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HYDROGEOLOGY

Geoelectrical investigation to delineate potential aquifers in Shahroud, Iran

Ilnaz Zarif Mahdizadeh[1], Ali Beitollahi[2], Sanaz Zarif Mahdizadeh[3]*
1. Department of Earth sciences, Faculty of Basic Sciences, North Tehran Branch, Islamic Azad University, Tehran, Iran.
2. Department of Geophysics, Head of Seismology Engineering and Risk, Road, Housing and Urban Development Research Center, Tehran, Iran.
3. Department of Earth sciences, Faculty of Basic Sciences, Science and Research Branch, Islamic Azad University, Tehran, Iran.
Corresponding Author Email*: Beitollahi@bhrc.ac.ir

ABSTRACT

One of the world's most pressing needs today is access to groundwater. Although hydrological parameters can generally be estimated using underground studies, these methods are time-consuming and expensive. By taking the direct relationship of these parameters with electrical resistivity and measuring it with a cheaper and faster geoelectric method, a qualitative estimate of these parameters will be obtained. The electrical resistivity method is one of the most widely used methods to probe aquifers. The main objective of this paper is to show how, by interpreting and modeling the data of this exploratory method along with other geological information, the hydrogeological modeling of groundwater reservoirs can be done, and then, with an informed vision, the wells can be drilled for exploitation. For this purpose, the electrical resistivity data at 189 points and 9 profiles in the Shahroud region with Schlumberger array, after reviewing and making some modifications, were subjected to one-dimensional inverse modeling. According to the peripheral vision, the electrode distance was considered to be 50 meters and the length of the profiles is different. The longest profile was 1000 meter and related to profile 3. Then, using the results of modeling along with other available information, the hydrogeological models of the area were prepared in the form of iso-resistivity contour map and interpreted in terms of resistivity and thickness of subsurface layer using computer software Geographic Information System (GIS). Similarly, the thickness map of the aquifer unit (s) was also prepared to classify the good and poor zones. Using the prepared models and also considering the direction and piezometric of the groundwater flow inside the aquifer, suitable places were identified and suggested for future exploitation.

Keywords: Electrical Resistivity Method; Inversion; Groundwater Exploration; GIS.

Investigación geoeléctrica para delinear potenciales acuíferos en Shahroud, Irán

RESUMEN

Una de las necesidades más apremiantes en el mundo es el acceso al agua subterránea. Si bien algunos parámetros hidrológicos se pueden estimar generalmente con estudios subterráneos, estos métodos suelen ser costosos en tiempo y en dinero. Una estimación cualitativa de estos parámetros se puede obtener al tomar la relación directa de estos parámetros con la resistividad eléctrica y medir con un método geoeléctrico más barato y más rápido. El método de resistividad eléctrica es uno de los más usados para hacer pruebas en acuíferos. El objetivo principal de este trabajo es mostrar cómo se puede hacer, por interpretación y modelado de la información de este método exploratorio junto con otra información geológica, el modelado de reservorios de agua subterránea y luego, con una visión informada, la perforación de pozos para su explotación. Para este fin la información de resistividad eléctrica de 189 puntos y de 9 perfiles en la región de Shahroud con la configuración de Schlumberger, después de revisarla y hacer algunas modificaciones, fue objeto de un modelado unidimensional inverso. De acuerdo con la visión periférica, la distancia de los electrodos se consideró en 50 metros mientras que la longitud de los perfiles es diferente. El perfil 3 fue el más largo, con unos 1000 metros. Luego, al combinar los resultados del modelado con otra información disponible se prepararon los modelos hidrogeológicos en la forma de un mapa de contornos de iso-resistividad y se interpretaron en términos de resistividad y espesor de la capa de la subsuperficie con el software Sistema de Información Geográfica. De manera similar se preparó el mapa de espesor de las unidades acuíferas para clasificar las zonas más y las menos profundas. Al usar los modelos preparados y también considerar la dirección y piezometría del flujo de las aguas subterráneas al interior del acuífero se identificaron los lugares más adecuados y se sugirieron para futuras explotaciones.

Palabras clave: Método de resistividad eléctrica; Inversión; Exploración de aguas subterráneas; Sistema de Información Geográfica.

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1. Introduction

The method of electrical resistivity in hydrological issues dates back to the very beginning of the emergence of this science. New methods and various theoretical topics have been presented and finally today it has led to its comprehensive use, especially in hydrological issues (Surinaidu and Bacon, 2023). The first research on geoelectric methods was conducted in 1912 by Schlumberger, and Wenner separately but simultaneously (Schlumberger, 1912; Wanner, 1912).

Due to the wide range of resistivity relative to other geophysical parameters, the electrical resistivity technique is a versatile and cost-effective technique for groundwater study under different geological conditions. By determining the geological structures, and maintaining a basic relation between the hydrogeological and geophysical parameters of the aquifer environment, the electrical resistivity sounding models the groundwater reliably. (Mozac *et al.,* 1985; Asfahani, 2007; Soupios *et al.,* 2007; Lesmes and Friedman, 2005; Akhter and Hasan, 2016). The effectiveness of electrical resistivity tomography (ERT; nonintrusive geophysical technique) in determining the hydrogeological conditions at surface groundwater was investigated by Koch *et al.* (2009). The vertical electrical sounding method is widely used in locating the low salinity groundwater in irrigation issues (Arshad *et al.,* 2007; Sikandar *et al.,* 2010), studying groundwater conditions such as depth, thickness, and aquifer boundaries (Lashkaripour and Nakhaei, 2005).

