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Vertical Electrical Sounding Technique for Assessing the Quaternary Aquifer Vulnerability to Contamination in the Semi-Arid Khanasser Valley Region, Northern Syria

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Abstract

The aim of this paper is to evaluate the vulnerability of groundwater to contamination by adapting aquifer vulnerability index (*AVI*) approach, based mainly on the hydraulic conductivity (*K*) of the aquifer and overburden layers' thickness (*h*). The technique of vertical electrical sounding (*VES*) with the configuration of Schlumberger was applied to model the Quaternary aquifer and its overburden layers in the Khanasseer Valley area in Northern Syria. According to *AVI* classification, 5.88% of the study area is hugely polluted, 67.00% highly polluted, 23.53% moderately polluted, and 2.94% lowly polluted. Several hydro-geoelectrical parameters which affect the Aquifer Vulnerability Index (*AVI*) (such as anisotropy (λ) of the subsurface hydrogeological layers, thickness (*hOverb*), resistivity (ρ*Overb*), hydraulic conductivity (*K*), and hydraulic resistance (*C*) of the protecting layers) are statistically analyzed. Different mutual empirical relationships between the above parameters are established through analyzing their statistical correlation matrix. The derived empirical relationships highlight the mutual hydrological processes and the lithological connectivity nature between the study Quaternary aquifer and its overlaying layers. The obtained results highlighted the importance of safeguarding groundwater resources, and outlined resource allocation to protect the aquifer zones, for decision-makers. This was the first time that *AVI* approach is applied in Syria, and can be consequently extended to other Syrian aquifers. *AVI* can be also applied worldwide to estimate the conditions dominating the aquifer's protectivity in semi-arid regions.

Key words: aquifer vulnerability index, hydraulic conductivity, hydraulic resistance, Semi-arid Khanasser valley, Syria.

Resumen

El objetivo de este trabajo es evaluar la vulnerabilidad del agua subterránea a la contaminación mediante la adaptación del enfoque del índice de vulnerabilidad de acuíferos (*AVI*), basado principalmente en la conductividad hidráulica (*K*) del acuífero y el espesor (*h*) de las capas de sobrecarga. Se aplicó la técnica de sondeo eléctrico vertical (*VES*) con configuración Schlumberger para modelar el acuífero cuaternario y sus capas de sobrecarga en el área del valle de Khanasseer, en el norte de Siria. De acuerdo con la clasificación *AVI*, el 5.88% del área de estudio presenta contaminación muy alta, el 67.00% alta, el 23.53% moderada y el 2.94% baja. Se analizaron estadísticamente varios parámetros hidro-geoeléctricos que afectan el índice de vulnerabilidad del acuífero (*AVI*), tales como la anisotropía (λ) de las capas hidrogeológicas del subsuelo, el espesor (*hOverb*), la resistividad (ρ*Overb*), la conductividad hidráulica (*K*) y la resistencia hidráulica (*C*) de las capas protectoras. Se establecieron diferentes relaciones empíricas mutuas entre estos parámetros mediante el análisis de su matriz de correlación estadística. Las relaciones empíricas obtenidas destacan los procesos hidrológicos asociados y la conectividad litológica entre el acuífero cuaternario del área de estudio y sus capas suprayacentes. Los resultados obtenidos resaltan la importancia de salvaguardar los recursos de agua subterránea y orientan la asignación de recursos para proteger las zonas del acuífero, lo cual resulta relevante para la toma de decisiones. Este es el primer estudio en el que se aplica el enfoque *AVI* en Siria, por lo que puede extenderse a otros acuíferos del país. Asimismo, el *AVI* puede aplicarse a nivel mundial para estimar las condiciones que controlan la capacidad de protección de los acuíferos en regiones semiáridas.

Palabras clave: índice de vulnerabilidad de acuíferos, conductividad hidráulica, resistencia hidráulica, valle semiárido de Khanasser, Siria.

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1. Introduction

The contaminations originating from the surface affect the groundwater stored in the aquifers (Ikpe *et al.*, 2021). The anthropogenic activities negatively affect the groundwater quality due to poor waste disposal management, the leakages from the surface and underground storage tanks, mining activities, and latrines, sewage from oil spillage, and the movement of leachates from dumpsites into subsurface hydrogeological units (Oseji *et al.* 2018).

The hydrogeological aquifer systems are well protected from surface contamination and pollution when the overlaying earth layers above an aquifer have suitable hydrological conditions, regarding their resistivities, thicknesses, and hydraulic conductivities.

The aquifer overburden layers act as natural boundaries to filter percolating surface contaminated fluids, and the measure of such an ability determines the aquifer protectivity characteristics (Adeniji *et al.* 2014).

The protectivity of the underlying hydrogeological aquifer is considerably affected by some critical factors, which are the thickness, porosity, grain size, hydraulic conductivity, and anisotropy of the overburden-protecting layers (Mogaji *et al.*, 2011; Adeniji *et al.* 2014; Ekanem *et al.*, 2020; Ekanem *et al.*, 2021; Ikpe *et al.*, 2022; Asfahani, 2023a; Asfahani 2023b).

The high resistivity and high hydraulic conductivity of the permeable overlaying layers of sand and gravel facilitate the easy movement of the surface fluid contaminants and their infiltration into the aquifer system. On the contrary, the low hydraulic conductivity and low resistivity of the impervious overburden layers of clay and shale retard and slow the infiltration rate of the surface contaminants into the subsurface, such as the protectivity of the aquifer is improved considerably (Adeniji *et al.*2014; Ayuk 2019; Ekanem *et al.* 2021; Asfahani 2023a; Asfahani 2023b).

Electrical resistivity technology, with its different approaches and different configurations, particularly the *VES* one, has been largely practiced in solving and characterizing different groundwater and hydrological problems related to aquifer potentiality, and contamination, by locating vulnerable zones, migration and the extent of contamination (Ebong *et al.*, 2014; Obiora *et al.*, 2016; Laouini et al, 2017; Eyankware, 2019; Oli *et al.*, 2020; Ekwe *et al.*, 2020; Eyankware *et al.* 2020a, b, & 2021; Eyankware *et al.*, 2022).

The aquifer vulnerability conditions of a given region can be easily determined by using the vertical sounding technique (*VES*), and the fast and simple aquifer vulnerability index *AVI* approach (Stempvoort *et al.*, 1993; Obiora and Ibuot, 2020; Ossai *et al.*, 2020).

The conductivity of the most contaminants is much higher than the conductivity of natural groundwater, where such pronounced conductivity contrast enables an easy identification of contamination plumes by using geoelectrical methods, particularly the *VES* one. The *VES* technique can be used to describe the aquifer hydrogeological units in detail and detect their contaminant plume.

The overburden-protective capacity of an aquifer is controlled by several geoelectrical parameters, which are the resistivity ($\rho Over$), thickness ($hOver$), the anisotropy of the subsurface hydrogeological layers (λ), and the hydraulic conductivity (K) of the overburden layers.

The modeling of the influence of those parameters through analyzing their quantitative results by the *AVI* approach allow us to characterize and describe the protected aquifer areas and determine the contamination conditions surrounding the study aquifer. The mutual hydrological processes and the lithological connectivity between the studied aquifer and its overlaying layers can be quantitatively estimated by developing and establishing specific empirical relationships between the different related hydro-geophysical parameters.

