

Geoelectrical parameters measurements using an Asymmetrical Schlumberger Sounding technique in the southern part of the Dokan area, NE-Iraq

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Abstract: Fifteen Asymmetrical Vertical Electrical Sounding (AVES) points were acquired along three traverses extending in the southern Dokan area. The results are quantitatively interpreted through forward and inverse modelling to calculate Dar-Zarrouk parameters include transverse resistance (R_T) and longitudinal conductance (S_L) calculated from true resistivity (ρ), depth (d) and thickness (h) of sequence layers succession revealing aquifers from recent sediments overlying the upper part of the rhythmic cycle of the middle Tanjero Formation. Hydraulic parameters deduced from pumping test includes aquifer transmissivity (T) and hydraulic conductivity (K) calculated from equation $K = T/h$. Three relationships between the Dar-Zarrouk parameters and hydraulic parameters were established. Among these, the relationship between transmissivity (T) and transverse resistance (R_T) shows the highest correlation coefficient ($R^2 = 0.9956$), indicating that it is the most precise and reliable relationship. The derived equation ($T = -0.0006 R_T + 23.227$) can therefore be used to estimate transmissivity directly from transverse resistance values for the studied area, as well as for nearby areas with similar geological conditions, where recent alluvial sediments overlie the Middle Tanjero Formation.

Key words: Dar-Zarrouk parameters, transmissivity, hydraulic conductivity, asymmetrical VES

1. Introduction

The non-invasive, relatively cheap and quantitative evaluation technique uses surface geoelectrical methods, especially the Vertical Electrical Sounding (VES) method of geophysical investigation, for locating the depths of sites for groundwater exploitation. The relationship between hydraulic and electrical properties is feasible, given that both are connected to the structure and heterogeneity of the pore space (Mazáč *et al.*, 1985).

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Traditional geotechnical techniques offer data at specific points to assess geotechnical characteristics and therefore the integration of surface electrical and borehole measurements has gained significant popularity in recent years. A pumping test is considered to yield the main data for estimating the transmissivity of an area by matching the special type of curves in a mathematical model to changes in the water level response data (*Valigi et al., 2021*). Furthermore, without accurate pumping test data or a clear understanding of the hydraulic boundaries and aquifer geometry, the application of any pumping test methods becomes unfeasible (*Uma et al., 1989*). The aquifer parameters such as hydraulic conductivity and transmissivity are highly essential for the management and development of groundwater resources (*Soupios et al., 2007*).

The estimation of aquifer transmissivity by the application of electrical resistivity and Dar-Zarrouk parameters have been carefully reviewed and utilised by many geophysicists in previous studies (*Udoinyang and Igboekwe, 2012; Achilike, 2020; de Almeida et al., 2021*). Many techniques have been proposed to determine the saturated hydraulic conductivity of soils, for instance field methods (well pumping test, auger hole test and tracer test), while laboratory methods (constant head) and (falling head) permeameters provide formidable issues in the sense of gaining true representative samples and calculations from empirical formulae (*Todd and Mays, 2005*).

Hydraulic properties including porosity (ϕ), hydraulic conductivity (K), transmissivity (T) and storability (S) are best obtained through pumping tests and down-hole well logging. The implementation of resistivity methods in the evaluation of the connection between aquifer electrical resistivity and hydraulic characteristics through the study and analysis of Dar-Zarrouk parameters, which are longitudinal conductance (S_L) and transverse resistance (R_T) deduced from surface Vertical Electrical Sounding (VES) interpretation have provided a useful and confident solution in differentiating between saline and fresh water aquifers (*Abu Heen and Muhsen, 2017*).

Furthermore, hydraulic conductivity is the single most important hydraulic parameter for flow and transport related phenomena in soil, but there is concern arising from the suitability, efficiency and ease of the different measuring methods under different conditions. A review of the various methods for determining saturated hydraulic conductivity, encompassing field methods, laboratory methods, and empirical formulas, has been con-

ducted to assess the appropriateness and acceptability of these methods as indicated in the literature (*Ibrahim and Aliyu, 2016*). A prior study indicated that prior to performing a pumping test, it is essential to consider factors including the lithological properties of subsurface layers, the thickness and lateral extent of the aquifer, as well as the lateral boundary of the recharge zone in relation to the river (*Kruseman and de Ridder, 2000*). In addition, a recent study by *Nyaberi (2022)* had investigated aquifer layers and determined their parameters through utilising modelled geoelectric layers from Vertical Electrical Sounding (VES) outcomes, these being used in the study area to distinguish the major aquifer from the minor ones. A significant correlation could be observed between the geoelectric layers and the lithologies as indicated by the driller's log, which explicitly delineates four aquifer strata.

When detailed groundwater data are unavailable to fully characterise an unconfined aquifer, researchers often use lumped parameter methods. Lumped parameter methods could be employed to estimate hydraulic properties, which include the initial depth of the water table (D), saturated hydraulic conductivity (K_o) for a given value of drainable porosity (f) and residence time, drainage time scale (t). Current procedures require the construction of recession-slope plots and their interpretation to estimate the parameters in two of the three expressions and a novel procedure was proposed to estimate D , K_o and separately scale time (t) (*McMahon and Nathan, 2025*).

2. Location of the study area

The studied area is located to the northwest of Sulaymaniyah city, in the southern part of the Dokan area, NE-Iraq. Its coordinates lie between longitudes $46^{\circ} 26' 15''$ to $46^{\circ} 32' 40''$ East and latitudes $35^{\circ} 26' 45''$ to $35^{\circ} 28' 30''$ North. The study area runs parallel to the eastern part of little Zab stream and covers an area of a suitable topography for conducting asymmetrical Schlumberger-VES, as shown in Fig. 1.

The designated area for this study is marked by smoothly rolling terrain interspersed with broad valleys that run along the dip direction towards the minor Zab stream. This setting is well-suited for the application of Asymmetrical Vertical Electrical Sounding (AVES) to bypass valleys and is fitting

for the evaluation of aquifer Hydraulic parameters in relation to the aquifer characteristics within the recharge zone.

