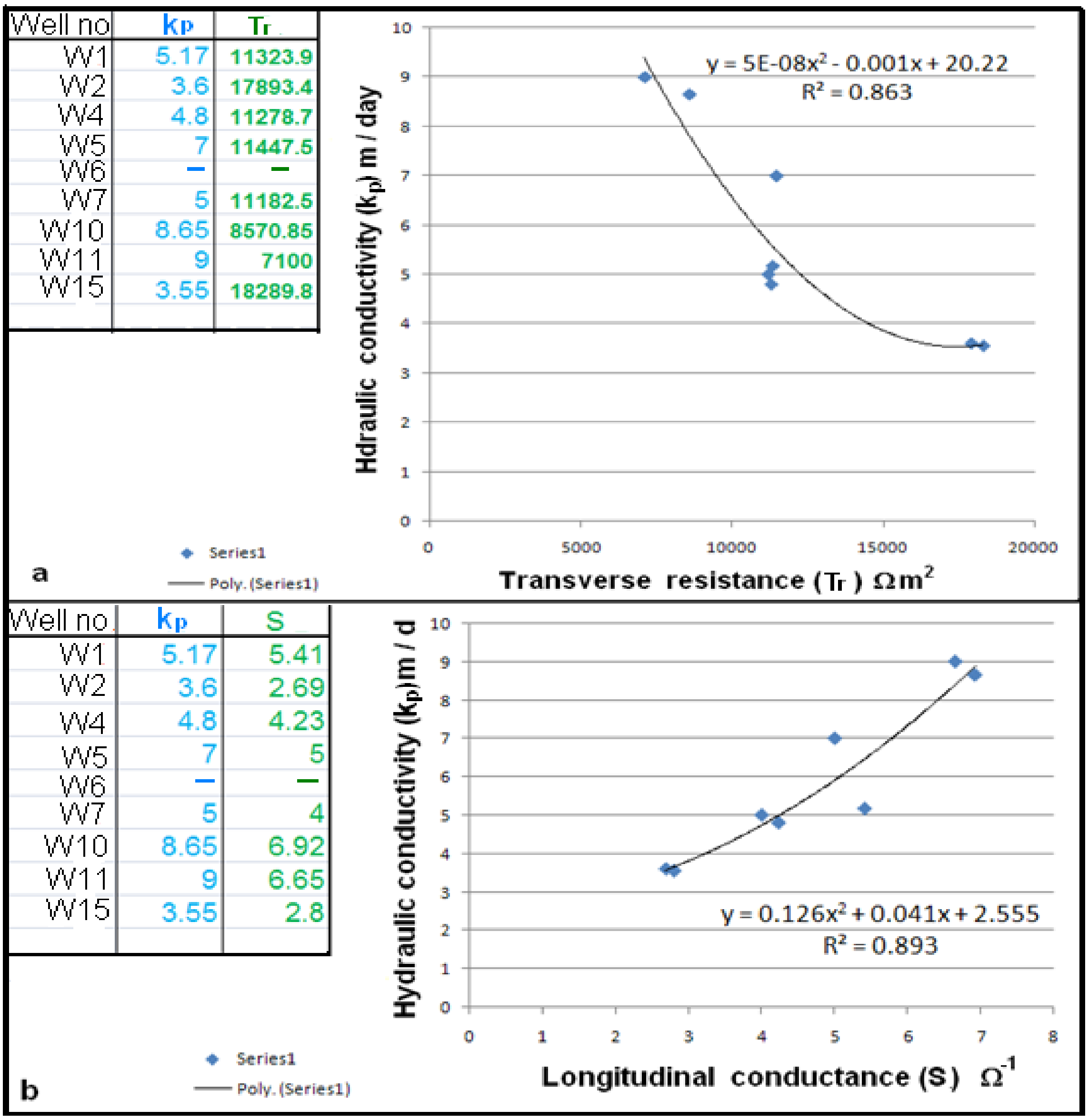
$$Sw = \sqrt[2]{F\,\rho w/\,\rho o} = \sqrt[2]{21.35 \times 3.25/\,70.15} = 0.9 \quad \ldots\ldots (12)$$

These estimated values of effective porosity and water saturation are (22%) and (0.9) respectively, and closed from the typical average values of saturated fractured carbonate rocks as (27%) (Younger, 1993).

Also the calculated values agree with the prevail knowing about this region, as a discharge area of the huge catchment of Al-Shbecha hydrogeological basin **(**Hassan and Al Kubaisi, 2002).