The direct focus on determining the protectivity conditions and the contamination of the Quaternary aquifer in the semi-arid Khanasser Valley region, Northern Syria is the originality of this work through the application of both the *VES* technique and the aquifer vulnerability index *AVI* method.

The quantitative modeling of *VES* and *AVI* results allows determining the hydrogeological connectivity conditions between the Quaternary aquifer and its overlaying layers. The different geoelectrical parameters affecting the aquifer protectivity and its contamination are discussed, documented, and compared with other new geoelectrical contamination approaches (Asfahani 2023a; Asfahani 2023b). The new geoelectrical research works oriented towards determining the protectivity and the contamination of the aquifers, recently carried out, are undertaken in Syria for the first time (Asfahani 2023a; Asfahani 2023b).

The main goals of this research are therefore the following:

1. To apply the integrated electrical resistivity (*VES*) technique and the *AVI* approach to estimate the Quaternary aquifer susceptibility to surface contamination, and to locate the possible contaminated vulnerable zones in the study area;
2. To analyze the different geoelectrical parameters influencing and affecting the vulnerability to contamination conditions, by applying the statistical correlation matrix;
3. To fellow the different spatial variations of those parameters in the study region;
4. To derive different empirical equations between the analyzed parameters in 2.

2. Hydrogeology of the Khanasser Valley

Khanasser Valley region is one of the integrated research sites of the International Center for Agriculture in Arid Dry Areas (*ICARDA*) National Resource Management Program. The choice of this site location was oriented basically towards addressing the different problems related to the marginal dryland environments. The dynamics and diversity of the natural resources and livelihoods, poverty, and the relatively easy accessibility to the study area make the Khanasser region a prime preferable candidate (Asfahani, 2007). The vulnerability to contaminations in the semi-arid regions is an important critical matter, where the geoelectrical researches are mainly concentrated on locating the areas of acceptable contamination ranges for fresh, drinkable groundwater sites.

Khanasser Valley is located approximately 70 km southeast of Aleppo City (Figure 1), and situated between two hills, Jabal Al Hoss in the west and Jabal Shbeith in the east. The drain of the northern and southern parts of the valley is towards Jaboul salt lake and the Adami depression respectively, as indicated by figures (1 and 2).

Three aquifers exist in the semi-Khanasser Valley region to extract groundwater. The deepest one related to the upper

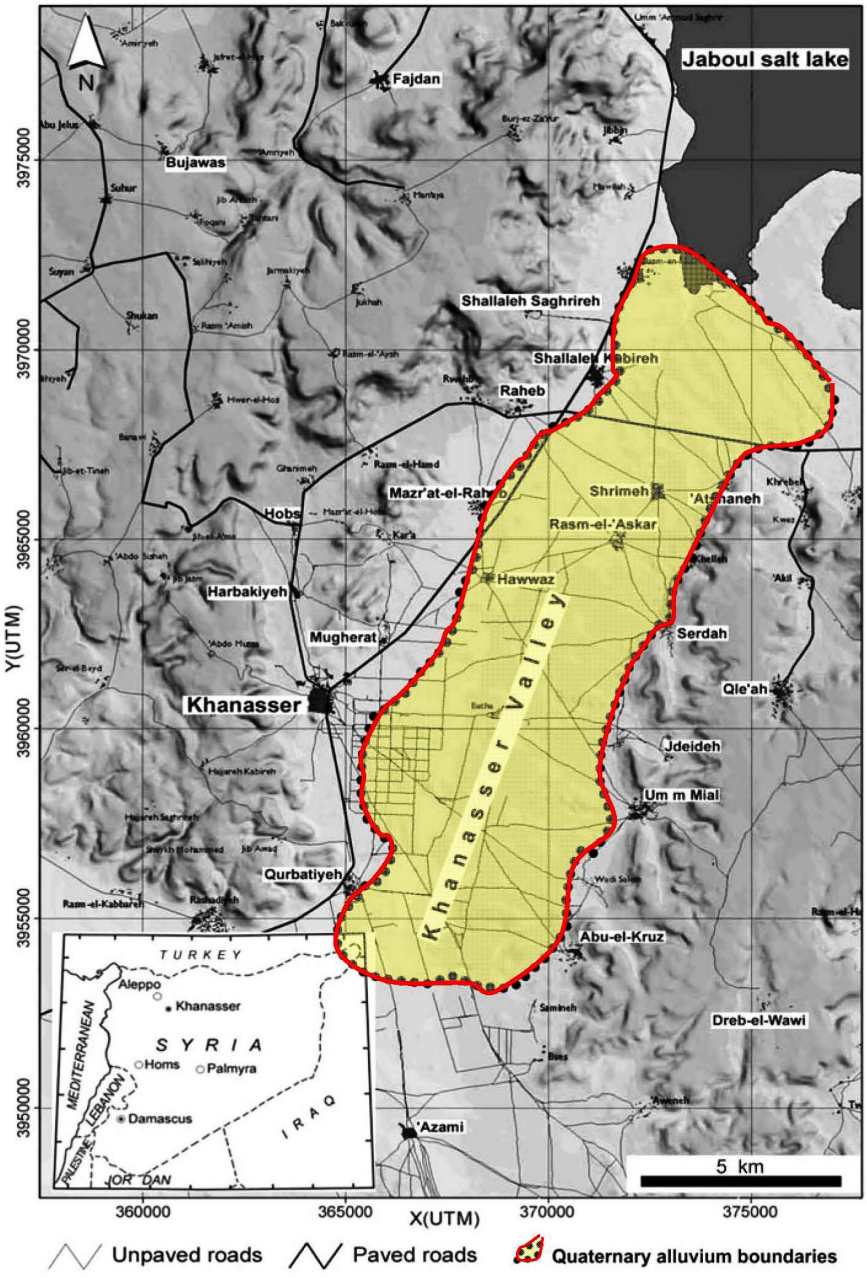

Figure 1. Location of the Khanasser Valley study region, Northern Syria.