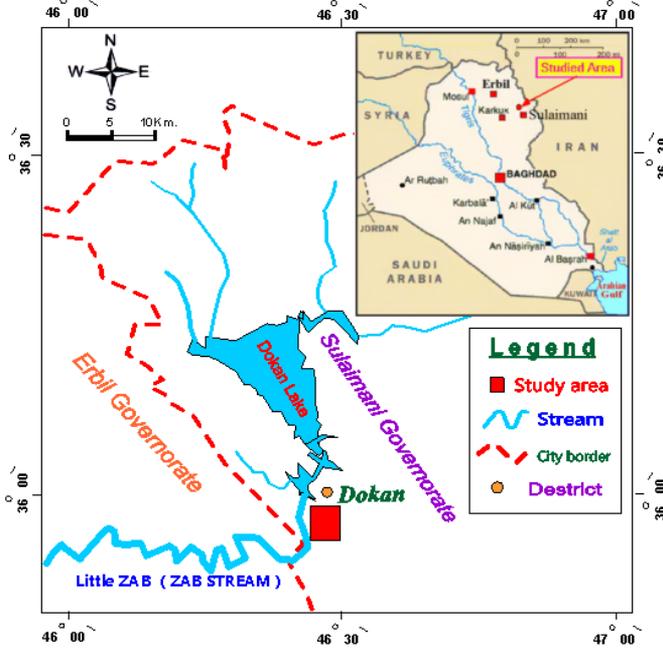


Fig. 1. Location of the studied area in south part of Dukan area (drawn by Surfer® 10, Golden Software, 2011).

3. Hydrogeology of the study area

A dendritic pattern is formed by the numerous sporadic canals that run from NE to SW throughout the surface area. Additionally, the region has abundant groundwater for humanitarian purposes, irrigation, poultry projects, private sector irrigation, and water supplies for communities and regions, as given in Table 1.

The depths of the wells vary from region to region as follows:

1. Wells located in the studied area (Dokan area) and its continuation to the south (Surdash area)
 - Dokan district has 70 wells; the least depth is (20.2 m) in Qashkoli village (study area) and the deepest is (128 m) away from the southern part of the study area.

- Surdash district includes more than 350 wells; the least depth is (31 m) in Charmaga village and the deepest is (385 m) in Goezala village.
2. Wells located in the north part of the studied area
- Khalakan district; there are 11 wells, the least deep well is in Benkadan village with (111 m) and the deepest well is in Khalkan with (350 m) depth.
 - Khdran district has 8 wells; the least deep is (99 m) in Shushka village and the deepest is (251 m) in Khdran village.

Table 1. Wells drilled within and from the northern part of the studied area.

Dokan Area	Districts of Dokan area	No. of wells	Min. and max. depths of the wells (m)
	Dokan	70	20.2 to 128
	Surdash	350	31 to 385
	Khdran	8	99 to 251
	Bengerd	107	54 to 505
	Khalakan	11	111 to 350

4. Tectonic setting

The undulating surface study area is situated at the base of the Peramagroon mountain range. The area is covered by a recent deposit known as the Alluvial deposit, which is composed of gravel, sand, silt, and clay and ranges in thickness from 5 to 20 m. It is particularly thick in the valleys that cover the Tanjero Formation, which is distinguished by the presence of a rhythmic cycle of alternating sandstone, marl, siltstone, conglomerate and limestone. Marl and marly limestone are indicators of the Shiranish Formation, which covers the Kometan Formation, which is characterized by massive beds of limestone, dolomite and dolomitic limestone. Furthermore, in the study area the upper part of the Tanjero Formation comprised of sandstone layers with silty marl, conglomerates, and silty organic detrital limestone. Green igneous and metamorphic rocks and chert grains made up majority of the clasts and as one moves southwest, the Tanjero Formation

gets thinner and finer-grained. The flysch sediments constituting this Formation accumulated in the rapidly subsiding foredeep basin located directly in front of the thrust plates of the abducted margin of the Southern Neo-Tethys, which is in proximity to the Dokan area (stream passage). The age of the coarse sandstone layer in the study area is Maastrichtian (*Jassim and Goff, 2006*), as in Fig. 2A.

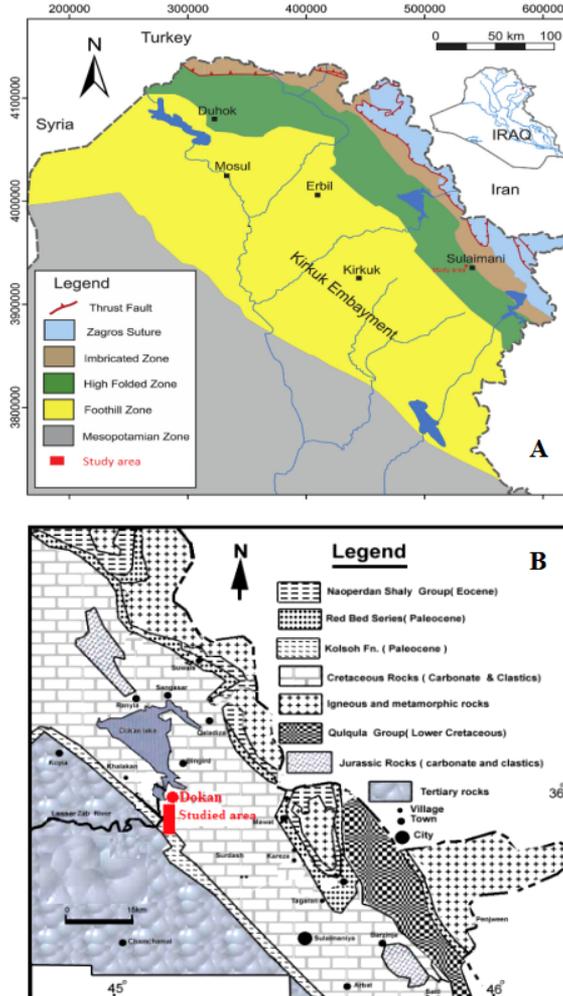


Fig. 2. A. Tectonic setting of the entire and surrounding area (after *Jassim and Goff, 2006*); B. Geological map of the studied area (after *Al-Barzani, 2008*).

In the study area, the upper part of the middle Tanjero Formation is formed of a rhythmic cycle comprising sand layers with silty marl, marl and marly limestone and it is covered by the overlying recent deposit and a top soil layer, see Fig. 2B (after *Al-Barzani, 2008*).