HYDRAULIC AND GEOELECTRICAL PARAMETERS CORRELATION

Two relations are derived between hydraulic conductivity (kp) estimated by pumping test and Dar Zarrouk parameters [transverse resistance (Tr) and longitudinal conductance (S)], as shown in (Fig.6a and b). The first (a) displays a nonlinear curve of inverse relation between hydraulic conductivity (kp) and transverse resistance (Tr) with a polynomial equation of second order having very good Reliability (R^2 = 0.863). The second (b) appears a nonlinear curve of direct relation between the hydraulic conductivity (kp) and the longitudinal conductance (S) with polynomial equation of second order having best Reliability (R^2 = 0.893). These values are obtained, where the information of (VES6) station is missing from the input of the curve, as shown in the table present in (Fig.6).



Well no	kp	Tr
W1	5.17	11323.9
W2	3.6	17893.4
W4	4.8	11278.7
W5	7	11447.5
W6	–	–
W7	5	11182.5
W10	8.65	8570.85
W11	9	7100
W15	3.55	18289.8

Well no	kp	S
W1	5.17	5.41
W2	3.6	2.69
W4	4.8	4.23
W5	7	5
W6	–	–
W7	5	4
W10	8.65	6.92
W11	9	6.65
W15	3.55	2.8

Fig.6: Relationships between hydraulic conductivity with both; the transverse resistance of inverse relation (**a**), and longitudinal conductance of direct one (**b**)

There are very good values of (R^2) related to the equations in (Fig.6a and b). As the fundamental concept is the passage of the electric current within the underground drainage of the fractured aquifer, by means of the present ions and in same direction. So the direct relation between the hydraulic conductivity (kp) and the longitudinal conductance (S) may explain this fact obviously. Therefore, the equation in part (b) can be directly used to calculate the hydraulic conductivity values, using the values of longitudinal conductance. They have been easily obtained from the quantitative interpretation results of the (VES) data, by applying the equation:

$$k = 0.126(S)^2 + 0.041(S) + 2.555 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (13)$$

Also another two relationships are constructed between the transmissivity (Tp) estimated by pumping test with both; the transverse resistance (Tr) and the longitudinal conductance (S) of the inverse and direct relations, as shown in (Fig.7a and b).