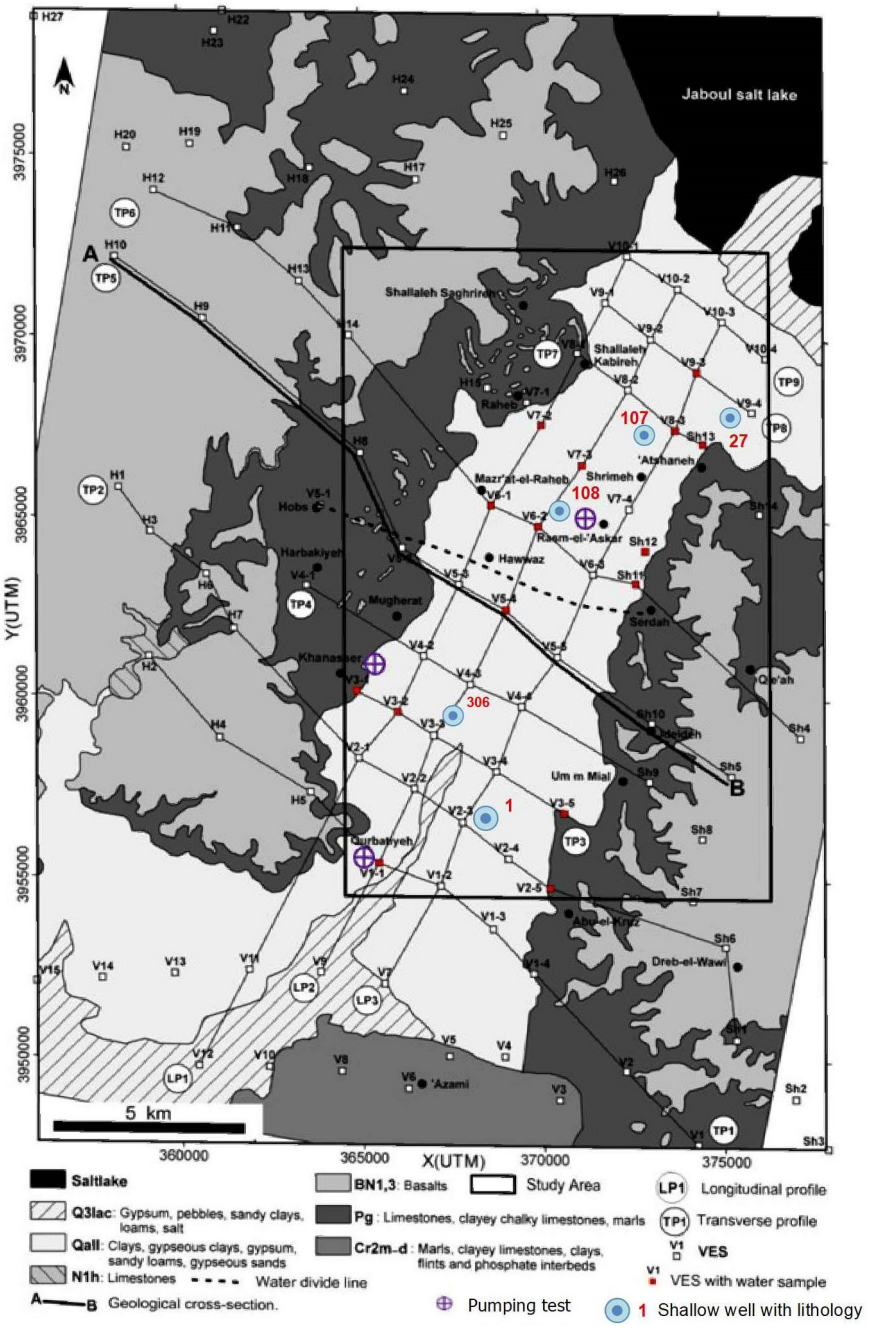

Figure 2. The *VES* points locations, on the geological map of the Khanasser Valley and its surroundings (After Ponikarov, 1964).

Cretaceous is 400 m under the ground level. Low-productive aquifer of Paleocene-Lower Eocene limestone is found above the Maestrichtian (*ACSAD, 1984*). The average hydraulic conductivity (k) of this aquifer is equal to 0.0054 m/day (Schweers *et al.*,2002). The Paleogene strata of about 50 m of Paleocene and lower Eocene in the central part of the Khanasser valley are not sufficiently thick over the Maestrichtian formation. The Quaternary aquifer, located near the surface and covered by the alluvial and colluvial sediments of about 10 m is the most transmissive hydrological structure in the study area.

The rainwater, the infiltrating runoff, and the subsurface flow from the Jabal Shbeith and Jabal Al Hoss slopes provide the direct recharge for this aquifer.

3. Methodology

3.1. *VES* technique

The electrical resistivity sounding technique is applied to

measure the subsurface resistivity distribution in the study Khanasser region, Northern Syria. Thirty-four (34) vertical electrical soundings (*VES*) points are measured by using Schlumberger electrode array.

The electrical current (*I*) is injected into the earth by two electrodes (*A* and *B*), while the generated potential differences (ΔV) is measured by two potential electrodes (*M* and *N*) as indicated by Figure 3-a.

The Indian resistivity meter (*DDR1*) directly measures the apparent resistance ($\Delta V/I$) of the layers the electrical current penetrates. The apparent resistivity was thereafter evaluated through using the following equation (Dobrin, 1988):

$$\rho a = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}} \frac{\Delta V}{I} \qquad (1)$$

The half-current electrode spacing *AB/2* are between 3.0 and 500 m, and the half-potential electrode spacing *MN/2* are between 0.25 and 20 m. The increasing of the electrode spacing *AB/2* about a fixed point allows the establishment of the complete field apparent resistivity curve in this point ($\rho a = f(AB/2)$). The field apparent resistivity curve is thereafter quantitatively interpreted by the inversion WINRESIST software of Velpen 2004 in order to obtain the final *1D* corrected optimum model, which verifies as well the goodness of fit between the field resistivity curve and the final theoretical regenerated model (Zohdy, 1989; Zohdy and Bisdorf, 1989).

Figure 3-b shows the field work during *VES* measurements in the Khanasser Valley region.

Figure 4-a indicates the snapshot WINRESIST for evaluating the theoretical inverted model, while Figure 4-b indicates the final corresponding *VES* resist graph display.

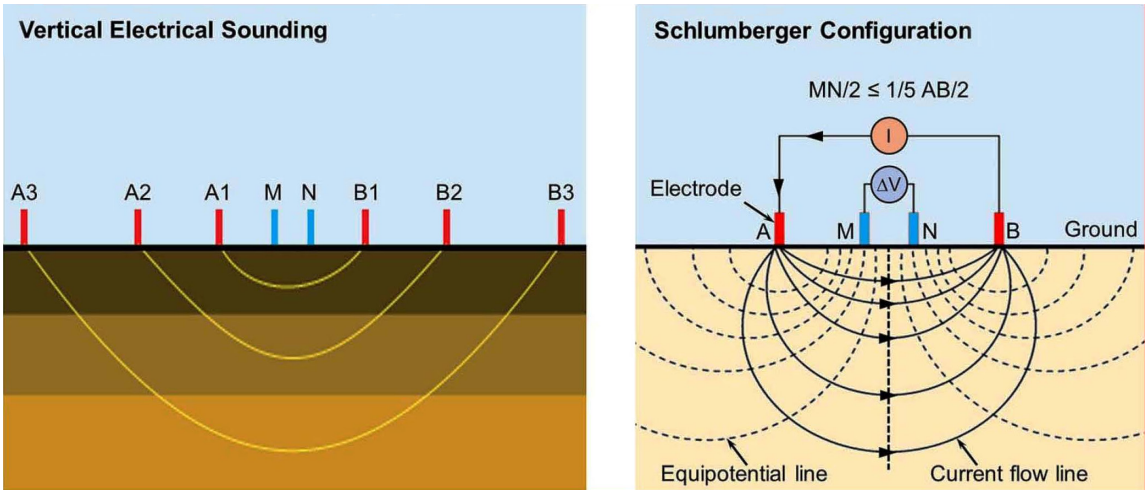

Figure 3 (a). *VES* Schlumberger configuration and its field operation in the field (Othman *et al.*, 2022).



Figure 3 (b). Field *VES* technique.