5. Field work and data acquisition

The area of study was surveyed by employing measurements of VES-points using a modern computerized static resistivity meter (model SYSCAL Junior Switch-72, *IRIS Instruments, 2002*) type. The basis of electrical resistivity surveying lies in the concept that the arrangement of the surrounding rocks and soils influences the distribution of the electrical potential in the

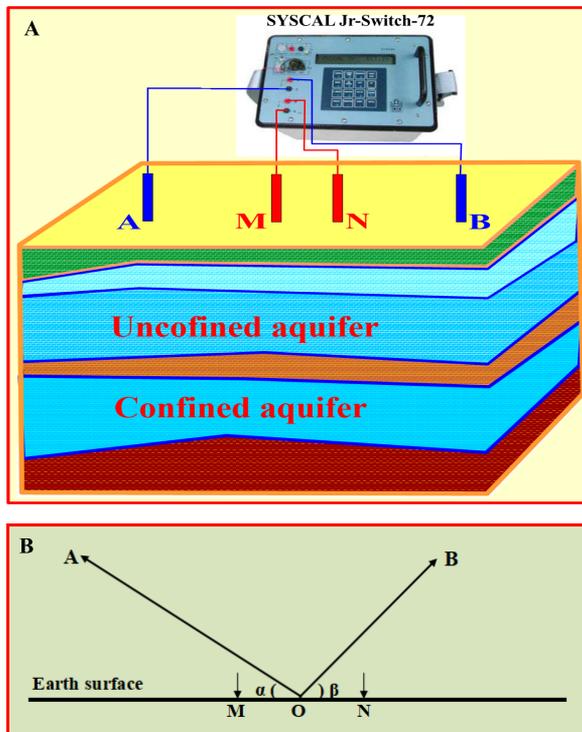


Fig. 3. A. Modern resistivity meter (SYSCAL Junior Switch-72, *IRIS Instruments, 2002*) connected to Schlumberger array; B. Asymmetrical Vertical Electrical Sounding (from *Zohdy, 1978*).

ground surrounding a current-carrying electrode. The measured potential differences along VES-points are directly converted to the apparent resistivity of the penetrated subsurface, see Fig. 3A.

The research’s fieldwork was performed using the asymmetrical VES technique, suitable for scenarios, where surveying traverses are confronted with a winding surface topography adjacent to or along their path (Zohdy and Bisdorf, 1990). The current electrodes were arranged along the winding path to facilitate a deep Schlumberger sounding, and the apparent resistivities obtained were adjusted using the geometric factor corresponding to the specific array geometry of a non-linear array, as opposed to a linear array geometry, as in Fig. 3B. The theory that underpins this technique states that the action of the electrodes A and B at a location O in the direction of MN gives the electric field components E^{AMN} and E^{BMN} for a horizontal stratified medium (Zohdy, 1978).

In this study, asymmetrical VES points of measurement were used to

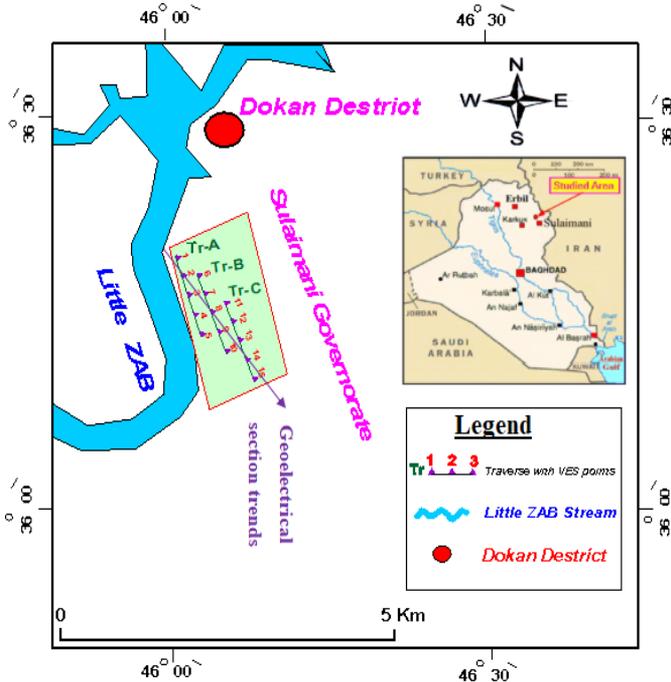


Fig. 4. Traverses and fifteen asymmetrical VES points (drawn by Surfer® 10, Golden Software, 2011).

evaluate aquifer resistivity, depth and thickness from interpretation of the results, which lead to measuring the Dar-Zarrouk parameters including Transverse resistance (R_T) and longitudinal conductance (S_L). On the other hand, pumping tests in four wells (P1, P2, P3, and P4) were used to calculate transmissivity (T) using a single well pumping test (*Cooper and Jacob, 1946*), leading to calculation of the hydraulic conductivity (K) from the measured aquifer thickness (h), using the relation $T = K \cdot h$.

The field work was conducted along three traverses (A, B, and C) with fifteen asymmetrical VES-points. Each traverse has five VES points of measurements that run parallel to the beds' strike direction with a distance of 500 m between them. For the purpose of improving measurements of the layers' depth, thickness and resistivity, the half-length of the spread was increased from $AB/2 = 300$ m to $AB/2 = 500$ m, see Fig. 4.

6. Interpretation and results

The measured apparent resistivity values (ρ_a) are plotted against half distances electrodes spacing ($AB/2$) on the logarithmic paper enabled the interpretation of the field curves of the observed apparent resistivity for each measuring point to deduce results of the layers thicknesses, depths and true resistivity values derived from partial curve matching by Ebert method were entered into the computer program until the best fit was gained between the field curve and the master curve with the least percentage of deviations, furthermore the VES field curves were interpreted using an IPI2Win software program (*Bobachev, 2002*), by utilising forward calculation and inverse modelling programs to assess the reliability of the results, the forward calculation of the model being able to adjust the output results of the actual resistivities and thicknesses. In contrast, inverse modelling enhances the precision of the manual interpretation results by incorporating layers and aquifer resistivity and thickness values, engaging in an iterative process between the field curve and the master curve until the optimal fit is achieved with the minimal percentage of deviations, which consequently reflects the best true results as shown in Fig. 5.

The symbols in Fig. 5A, B and C reveal that: ρ : layers resistivity; ρ_a : apparent resistivity h: layers thickness; d: layers depth; Alt: depth range equal to Σh ; $AB/2$: half length of the current spread.