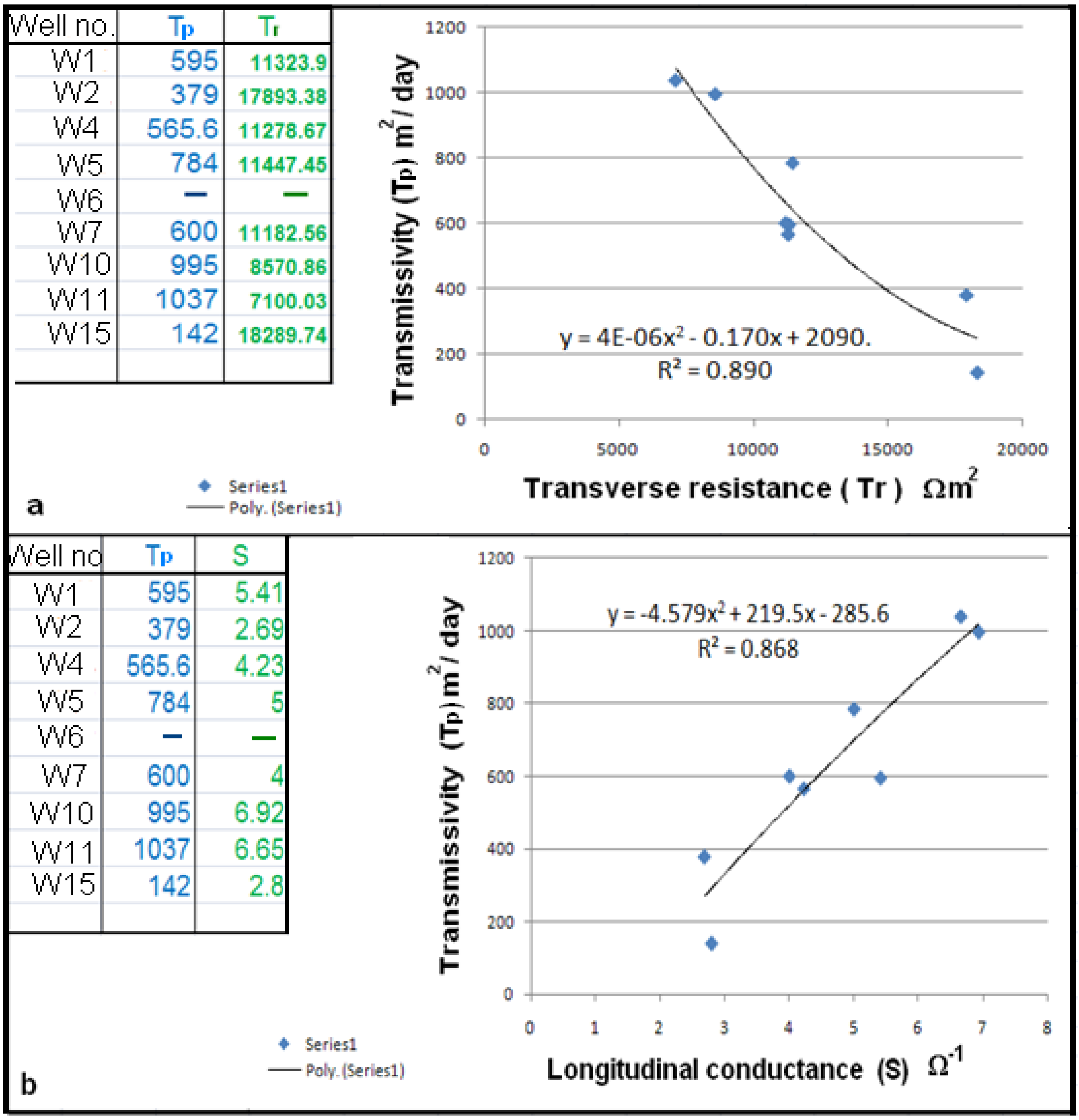


Fig.7: Relationships between transmissivity and both; the transverse resistance of inverse relation (**a**), and the longitudinal conductance of direct relation (**b**)

There are very good values of (R^2) related to the equations in (Fig.7a and b). For the same aforementioned reason, the equation in part (b) can be used to calculate the values of transmissivity (Tp) directly. By using the values of the longitudinal conductance, which have been easily obtained from the quantitative interpretation results of the (VES) data, when applying the equation below:

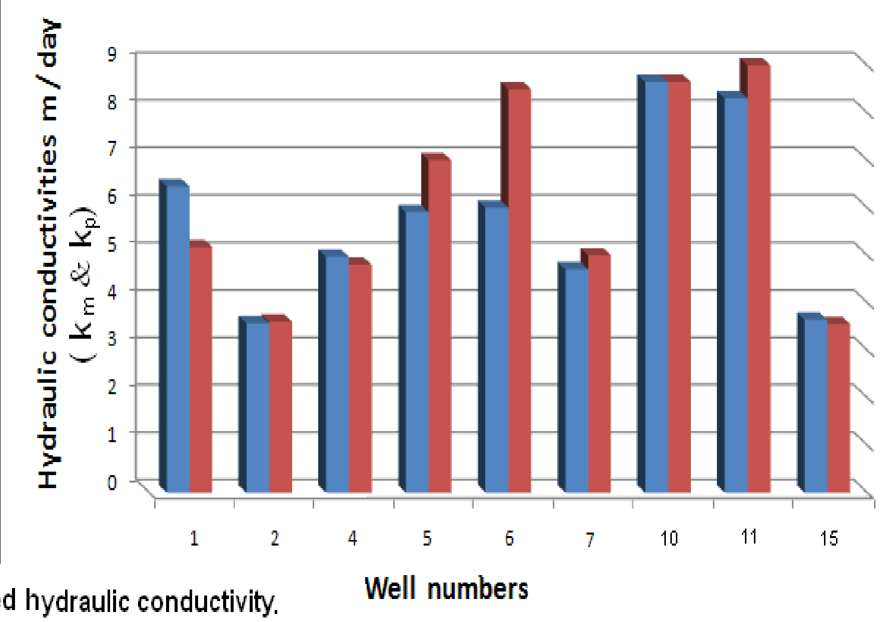
$$T = -4.579(S)^2 + 219.5(S) - 285.6 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(14)}$$

TESTING OF THE METHODOLOGY

A comparison is made between the field measurements of hydraulic conductivity (kp) and transmissivity (Tp) estimated by the pumping tests analyses with that values mathematically estimated by the equations (13) and (14). The later values of hydraulic conductivity and transmissivity are labeled (k_m) and (T_m), respectively. All compared values with the related histograms of the two kinds measurements are shown in the (Figs.8 and 9).