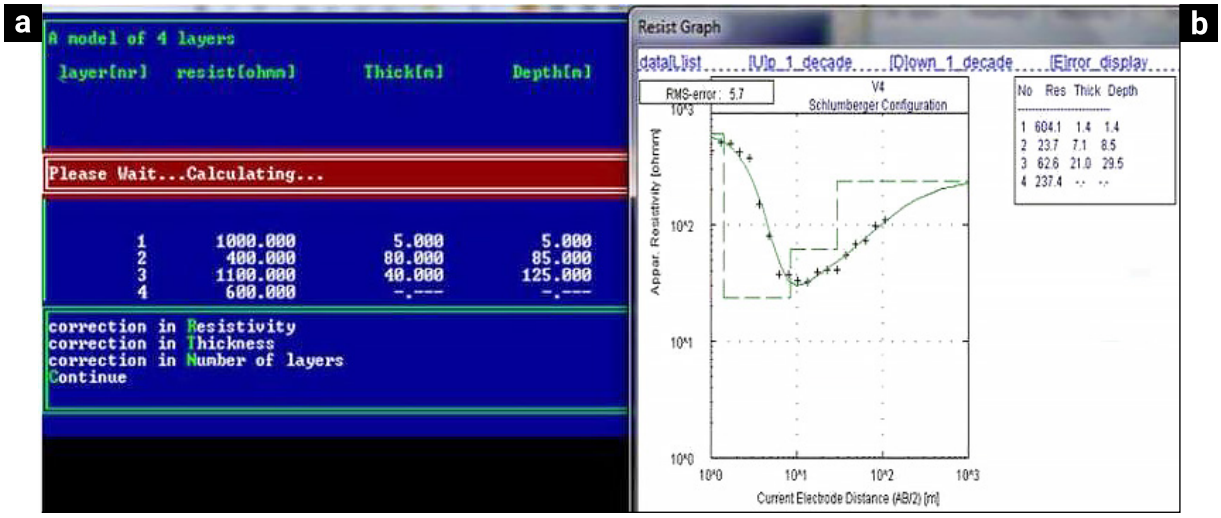

Figure 4. (a) A snapshot WINRESIST window during its running . (b) Final VES resist graph display.

The final optimized model includes the depth, thickness and actual resistivity of the traversed layers under the study *VES* point.

The two fundamental first-order geo-electric indices parameters of layer thickness (h) and resistivity (ρ) are used for interpreting the geoelectrical models to characterize the stratified subsurface lithological units under each studied *VES* location. The computation of both the hydraulic conductivity (K) and the hydraulic resistance (C) of the aquifer overburden layers are based on using (h) and (ρ).

3.2. Hydraulic conductivity (K)

The behavior of the vulnerability overburden protective layers and their hydraulic conductivities are assessed by using the following empirical equation, already proposed and applied for characterizing the alluvial aquifer in the Saharanpur area of India (Singh, 2005):

$$K = 0.0002 * e^{0.0897^{*}\rho} \tag{2}$$

where K (m/day) is the hydraulic conductivity and ρ (Ω.m) is the overburden aquifer resistivity layer. This hydraulic conductivity parameter describes the groundwater movements through the porous and fractured nature of the subsurface alluvial rocks in the study area.

4. Aquifer vulnerability index *(AVI)*

The *AVI* approach, proposed by Stempvoort *et al.* (1993), is used herein to characterize and compute the overburden aquifer vulnerability's hydraulic resistance (C). The parameter (C) expressed in days is evaluated through the parameters of vertical hydraulic conductivity K (*m/day*) and thickness h (*m*) of the layers overlaying the aquifer layer as follows (Stempvoort *et al.*, 1993):

$$C = \sum_{i=1}^{n} \frac{h_i}{K_i} = \frac{h_1}{K_1} + \frac{h_2}{K_2} + \ldots\ldots\ldots + \frac{h_n}{K_n} \tag{3}$$

where h_i is thickness and K_i is the hydraulic conductivity of each covering layer.

The logarithm of the hydraulic resistance (*Log C*) is also evaluated to measure the *AVI* of the overburden layers to the vertical flow of fluid, which expresses the average travel time of a contaminant from the surface to the subsurface aquifer. The relationship between the hydraulic resistance (***C***) and *AVI* is shown in Table 1 according to Stempvoort *et al.* (1993).

5. Results and discussion

The inversion WINRESIST software of Velpen 2004 is used to quantitatively interpret the thirty-four field apparent resistivity curves (*VES*) points in the Khanasser study region. The available lithological description of well No. 306 located close to *V3-3* point of *QH* geoelectrical curve type, with its quantitative interpretation (*1D*) is shown in Figure 5.

The Rammel Aswad, composed of alluvial gravels and sand is the source of the shallow Quaternary aquifer in the study region, where its high thickness gives high transmissivity and yields. The large changes of Rammel Aswad are responsible on the large

Table 1. Standard values for *Log C* and *AVI* ratings (Stempvoort *et al.*, 1993).

Hydraulic Resistance *C (day)*	***Log C (day)***	***Vulnerability (AVI)***
0-10	<1	Extremely high
10-100	1-2	High
100-1000	2-3	Moderate
1000- 10000	3-4	Low
> 10000	>4	Extremely low

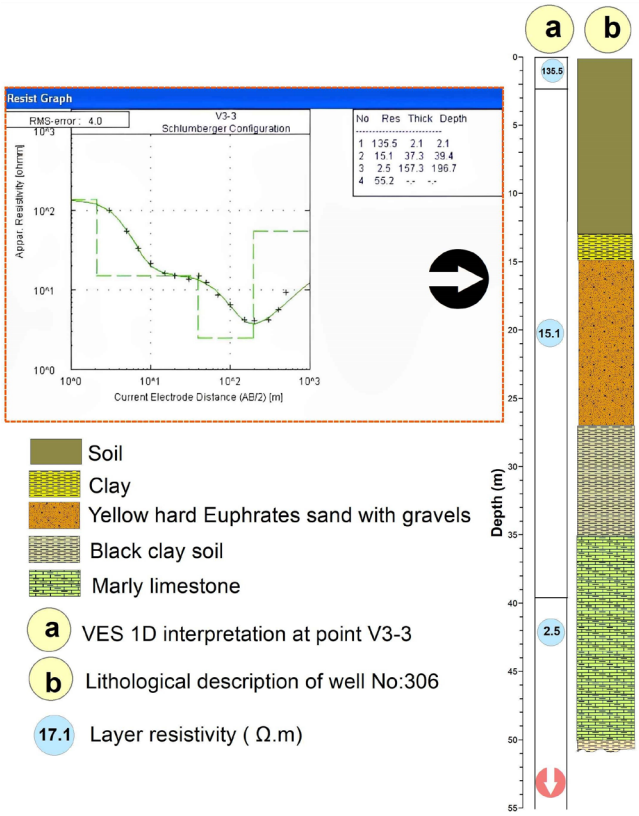

Figure 5. Lithology description of Well No: 306 with quantitative *VES* interpretation of *V3-3* point.

variation in productivity and yields of wells vertically and laterally, from place to place even in very short distances (Asfahani, 2016).