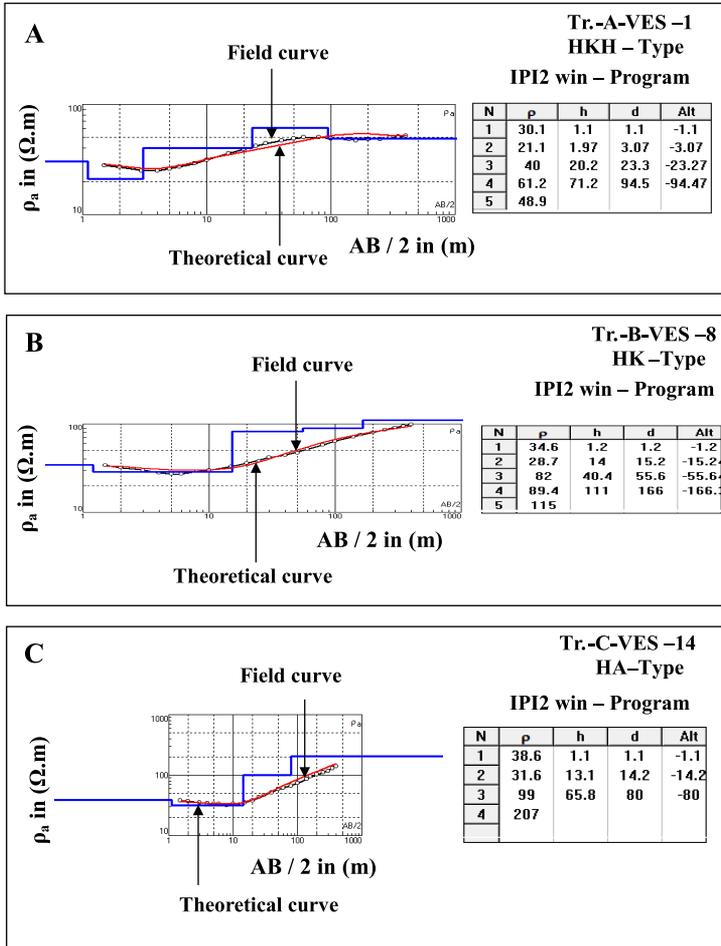


Fig. 5 A. Forward and inverse modelling output of IPI2Win-Software and manual interpretation, VES-2 of Traverse-A; B. VES-8 of Traverse-B and C. VES-14 of Traverse-C.

7. Dar-Zarrouk and hydraulic parameters

7.1. Dar-Zarrouk parameters

Dar-Zarrouk parameters include transverse resistance (R_T) and longitudinal conductance (L_C). The transverse resistance R_T of the homogeneous and isotropic layer is given by:

$$R_T = \rho \cdot h, \quad (1)$$

while the longitudinal conductance L_C is given by:

$$L_C = h/\rho. \quad (2)$$

The deduced manual interpretation results data include the aquifer resistivity, depth and thickness were inferred to forward and inverse modelling software program in order to evaluate the true results for all the detected layers, which were evaluated Dar-Zarrouk parameters used to draw the relationships with the aquifer hydraulic parameters. The resulted aquifer thickness (h_{Aq}) and resistivity (ρ_{Aq}) with their Dar-Zarrouk parameters include transverse resistance (R_T) and longitudinal conductance (S_L) are shown in Table 2.

Table 2. Dar-Zarrouk parameter measurements from Aquifer thickness and resistivity along traverses A, B and C.

Traverses	VES	Wells	Aquifer thickness and resistivity		Dar-Zarrouk parameters	
			h_{Aq} (m)	ρ_{Aq} ($\Omega \cdot m$)	R_T ($\Omega \cdot m^2$)	S_L ($1/\Omega$)
Traverse – A	VES-1	P1	20.2	42	848.4	0.48
	VES-2		26.6	48	1276.8	0.55
	VES-3		32.8	52	1705.6	0.63
	VES-4		39.8	55	2189	0.72
	VES-5		50.5	66	3333	0.77
Traverse – B	VES-6		58.8	55	3234	1.07
	VES-7	P2	25.8	60	1548	0.43
	VES-8		40.4	82	3312.8	0.49
	VES-9		35.5	96	3408	0.37
	VES-10		46.3	112	5185.6	0.41
Traverse – C	VES-11		29.4	70	2058	0.42
	VES-12	P3	35.7	86	3070.2	0.42
	VES-13		46.8	90	4212	0.52
	VES-14		65.8	99	6514.2	0.66
	VES-15	P4	70.6	116	8189.6	0.61

7.2. Hydraulic parameters

Hydraulic parameters, including transmissivity (T) and hydraulic conductivity (K), are tied with the aquifer thickness (h) given by Eq. (3) established from Darcy's law:

$$T = K \cdot h. \quad (3)$$

Solving for h in Eq. (2) and substituting in Eq. (3), thus it gives:

$$T = K \cdot \rho \cdot L_C. \quad (4)$$

In other words in a clay rich aquifer hydraulic conductivity is directly proportional to resistivity ($K \propto \rho$), thus:

$$K/\rho = C_1, \quad (5)$$

$$C_1 = \text{constant}.$$

In an unconsolidated, sandy, clay-free aquifer, a direct relationship exists between hydraulic conductivity and porosity ($K \propto \phi$), while an inverse relationship exists between porosity and resistivity ($\phi \propto 1/\rho$) (Frohlich and Kelly, 1985), thus:

$$K \cdot \rho = C_2, \quad (6)$$

$$C_2 = \text{constant}.$$

Substituting Eq. (5) into Eq. (4) and Eq. (6) into Eq. (4), the transmissivity is:

$$T = R_T \cdot C_1, \quad (7)$$

$$T = L_C \cdot C_2. \quad (8)$$

A single well pumping test was performed to determine the hydraulic conductivity (K) and transmissivity (T) of the aquifer using the method of Cooper and Jacob (1946). Prior to pumping, the static water level was recorded and then after pumping, the draw-down was measured again in the well after the specific time interval. Afifah (2022) found that groundwater availability and the productivity of local productive groundwater basins are reflected in measurements of water discharge from the surrounding area into the well borehole. The groundwater created will flow laterally from the recharge area to the discharge area through the productive layer due to gravity. The results of the conducted pumping test were plotted showing the duration time (t) on a logarithmic scale along the x-axis against

the drawdown (s) on the y -axis (ordinary scale). The results of such well pumping tests yield the fundamental idea of the Cooper-Jacob equation for determining the transmissivity of an unconfined aquifer (Fig. 6).

The Cooper-Jacob equation can be derived in terms of transmissivity (T) as follows:

Since $\log \Delta t = 1$ per one cycle t

$$\text{So } \frac{\Delta s}{1} = \frac{2.3 Q}{4\pi T}$$

$$T = 2.3 Q / 4\pi \Delta s, \tag{9}$$

where Q : is pumping rate (water discharge in the well by m^3/day); Δs : is the slope of the fitted line (change in drawdown in m per log cycle Δt).

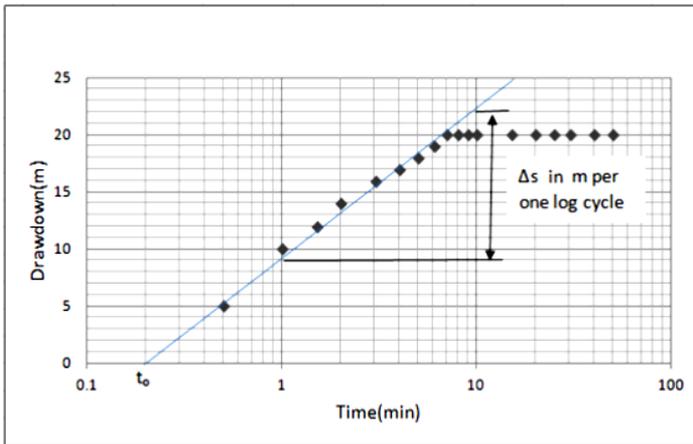


Fig. 6. Time-drawdown straight-line plotted from pumping test (Cooper and Jacob, 1946).