Mapping the intrusion of saltwater (Abdul Nasir *et al.,* 2000), identifying saltwater/freshwater interface (El-Waheidi *et al.,* 1992; Van Dam and Meulenkamp, 1967) and characterizing hydrogeological (Al-Fares, 2016) can be determined by electrical resistivity method.

Vertical electrical sounding technique is possible to utilize in groundwater investigation in the sedimentary area (Mallam and Ajayi, 2000; Lateef, 2012), the interpretation a computer iteration technique (Asokhia, 2000), planning, and management of groundwater resources (Arunbose *et al.,* 2021) and evaluating of the underground- water reservoir (Al-Khafaji, 2013; Coper, 2012).

Geoelectric methods estimated hydraulic parameters in a porous aquifer environment (Kazakis *et al.,* 2016). Fajana (2020) and Alile *et al.* (2011) determined the potential of the aquifer by the resistivity method and calculated the porosity. The same studies were performed to delineate potential groundwater aquifers using electrical resistivity methods (Oseji *et al*., 2006, 2005; Anomohanran, 2013; Hassan *et al.,* 2017; Emenike, 2001).

Geophysical studies to determine the potential of underground water in the Shahroud region have been done with several methods, among which we can refer to the article from Sharifi *et al.* (2014). This study used integrated results obtained from vertical electrical sounding (VES) and resistivity profiling. One-dimensional (1-D) modeling and interpretation of the sounding results, using master curves and IX1D software, and two-dimensional (2-D) modeling and interpretation of the profiling results using Res2DINV were made. As a result of the interpretation and combination of the results, karst water zones were found in the study area, and based on this, the best zones for access drilling and karst water extraction were included in the central and northern regions of the plain. It shows a good correlation with the results obtained in our paper.

In 2015, remote sensing and geological investigations were implemented in a GIS environment for the delineation of potential groundwater in Shahroud areas. For this purpose, fuzzy evidential maps (lithology and intersection point density maps) were combined using the fuzzy 'AND' operator. The evaluation of the presented karstic WP model was applied using geoelectrical resistivity surveys (Sharifi *et al.,* 2015).

The estimation of underground water potential in different areas has been done using the method studied in this project, some of which are mentioned in the following. An electrical resistivity survey involving Vertical Electrical Soundings (VES) by Schlumberger array was applied to investigate groundwater conditions such as aquifer boundaries, depth, and thickness, which were estimated from geoelectrical section, and R.T map, and zones with high yield potential have been determined for choosing drilling sites (Lashkaripour and Nakhaei, 2005; Tahmasbi Nejad and Lashkaripour, 2010).

In Guigou plain, the vertical electrical sounding (VES) technique was used to map the aquifer system. The main aims of this survey included the following: (i) to determine the geometry of the aquifer system; (ii) to determine the geological layers forming the aquifer; (iii) to estimate the depth of the impermeable bedrock. Iso-resistivity, the marl–limestone bedrock and basalt thickness maps were generated to characterize this aquifer (El Makrini *et al.,* 2022).

The purpose of this study is to evaluate the geoelectrical characteristics of the delineated aquifer and separate several subsurface regions of Shahroud, in terms of physical characteristics, considering their electrical resistivity. Finally, according to the studies conducted, the areas with a higher potential of groundwater suitable for drilling water wells were determined. In this research, at first, electrical resistivity data were interpreted using IPI2WIN software. Also, diagrams and sections were drawn using Geographic Information System (GIS) software with an interpolation algorithm of Inverse Distance Weighting (IDW), and the best points for drilling wells were estimated in the study area. The results could be used for further study of groundwater regimes in the study area and to improve the quality of groundwater resources and management.

2. The study area

2.1 Geographical situation

Shahroud is one of the cities of Semnan province in Iran. This city is on the northern edge of the desert plain and the southern slopes of the Alborz Mountain range with a geographical position of 36°25'N latitude and 54°58'E longitude in zone 39 and 40 of UTM coordinates. It is located at an altitude of 1380 meters above sea level in the northeast of Semnan province.

2.2 Geomorphological and Geological study of the area

Alborz heights in the north of the province are the highest areas of the province and to the south, the lower lands are spread. It is conceivable that based on the elevation characteristics of the province, steep areas have been spread in the northern parts of the province. Transport of surface sediments, river erosion, granulation, and sedimentation order according to its slope and direction are formed. Also, the recharge of aquifers and their effect on the moisture of surface deposits is done according to the direction and width of waterways. Map of main and secondary waterways of Semnan province has been prepared in Figure 1 based on the data from the National Geosciences Database (NGDIR).