The *VES* locations with high overburden thickness indicate areas of high protective capacity. The equivalent averaged overburden thickness (*hoverb*) ranges between 1.1m and 28.9m, with an average of 5.33m, as shown in Figure 6.

The equivalent averaged overburden resistivity (*ρoverb*) in the study region ranges between 1.5 *Ω.m* and 539 *Ω.m* with an average of 64 Ω.m as indicated in Figure 7.

Equation 2 is used to compute the hydraulic conductivity (*K*) of the overburden layers, where its variation ranges between 0.002 m/day and 32.64 m/day with an average of 1.59 m/day (Table 3). The spatial variations of the (*K*) in the study region are shown in Figure 8.

The hydraulic resistance (*C*), considered as the most critical parameter in quantifying groundwater vulnerability,is computed according to equation 3. It is based on the thickness and hydraulic conductivity of the layers above the Quaternary aquifer in the study Khanasser area. *C varies between* 0.55 and 1659.59 days with an average of 146.68 days (Table 3). The *Log C* ranges between -0.26 and 3.22 days with an average of 0.63 days (Table 3). The *Log C* variation with the *VES* locations is shown in Figure 9, while its spatial variations in the study region are shown in Figure 10. The capacity of the overburden alluvial rocks to retard and prevent fluid infiltration into the subsurface aquifer is a good indication of its protective capacity.

The influences of the two thickness (*hoverb*) and resistivity (*ρoverb*) parameters on the *Log C* are shown in Figure 11 (a, and b),

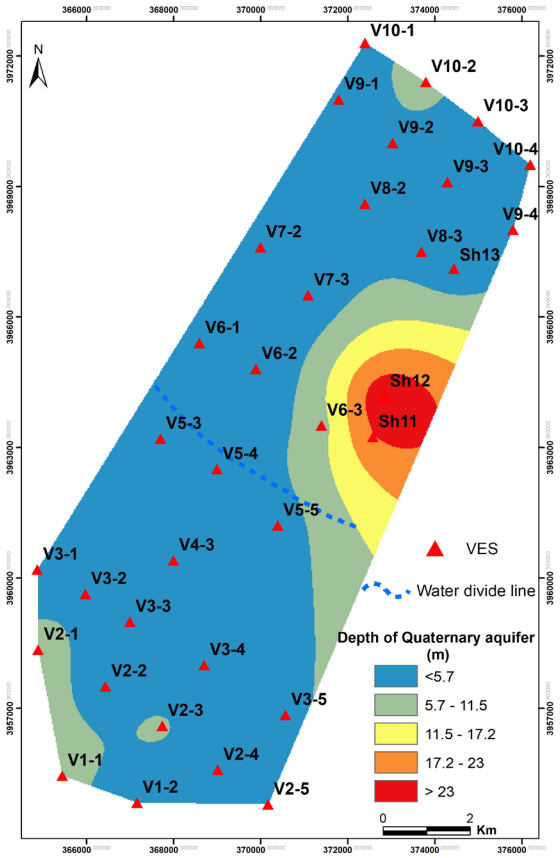

Figure 6. Quaternary aquifer overburden thickness of in the Khanasser valley region (Asfahani, 2023a)

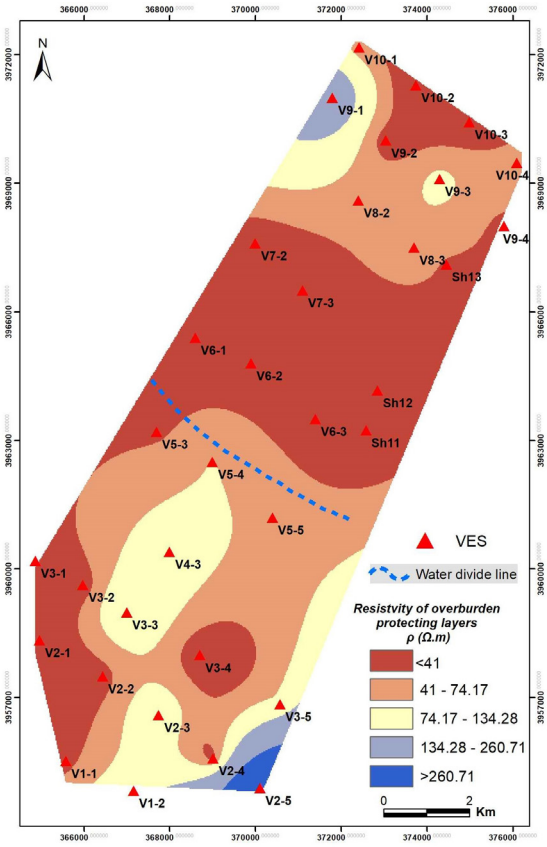

Figure 7. Quaternary aquifer overburden resistivity in the Khanasser valley region.

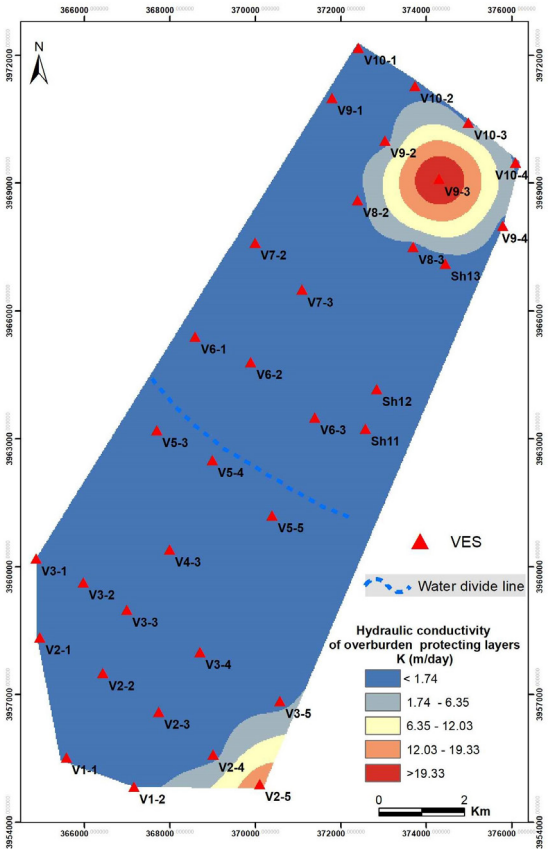

Figure 8. Hydraulic conductivity (K) of the overburden protecting layers of the aquifer Quaternary in the Khanasser valley region.