The calculated results of the transmissivity (T) and hydraulic conductivity (K) from wells pumping tests are shown in Table 3.

8. Dar-Zarrouk and hydraulic parameters relationships

8.1. Transmissivity (T) and transverse resistance (R_T) relation

The transmissivity and transverse resistance relation has an inverse negative relation (see Fig. 7A), with the higher relation coefficient (0.9956) showing that as transverse resistance increases, transmissivity decreases, thus the

Table 3. Calculation of transmissivity (T) and hydraulic conductivity (K) from well pumping tests and Dar-Zarrouk parameters.

Wells	Well's locations to the nearest VES-points	Aquifer thickness & resistivity		Dar-Zarrouk parameters		Wells discharge			Hydraulic parameters by Jacob method	
		h_{Aq} (m)	ρ_{Aq} ($\Omega.m$)	R_T ($\Omega.m^2$)	S_L ($1/\Omega$)	Q (gal/min)	Q (m^3/day)	Slope ($\Delta S/\Delta t$)	T (m^2/day)	K (m/day)
P1	Tr-A-VES-2	20.2	42	848.4	0.481	113.5	618.57	5	22.65	1.12
P2	Tr-B-VES-7	25.8	60	1548	0.43	90	490.5	4	22.46	0.87
P3	Tr-C-VES-12	35.7	86	3070.2	0.41	65	354.25	3	21.62	0.61
P4	Tr-C-VES-15	70.6	116	8189.6	0.60	40	218	2	19.96	0.28

equation of the relation is given by:

$$T = -0.0006 R_T + 23.227. \tag{10}$$

8.2. Hydraulic conductivity (K) and resistivity (ρ) relation

Consequently, an inverse hydraulic conductivity and resistivity relation with relation coefficient 0.9848 is revealed (Fig. 7B), its equation is given by:

$$K = -0.0096 \rho + 1.4828. \tag{11}$$

8.3. Hydraulic conductivity (K) and transverse resistance (R_T) relation

Alternatively, there is an inverse hydraulic conductivity and transverse resistance relation with relation coefficient 0.9085 (Fig. 7C), its equation is given by:

$$K = -0.0001 R_T + 1.1319. \tag{12}$$

The relationships between transmissivity and the transverse resistance (Fig. 5B) can be considered more suitable for direct calculation of transmissivity by direct substitution of the Dar-Zarrouk parameter for the aquifer in Eq. (10) for all VES measurement points throughout the study area with the same lithological situation, due to the higher relation coefficient (0.9956) and taking into account both the aquifer resistivity and thickness for calculating transmissivity values, which are ranged from 20.88 to 56.50 m^2/day and the hydraulic conductivity (K) from dividing transmissivity (T) by

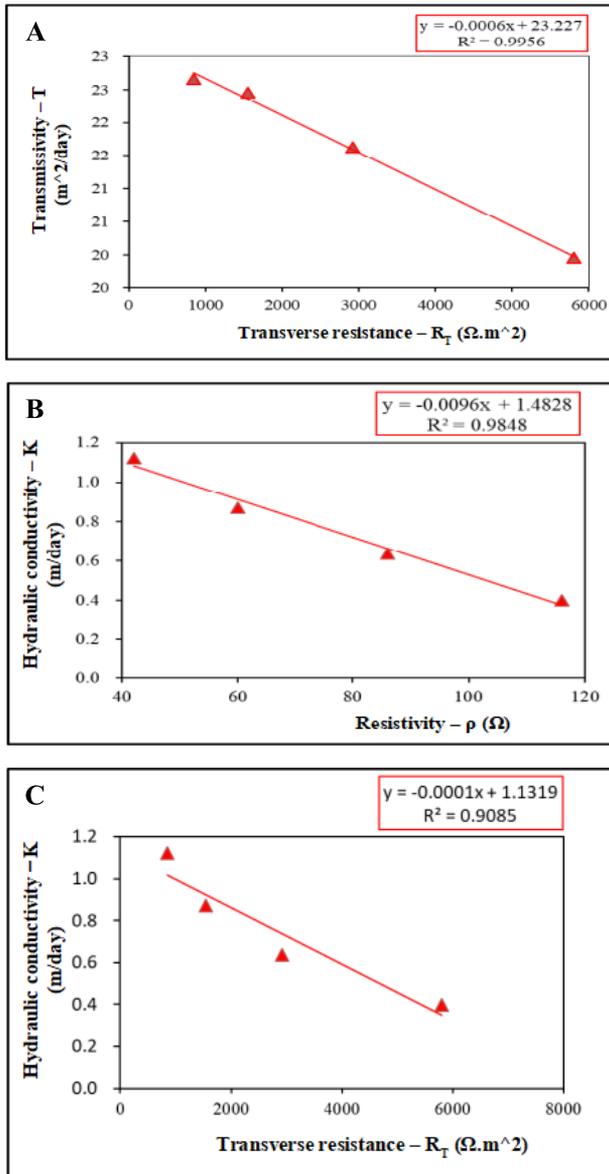


Fig. 7. A. Transmissivity (T) and transverse resistance (R_T) relation; B. hydraulic conductivity (K) and resistivity (ρ) relation; C. hydraulic conductivity (K) and transverse resistance (R_T) relation.

aquifer thickness (h), through equation $K = T/h$ are ranged from 0.55 to 1.12 m/day as shown in Table 4. This reflects the fact that the recent aquifer and the upper middle Tanjero Formation are conformable within the lithological range of the hydraulic conductivity variation due to the change of the grain size particles of unconsolidated sediments (see Table 5) modified from *Bouwer (1978)*.

Table 4. Estimated aquifer Dar-Zarrouk, hydraulic parameters for all the VES points.