Well no.	k_m	k_p
W1	6.46	5.17
W2	3.57	3.6
W4	4.98	4.8
W5	5.91	7
W6	5.91	8.5
W7	4.73	5
W10	8.87	8.65
W11	8.39	9
W15	3.65	3.55
$\sum$	52.47	55.27
Average	5.8	6.14

$RMS\% = \frac{6.14 - 5.8}{6.14} X100 = 5.53$

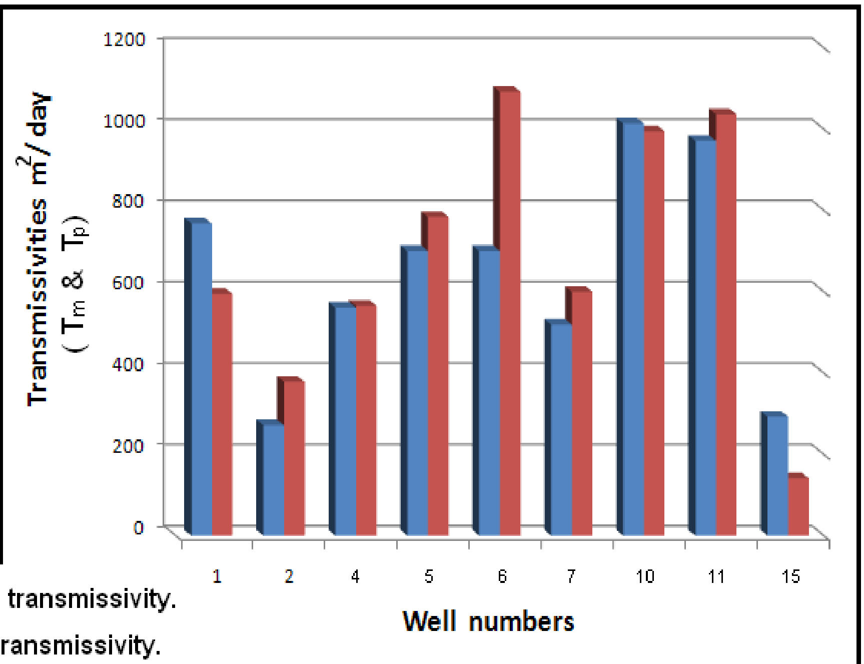


Mathematically estimated hydraulic conductivity.
Pumping test estimated hydraulic conductivity.

Fig.8: Comparison between values of hydraulic conductivity (k_m) estimated by mathematical equations, and those (kp) estimated by pumping test, respectively

Well no.	T_m	T_p
W1	767.9	595
W2	271.7	379
W4	561	565.6
W5	700	784
W6	700	1092
W7	519.1	600
W10	1014	995
W11	971.6	1037
W15	293	142
$\sum$	5798.29	6189.6
Average	644.25	687.73

$RMS\% = \frac{687.73 - 644.25}{687.73} x100 = 6.32$



Mathematically estimated transmissivity.
Pumping test estimated transmissivity.

Fig.9: Comparison between values of transmissivity (T_m) estimated by mathematical equations, and those (Tp) estimated by pumping test, respectively

The ratio of RMS % between the average values of hydraulic conductivities (k_m and kp) estimated mathematically and those by the pumping test analyses is (5.53), while the RMS % between average values of transmissivity (T_m and Tp) estimated mathematically to those by the pumping test analyses is (6.32), as shown in the (Figs.8 and 9), respectively. They are regarded as small values of RMS %, and refer to the large agreement between these two kinds of values. They also give a big potential for applying this methodology in other sites of the similar lithologies.

CONCLUSION

It can be inferred from the study that (VES) data can be used not only for groundwater exploration, but also contributes to estimating the aquifer hydraulic parameters as porosity, hydraulic conductivity and transmissivity, mathematically. The current results gave a useful first approximation about the variations in the magnitudes, and may enable to calculate them with a successful effective alternative. A close agreement between the values of hydraulic conductivity and transmissivity estimated by the pumping test analyses and those calculated from the (VES) data. These are determined from the small magnitudes of the error ratios (RMS %) between the two kinds of values, when comparing them with each other's graphically in order to verify the validity of this methodology. As it is well known, that using only the pumping test analyses for this reason is often prohibitively expensive and consumes time. Eventually, the high recording of Middle Dammam aquifer parameters over most parts of Bahr Al-Najaf basin reflects its hydrotectonic characteristics, which is affected by Euphrates fault and considered as a discharge zone of Al-Shbecha huge basin.

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