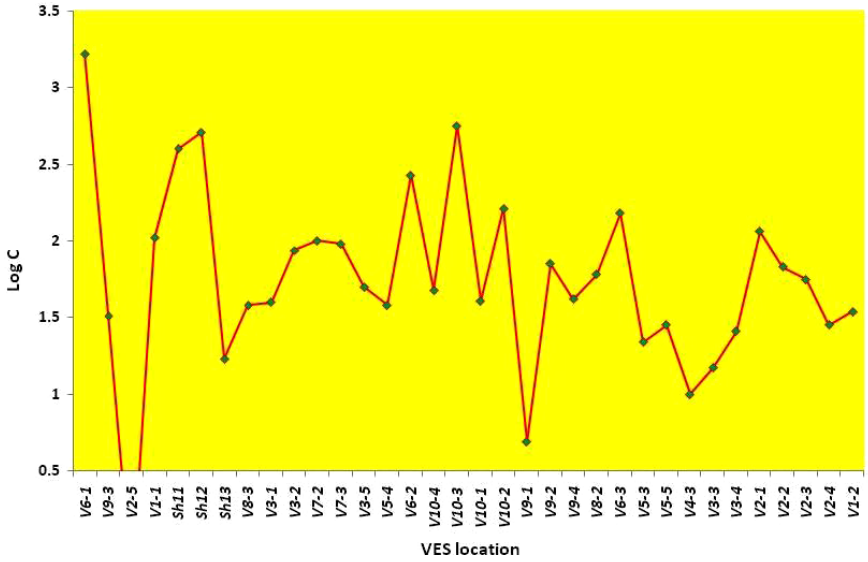

Figure 9. Variation of *Log C* with the thirty-four *VES* location points in the study area.

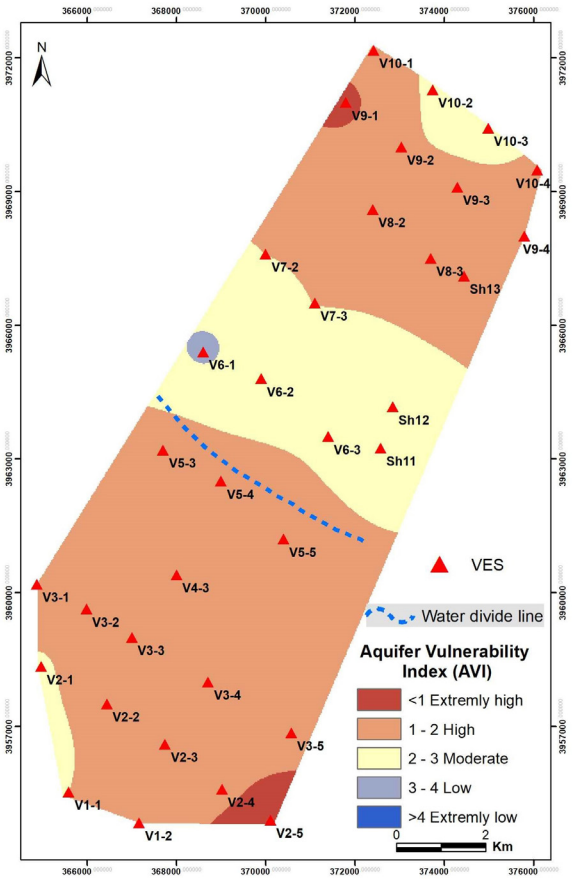

Figure 10. Spatial variations of *AVI* in the study Khanasser region.

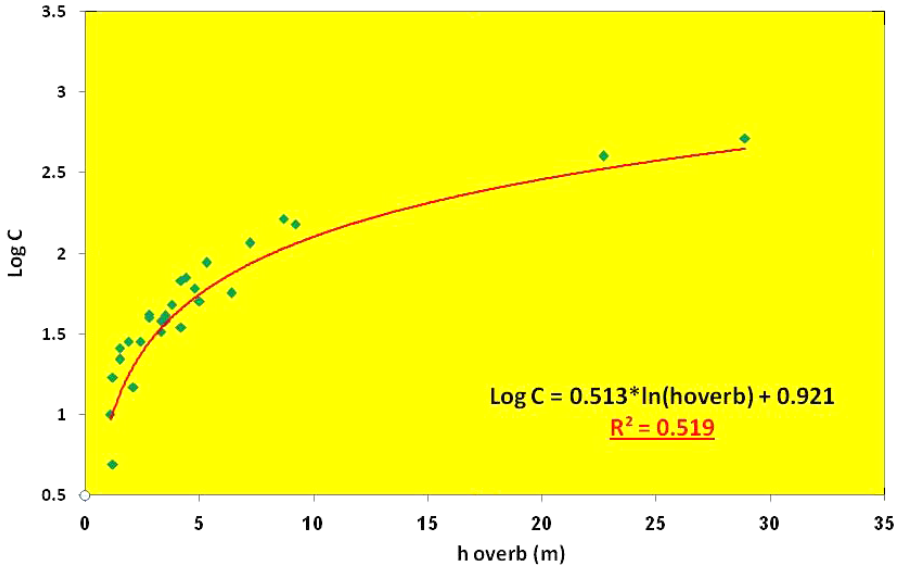

Figure 11(a). The empirical relationship between *Log C* and (*hoverb*) in the study area.

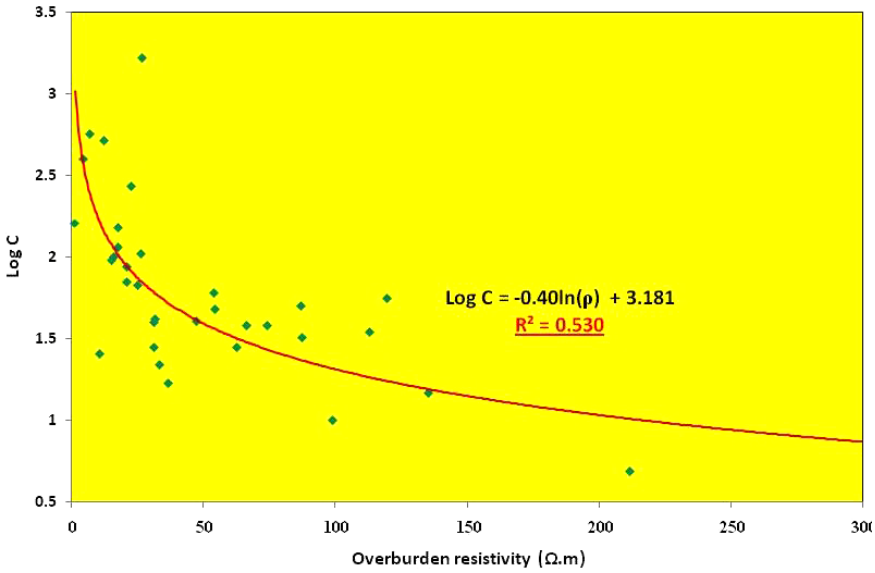

Figure 11(b). The empirical relationship between *Log C* and (*ρoverb*) resistivity in the study region.

where two empirical relationships are established between the *Log C* and h_{Overb}, *ρoverb* of the aquifer Quaternary as follows:

$$Log\ C = 0.513*\ln(hoverb) + 0.921\ (R^2 = 0.519) \quad (4)$$

$$Log\ C = -0.40\ln(\rho overb) + 3.181\ (R^2 = 0.530) \quad (5)$$

The variations of *Log C* with the hydraulic conductivity (*K*) of the overburden layers are shown in Figure 12, where a decreasing tendency is obtained between them, as much *K* is bigger, as much *Log C* is more minor.

The hydraulic conductivity (*K*) of the overburden layers is related to the anisotropy of the study region (Asfahani, 2023a; Asfahani, 2023b), as attested by Figure 13.