Traverses	VES	Wells	Aquifer thickness & resistivity		Dar-Zarrouk parameters		Hydraulic parameters	
			h_{Aq} (m)	ρ_{Aq} ($\Omega.m$)	R_T ($\Omega.m^2$)	S_L ($1/\Omega$)	T (m^2/day)	K (m/day)
Traverse – A	VES-1	P1	20.2	42	1000	0.44	20.88	1.12
	VES-2		26.6	48	1200	0.52	26.35	1.05
	VES-3		32.8	52	1664	0.62	32.27	1.01
	VES-4		39.8	55	2090	0.69	37.02	0.97
	VES-5		50.5	66	1936	1.00	48.38	1.10
Traverse – B	VES-6		58.8	55	3190	1.05	56.50	0.97
	VES-7	P2	25.8	60	1548	0.43	23.66	0.92
	VES-8		40.4	82	1767	0.46	25.49	0.89
	VES-9		35.5	96	2380	0.51	28.91	0.83
	VES-10		46.3	112	2556	0.50	27.86	0.78
Traverse – C	VES-11		29.4	70	2030	0.41	23.29	0.80
	VES-12	P3	35.7	86	2250	0.41	23.03	0.76
	VES-13		46.8	90	2505	0.45	24.92	0.75
	VES-14		65.8	99	2800	0.44	24.12	0.69
	VES-15	P4	70.6	116	3864	0.46	23.20	0.55

A recent study (*Ejepu et al., 2024*) measured hydraulic conductivity ranging from 0.465 to 0.534 m/day, while transmissivity varied from 9.589 to 26.029 m^2/day across different VES points. Regions exhibiting thick layers and low resistivity values indicated high longitudinal conductivity. Based on geoelectrical characteristics, the study area was divided into three ground-water potential zones: low, medium and high, these findings provide valuable insights into the ground water potential and protective capacity of the Shango area.

Table 5. Range of the hydraulic conductivity variation due to change of the grain size particles of unconsolidated sediments, modified from *Bouwer (1978)*.

Unconsolidated materials and rocks	Hydraulic conductivity K (m/day)
Clay	$10^{-8} - 10^{-2}$
Fine sand	1 – 5
Medium sand	5 – 20
Coarse sand	20 – 100
Gravel	100 – 1000
Sand and gravel mixes	5 – 100
Sandstone	$10^{-3} - 1$
Carbonate rock with secondary porosity	$10^{-2} - 1$
Shale	10^{-7}
Dense solid rock	$<10^{-5}$

9. Discussions

Several researchers have extracted nonlinear empirical connections for alluvial aquifers, including *Heigold et al. (1979)*; *Chen et al. (2001)*; *Singh (2005)*, they came to the conclusion that transmissivity (T) and hydraulic conductivity (K) increase and decrease non-linearly with increasing resistivity. The analysis of the current study findings, utilising forward and inverse modelling software, indicates the existence of an aquifer situated within the recent alluvial sediments that cover the middle Tanjero Formation. Inverse linear relationships are observed across the transition from recent sediments to the rhythmic lithological succession of silty sand, marl, and marly limestone within the middle part of the Tanjero Formation, these relationships reflect the hydraulic interaction between the stream and the aquifer through a recharge zone.

The interpretation of such a condition is related to the presence of clay content both within the gravel and sand particles of the recent deposit and in part of the middle Tanjero Formation, which would lead to a decrease in the values of hydraulic conductivity (K) for the aquifer of the studied area. This is because the value of (K) is dependent on the type of sediment, grain size and presence of clay. *Butler (2005)* had revealed that hydraulic conductivity can be considered the basic and main aquifer parameter for estimating the characteristics of the aquifer. There can be no physical or

potential relationship between the electric resistivity and hydraulic conductivity due to its site restriction.

The virtual increase of clay content towards the southern part of the study area is reflected by the higher value of (K) at the beginning part of the study and its decrease towards the end of the southern part. The deduced results are supported when the hydraulic conductivity (K) is correlated with normalized aquifer resistivity (ρ) and transmissivity (T) with normalized transverse resistance (R_T) of the water-bearing formation. From the scatter plots of K versus ρ and T versus R_T , the following relationships were obtained (Krishnaiah, 2015):

$$K = 2.127 + 0.205 \rho ,$$

$$T = 14.96 + 0.236 R_T .$$

An empirical power-law correlation between permeability and void ratio was established, which closely reproduces the observed permeability values, yielding a mean absolute error between 0.1 and 0.2 orders of magnitude and coefficient of determination R^2 values exceeding 0.90%.

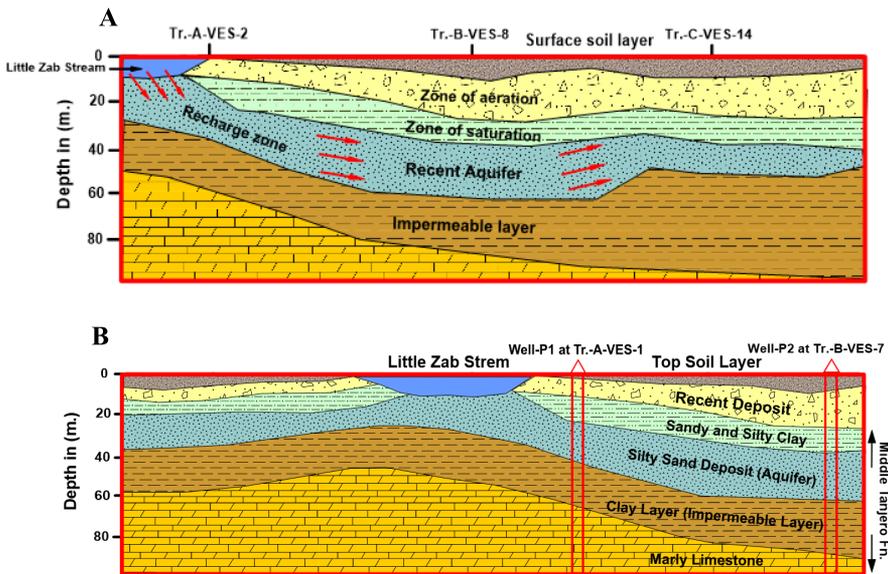


Fig. 8. A. Geological cross section of the studied area from geoelectrical Dar-Zarrouk parameters results; B. Complete hydro-geological cross section of area with the layers lithology penetrated by wells P1 & P2.

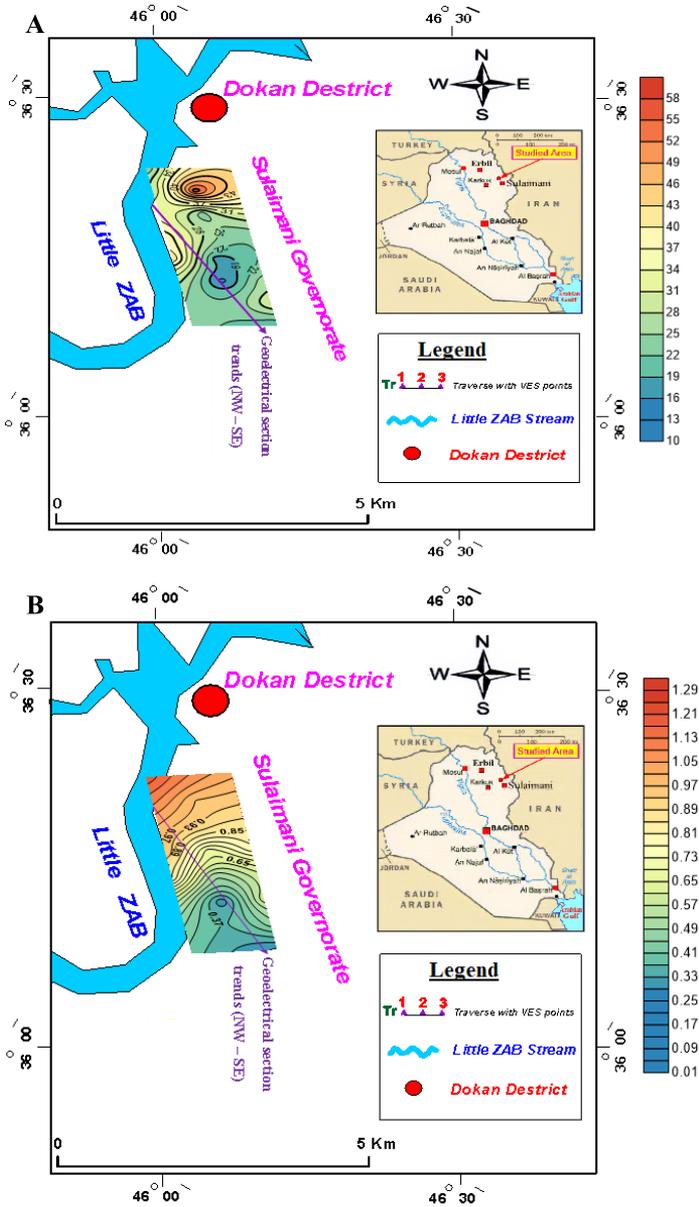


Fig. 9. A. Transmissivity map of the aquifer; B. Hydraulic conductivity map of the aquifer.

The permeability of sand–clay mixtures shows a strong contrast between the behaviour of natural sediments and experimental homogeneous sand–clay mixtures. The experimental binary sediment mixture’s permeability demonstrated a quick reduction with rising clay content, ultimately decreasing to its lowest values at approximately 20% clay content (*Luijendijk and Gleeson 2015*).

A good correlation between hydraulic conductivity and resistivity reveals inverse linear relationships (see Fig. 7B). The hydraulic conductivity (K) can be evaluated directly from the Eq. (11) through direct substitution of the deduced resistivity values of VES points in the area under study at other surrounding areas, where pump tests could not be performed.

The geological section constructed from the geoelectrical results and the Dar-Zarrouk parameter results reveals a combination of the aquifer with the little Zab stream leading water to move from the stream to the aquifer through a recharge zone due to the hydraulic gradient of the successive layers relevant to the stream (Fig. 8A).

Interpretation of the electrical results for the deduced successive lithological layers is combined with data from the penetrated wells to construct a complete hydro-geological cross section (Fig. 8B).

The colour scale of the constructed transmissivity and hydraulic conductivity maps indicates a gradual decline in aquifer transmissivity and hydraulic conductivity values from the northern part towards the southern part of the study area. This trend is consistent with the inverse relationship between aquifer transmissivity and hydraulic conductivity and transverse resistance, as illustrated in Fig. 9A and 9B.

10. Conclusions

Inverse linear relationships were constructed between measured transmissivity (T) from well pumping tests transmissivity values and Dar Zarrouk parameters measured from asymmetrical VES points. The measured transmissivity values are converted to hydraulic conductivity (K) through the aquifer thicknesses (h_{Aq}) deduced from both interpretation results and wells data by equation $K = T/h$, the deduced transmissivity variation from 19.96 to 22.65 m²/day and hydraulic conductivity from 0.28 to 1.22 m/day, as in (Table 3). Furthermore, among the constructed relationships between hy-

draulic and geo-electric parameters, three relationships are more applicable for the lithological situation of the studied area.

The more reliable conducted relationship is the transmissivity (T) and transverse resistance (R_T), due to its higher relation coefficient ($R^2 = 0.9956$) and taking into account both the aquifer resistivity and thickness were used for direct calculation of aquifer transmissivity from its Eq. (10) given as $T = -0.0006 R_T + 23.227$, through direct substituting of the aquifer transverse resistance of all the VES points giving outcome of the transmissivity ranges between 20.88 and 56.50 m²/day. Then the calculated aquifer hydraulic conductivity (K) for all VES points by equation $K = T/h$ are ranged between 0.55 and 1.12 m/day, as in (Table 4), thus, the recent sediments overlying the Middle Tanjero Formation aquifer are conformable, reflecting lithological controls on the observed variations in hydraulic conductivity.

Consequently, another two constructed relationships are delineated to direct calculation of hydraulic conductivity from resistivity (ρ), in Eq. (11) given as $K = -0.0096 \rho + 1.4828$ and from transverse resistance (R_T), through Eq. (12) given as $K = -0.0001 R_T + 1.1319$.

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References

- Abu Heen Z. H., Muhsen S. A., 2017: Estimation of Aquifer Parameters from Vertical Electrical Sounding Measurements South Gaza Strip, Palestine. *IUG J. Nat. Stud.*, **25**, 2, 95–105.
- Achilike K. O., 2020: Hydrogeophysical studies for the determination of aquifer hydraulic characteristics and evaluation of groundwater potential: A case study of some selected parts of Imo River Basin, South Eastern Nigeria. *Int. J. Sci. Res. Publ.*, **10**, 7, 738–755, doi: 10.29322/IJSRP.10.07.2020.p10382.
- Afifah R. S., 2022: Falling Head (FH) untuk hubungan sifat batuan dengan koefisien kelulusan air di daerah “BRG” Sekitarnya (Using Falling Head (FH) method to determine the relationship between rock properties and water passage coefficient in the “BRG” area and surrounding areas). *Al Ulum: Jurnal Sains dan Teknologi (J. Sci. Technol.)*, **8**, 1, 30–35, doi: 10.31602/ajst.v8i1.8918 (in Indonesian with English abstract).