Figure 13 indicates three trends between *K* and λ, that reflect different hydraulic systems in the study area. Those exponential trends are quantified by the following three regression equations:

$$K\ (m/day) = 0.007e^{2.713\lambda} \quad (R^2 = 0.961) \quad (6)$$

$$K\ (m/day) = 0.007e^{2.041\lambda} \quad (R^2 = 0.963) \quad (7)$$

$$K\ (m/day) = 0.016e^{0.898\lambda} \quad (R^2 = 0.99) \quad (8)$$

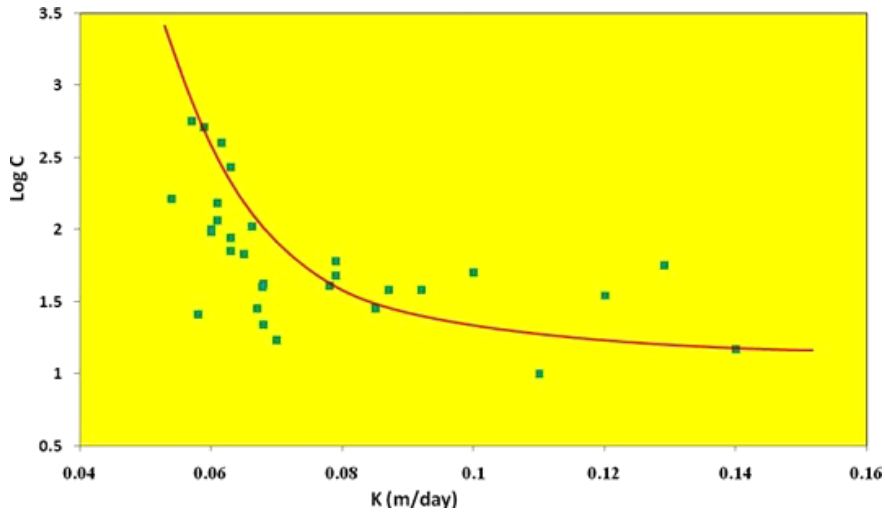

Figure 12. Variations of *Log C* with *K* parameter in the study region.

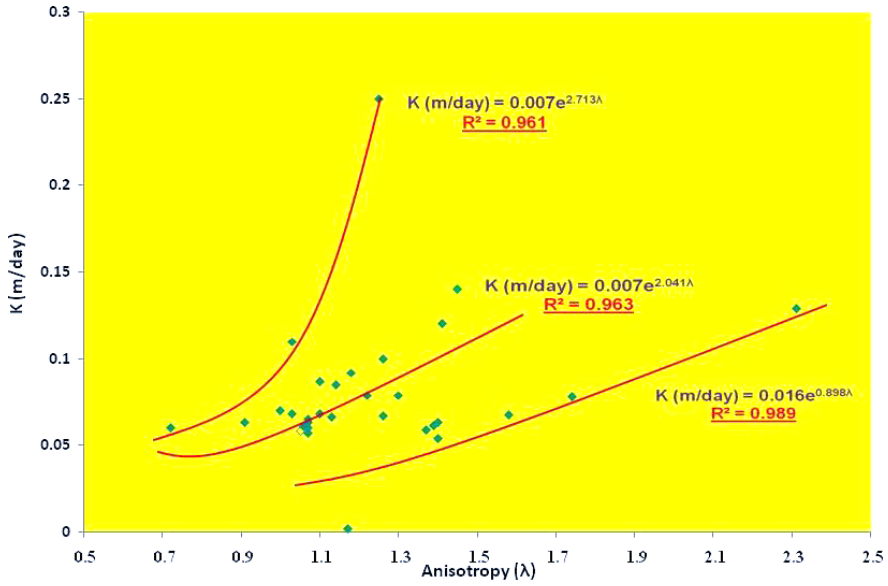

Figure 13. Different relationship trends between anisotropy (λ) and hydraulic conductivity (K) in the study area.

The variations of *hOver*, *ρOver*, *K*, *C*, *Log C*, *λ*, and *OPC* for the measured thirty-four *VES* points are shown in Table 2.

Based on the relationship between (*C*), (*Log C*), and the aquifer vulnerability index (*AVI*) indicated in Table 1 (Stempvoort *et al.*, 1993), the thirty-four *VES* locations in the Khanasser area are classified as follows (Table 2):

The rating of (*AVI*) is exceptionally high in the *VES* (V2-5 and V9-1).

The rating of (*AVI*) is high in the *VES* (V9-3, Sh13, V8-3, V3-1, V3-2, V7-2, V7-3, V3-5, V5-4, V10-4, V10-1, V9-2, V9-4, V8-2, V5-3, V5-5, V4-3, V3-3, V3-4, V2-2, V2-3, V2-4, and V1-2).

The rating of (*AVI*) is moderate in the *VES* (V2-2, Sh11, Sh12, V6-2, V10-3, V10-2, V6-3, and V2-1).

The rating of (*AVI*) is low in the *VES* (V6-1).

The overburden protective capacity (*OPC*) of the aquifer Quaternary in the study area has been already modeled by applying the following equation (Asfahani, 2023a; Asfahani, 2023b):

$$OPC\left(\Omega^{-1}\right) = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \ldots\ldots\ldots + \frac{h_n}{\rho_n} \quad (9)$$

where ρ_i is the resistivity and h_i is thickness of each covering layer.

It has been indicated, according to the classification of Heinret (1976), that as much the longitudinal conductance (Ω^{-1}) of the overburden protecting layers is bigger, as much the *OPC* is bigger (Asfahani, 2023a).

Figure 14 shows a good positive concordance between the results of both (*OPC*) and *AVI* techniques, where the correlation coefficient R^2 of 0.60 is obtained for them. The equation between *OPC* and *Log C* has the following form:

$$Log\ C = 0.270*\ln(OPC) + 2.267\ (R^2 = 0.60) \quad (10)$$

The correlation matrix indicated in Table 3 shows the different relationships between (*Log C*), and the thickness, resistivity, hydraulic conductivity, anisotropy (*λ*), and (*OPC*) of the overburden layers.

An acceptable correlation is shown in Table 3 between h_{Overb} and *Log C* (0.56), overburden resistivity and *Log C* (-0.75), and *K* and *Log C* (-0.34). Table 4 summarizes the statistical results of the different treated parameters related to the measured thirty-four *VES* points in the study area.

This paper discus the influence of those different parameters in affecting the protectivity of the aquifer Quaternary from the fluid contaminations originated in the study area. The different geoelectrical results thus obtained in this paper are important and help the decision makers for locating the effective protected groundwater area in the study region.

6. Conclusion

The aquifer vulnerability index (*AVI*) methodology with using the (*VES*) technique is undertaken to assess the aquifer

Table 2. Values of geoelectrical, hydrological, and vulnerability parameters for the measured thirty-four *VES* points.