- Al-Barzani M. D., 2008: Engineering-Geological study of rock slope stability in Harir area, Kurdistan region, Iraq. Unpublished M.Sc. Thesis, University of Salahaddin, Erbil, Iraq. 137 p.
- Bobachev C., 2002: IPI2Win: A Windows Software for an Automatic Interpretation of Resistivity Sounding Data. PhD Thesis, Moscow State University, Russia, 320 p.
- Bouwer H., 1978: Groundwater hydrology. McGraw-Hill Book, New York, 480 p.
- Butler J. J., 2005: Hydrogeological methods for estimation of spatial variations in hydraulic conductivity. In: Rubin Y., Hubbard S. (Eds.): Hydrogeophysics (Chapter 2), Water Science and Technology Library, **50**, Springer, Netherlands, 23–58, doi: 10.1007/1-4020-3102-5_2.
- Cooper H. H., Jacob C. E., 1946: A generalized graphical method for evaluating formation constants and summarizing well field history. *Trans. Am. Geophys. Union*, **27**, 4, 526–534, doi: 10.1029/TR027i004p00526.
- Chen J., Hubbard S., Rubin Y., 2001: Estimating hydraulic conductivity at the south Oyster Site from geophysical tomography data using Bayesian techniques based on the normal linear regression model. *Water Resour. Res.*, **37**, 6, 1603–1613, doi: 10.1029/2000WR900392.
- de Almeida A., Maciel D. F., Sousa K. F., Nascimento C. T. C., Koide S., 2021: Vertical Electrical Sounding (VES) for estimation of hydraulic parameters in the porous aquifer. *Water*, **13**, 2, 170, doi: 10.3390/w13020170.
- Ejegu J. S., Jimoh M. O., Abdullahi S., Abdulfatai I. A., Musa S. T., George N. J., 2024: Geoelectric analysis for ground water potential assessment and aquifer protection in a part of Shango, North-Central Nigeria. *Discov. Water*, **4**, 33, 1–26, doi: 10.1007/s43832-024-00091-z.
- Frohlich R. K., Kelly W. E., 1985: The relation between hydraulic transmissivity and transverse resistance in a complicated aquifer of glacial out wash deposits. *J. Hydrol.*, **79**, 3–4, 215–229, doi: 10.1016/0022-1694(85)90056-3.
- Golden Software, 2011: Surfer, mapping system (ver. 10) [computer software]. Golden, CO: Golden Software, LLC, <https://www.goldensoftware.com>.
- Heigold P. C., Gilkeson R. H., Cartwright K., Reed P. C., 1979: Aquifer transmissivity from surficial electrical methods. *Groundwater*, **17**, 4, 338–345, doi: 10.1111/j.1745-6584.1979.tb03326.x.
- Ibrahim M. M., Aliyu J., 2016: Comparison of Methods for Saturated Hydraulic Conductivity Determination: Field, Laboratory and Empirical Measurements. *Br. J. Appl. Sci. Technol.*, **15**, 3, 1–8, BJAST.24413, doi: 10.9734/BJAST/2016/24413.
- IRIS Instruments, 2002: SYSCAL Junior Switch-72: One and two dimensional resistivity meter system [Technical Brochure/Manual]. Orléans, France.
- Jassim S. Z., Goff J. C., 2006: Geology of Iraq. First Ed., Dolin, Czech Republic, 352 p.
- Krishnaiah C., 2015: Establishing hydrogeophysical relationship between geoelectric and hydraulic parameters for a basaltic aquifer, Ahmednagar district, Maharashtra, India. *J. Indian Geophys. Union*, **19**, 3, 282–289, available online: <https://iguonline.in/journal/19-3/4paper.pdf>.

- Kruseman G. P., de Ridder N. A., 2000: Analysis and Evaluation of Pumping Test data. International Institute for land reclamation and improvement, Second Edition, The Netherlands, Reprinted, 377 p.
- Luijendijk E., Gleeson T., 2015: How well can we predict permeability in sedimentary basins? Deriving and evaluating porosity–permeability equations for non-cemented sand and clay mixtures. *Geofluids*, **15**, 1–2, 67–83, doi: 10.1111/gf1.12115.
- McMahon T. A., Nathan R. J., 2025: Estimating hydraulic properties and residence times of unconfined aquifers. *J. Hydrol.*, **654**, 132861, doi: 10.1016/j.jhydrol.2025.132861.
- Mazáč O., Kelly W. E., Landa I., 1985: A hydrogeophysical model for relations between electrical and hydraulic properties of aquifers. *J. Hydrol.*, **79**, 1–2, 1–19, doi: 10.1016/0022-1694(85)90178-7.
- Nyaberi D. M., 2022: Determination of the Aquifer and Its Hydraulic Parameters Using Vertical Electrical Sounding, Borehole Log Data and Borehole Water Conductivity: A Case Study of Albanita Menengai Area, Nakuru, Kenya. *J. Geosci. Environ. Prot.*, **10**, 11, 204–224, doi: 10.4236/gep.2022.1011014.
- Singh K. P., 2005: Nonlinear estimation of aquifer parameters from surficial resistivity measurements. *Hydrol. Earth Syst. Sci. Discuss.*, **2**, 3, 917–938, doi: 10.5194/hessd-2-917-2005.
- Soupios P. M., Kouli M., Valliantos F., Vafidis A., Stavroulakis G., 2007: Estimation of aquifer hydraulic parameters from surficial geophysical methods: A case study of Keritis Basin in Chania. *J. Hydrol.*, **338**, 1–2, 122–131, doi: 10.1016/j.jhydro1.2007.02.028.
- Todd D. K., Mays L. W., 2005: *Groundwater Hydrology* (Third Ed.). John Wiley and Sons, Inc., 652 p.
- Udoinyang I. E., Igboekwe M. U., 2012: Aquifer Transmissivity, Dar Zarrouk Parameters and the direction of flow of suspended particulate matter in Boreholes in MOUAU and the Kwa Ibo River, Umudike-Nigeria. *Greener J. Phys. Sci.*, **2**, 3, 70–84, available online: <https://gjournals.org/GJPS/archive/vol-2-3-september-2012/udoinyang-and-igboekwe.html>.
- Uma K. O., Egboka B. C. E., Onuoha K. M., 1989: New statistical grain-size method for evaluating the hydraulic conductivity of sandy aquifers. *J. Hydrol.*, **108**, 343–366, doi: 10.1016/0022-1694(89)90293-X.
- Valigi D., Cambi C., Checucci R., Di Matteo L., 2021: Transmissivity Estimates by Specific Capacity Data of Some Fractured Italian Carbonate Aquifers. *Water*, **13**, 10, 1374, doi: 10.3390/w13101374.
- Zohdy A. A. R., 1978: Total field resistivity mapping and sounding over horizontally layered media. *Geophysics*, **43**, 4, 748–766, doi: 10.1190/1.1440851.
- Zohdy A. A. R., Bisdorf R., 1990: Schlumberger sounding near Medicine Lake, California. *Geophysics*, **55**, 8, 956–964, doi: 10.1190/1.1442925.