VES Location	*ρOver*	*h Over*	*K*	*C*	*Log C*	*λ*	*OPC*
V6-1	26.8	3.7	0.002	1659.59	3.22	1.17	0.14
V9-3	87.6	3.3	32.64	32.3594	1.51	1.12	0.037
V2-5	539	3.9	18.93	0.54954	-0.26	1.85	0.012
V1-1	26.4		0.0662	104.713	2.02	1.13	-
Sh11	4.8	22.7	0.0616	398.107	2.6	1.39	3.26
Sh12	12.5	28.9	0.0589	512.861	2.71	1.37	4.57
Sh13	36.7	1.2	0.07	16.9824	1.23	1	0.033
V8-3	66.5	3.3	0.087	38.0189	1.58	1.1	0.05
V3-1	31.5	2.8	0.0678	39.8107	1.6	1.58	0.09
V3-2	21.1	5.3	0.063	87.0964	1.94	0.91	0.6
V7-2	16		0.06	100	2	1.07	0.37
V7-3	15.4		0.06	95.4993	1.98	0.72	0.37
V3-5	87	5	0.1	50.1187	1.7	1.26	0.057
V5-4	74.4	**3.5**	**0.092**	**38.0189**	**1.58**	**1.18**	**0.047**
V6-2	22.6		0.063	269.153	2.43	1.07	0.76
V10-4	54.5	3.8	0.079	47.863	1.68	1.22	0.07
V10-3	7.2		0.057	562.341	2.75	1.07	2.5
V10-1	47.45	3.5	0.078	40.738	1.61	1.74	0.094
V10-2	1.5	8.7	0.054	162.181	2.21	1.4	13.75
V9-1	212	1.2	0.25	4.89779	0.69	1.25	0.006
V9-2	21	4.4	0.063	70.7946	1.85	1.4	0.21
V9-4	31.7	2.8	0.068	41.6869	1.62	1.1	0.09
V8-2	54	4.8	0.079	60.256	1.78	1.3	0.09
V6-3	18	9.2	0.061	151.356	2.18	1.06	1.29
V5-3	33.5	1.5	0.068	21.8776	1.34	1.03	0.045
V5-5	63	2.4	0.085	28.1838	1.45	1.14	0.04
V4-3	99	1.1	0.11	10	1	1.03	0.01
V3-3	135.5	2.1	0.14	14.7911	1.17	1.45	0.015
V3-4	10.8	1.5	0.058	25.704	1.41	1.05	0.14
V2-1	18	7.2	0.061	114.815	2.06	1.06	0.49
V2-2	25.4	4.2	0.065	67.6083	1.83	1.07	0.23
V2-3	119.6	6.4	0.129	56.2341	1.75	2.31	0.061
V2-4	31.5	1.9	0.067	28.1838	1.45	1.26	0.06
V1-2	113	4.2	0.12	34.6737	1.54	1.41	0.04

Quaternary protectivity in the semi-arid Khanasser Valley region of northern Syria. The inversion WINRESIST computer software program is used to quantitatively interpret the measured thirty-four *VES* points in terms of *1D* structure, to obtain the final geoelectrical inverted optimized models for the treated *VES* points. The different geoelectrical parameters and their influences on the aquifer protectivity and contamination conditions are well determined. This work also discusses the effects of the geoelectrical parameters controlling the overburden protective capacity of the aquifer Quaternary by analyzing the results obtained by the *AVI* approach with its related *Log C*. Those parameters are the thickness (*hOver*), the resistivity (*ρOver*), the hydraulic conductivity (*K*) of the overburden protecting layers, and the anisotropy of the subsurface hydrogeological layers (*λ*). It is found that as the layers covering the aquifer are thinner, and their hydraulic conductivities are higher, the aquifer will be

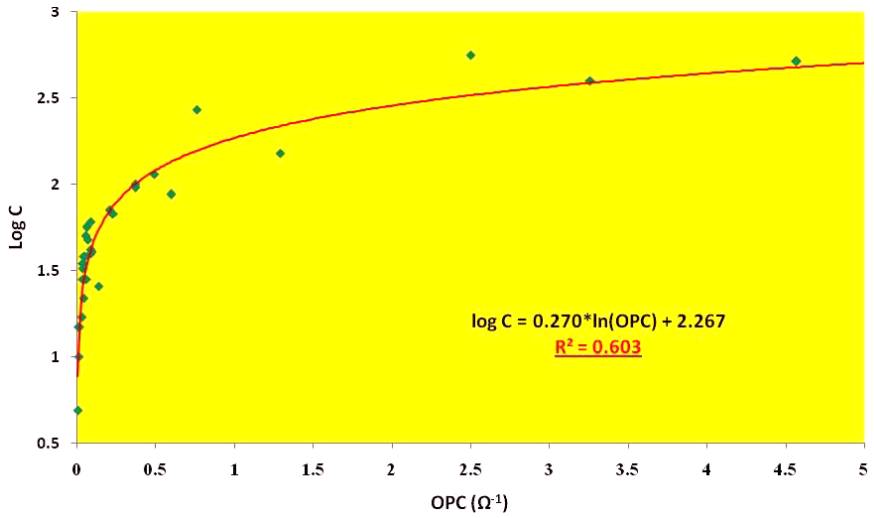

Figure 14. Empirical regression relationship between *OPC* and *Log C* in the study area.

Table 3. Correlation matrix between the *hOver*, *ρOver*, K, λ, *OPC* and (*Log C*) in the study area.

Variables	*ρOverb*	*λ*	*Log C*	*OPC*	*hOverb*	*K*
ρOverb	1	0.44	-0.75	-0.21	-0.21	0.48
λ		1	-0.16	0.08	0.15	0.1
Log C			1	0.35	0.56	-0.34
OPC				1	0.47	-0.09
hOverb					1	-0.082
K						1

Table 4. Statistical results of the treated geoelectrical parameters in the study region.

Statis	*hOver (m)*	*Over (Ω.m)*	*K (m/day)*	*C (day)*	*Log C*	*OPC* (Ω^{-1})	*λ*
Min	1.1	1.5	0.002	0.55	-0.26	0.006	0.72
Max	28.9	539	32.64	1659.59	3.22	13.75	2.31
AV	5.33	64	1.59	146.68	1.74	0.87	1.24
SD	6.1	95	6.37	299.88	0.63	2.49	0.29

increasingly vulnerable to pollution. The correlation matrix of the geoelectrical parameters with the different mutual empirical equations already established clearly indicate the considerable influence of those parameters (*hOverb*, *ρOverb*, *K*, and *λ*) on the spatial distribution of the *Log C in the study region*. The derived empirical relationships between the different analyzed hydro-geophysical parameters are essential to understand both the mutual hydrological processes and the lithological connectivity nature between the study aquifer Quaternary and its overlaying layers. This paper provides useful geoelectrical information, which help in locating the effective protected groundwater area in the semi-arid Khanasser Valley region in Syria. The results obtained in this paper allow decision makers to assess management scenarios and coordinate surface and groundwater resources effectively. As such, the *VES* technique with the *AVI* methodology developed in this article helps the decision-makers for locating the polluted and protected aquifer zones.

It can be practiced successfully to characterize other similar hydro-geological context in Syria, and worldwide outside of the Khanasser region. The *AVI* approach as described above is practiced herein for the first time in Syria, and can be easily extended to cover and deal with other Syrian aquifers to determine their

protectivity and contamination conditions. The *AVI* approach can be also applied worldwide to evaluate the protection conditions surrounding an aquifer in similar semi-arid regions.

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9. Data availability

The datasets related to this research paper are available with the author; however, accessing these data or making them available to others upon a reasonable request requires special permission from the Syrian Atomic Energy Commission.

10. Declarations

Conflict of interest: The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this.

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