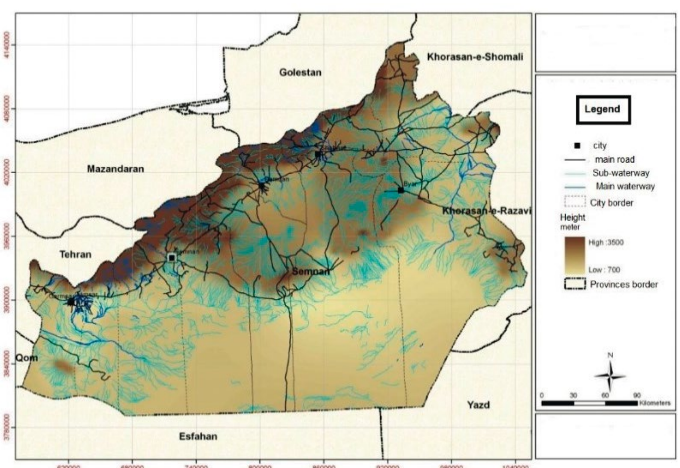


Figure 1. Map of main and secondary waterways of Semnan province.

The distribution of waterways determines the distribution of fluvial sediments and floods, as well as the order of granulation, all of which influence the geoelectric characteristics. Coarse-grained environments with high electrical resistance and fine-grained deposits with lower electrical resistance will also appear. Moisture in deposits and salinity also causes a significant decrease in electrical resistance (Darayan *et al.,* 1998; Yoon and Park, 2001). A wide range of study areas is covered by younger and older alluvium. In the southern regions, soil debris and gravel are visible, and the fine-grained and clay alluviums are spread. In the northern regions of Shahroud, older alluvium and alluvial fans are observed. In Figure 2, the status of surface deposits and protrusions of geological formations in the studied areas are shown.

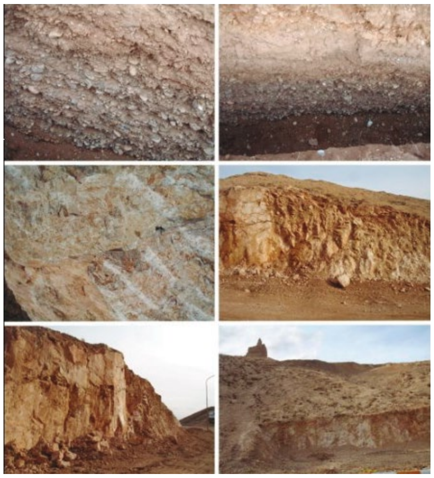


Figure 2. Status of surface deposits and protrusions of geological formations in the studied areas.

3. Materials and Methods

3.1. Vertical Electrical Sounding (VES) Basic Principle and Data Acquisition

The geoelectrical method, using the vertical electrical sounding (VES) technique, consists of measuring the variations in apparent resistivity (ρ_a) as a function of depth. In principle, the measurement protocol consists of injecting an electric current of intensity (I) through two current electrodes (A and B) and measuring the potential differences (ΔV) created between the two receiving electrodes (M and N), called potential electrodes (Figure 3).

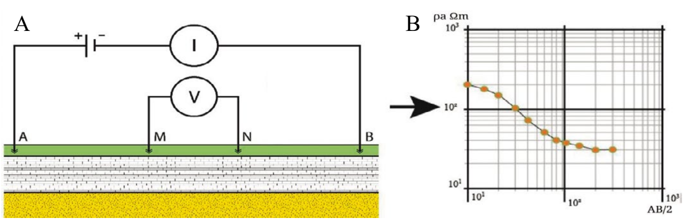


Figure 3. (**a**) General scheme of a soil-resistivity measurement using the Schlumberger configuration with a four−electrode device (ABMN), (**b**) bi−logarithmic diagram for the representation of VES measurements. (El Makrini *et al.,* 2022)

According to Ohm's law, the apparent resistivity is a function of ΔV, I and the geometric coefficient (K). It is calculated by the following formula:

$$\rho_a = \frac{\Delta V}{I} * K \tag{1}$$

$$K = 2\pi\left(\frac{1}{\frac{1}{AM}+\frac{1}{AN}+\frac{1}{BM}+\frac{1}{BN}}\right) \tag{2}$$

The curve ρ_a = f (AB / 2) is obtained by plotting the apparent resistivity values ρ_a against AB/2 (half spacing of the current electrodes, which can reach up to 10 (km) in a bi-logarithmic scale (Telford *et al.,* 2012).

The geoelectrical survey of Shahroud area involved 189 vertical electrical soundings by Schlumberger array and 9 profiles, considering the possibility of expanding the wires, which were determined up to 1000 meters. The main problem of geoelectric field surveys inside Shahroud is the existence of urban buildings and facilities which made it difficult to extend the wires for deeper studies. Determining the location of points for measuring took up a lot of time from the field team. Figure 3(a) shows the location map of geophysical studies. Electrode distances have been chosen as regularly as possible and 50 meters apart. However, it is observed that in some places, especially in crowded and dense areas, due to the impossibility of geoelectric withdrawals, the sounding distances are longer. The measurements will not be possible in places where it is not possible to connect the electrode to the ground and inject current. In Shahroud's studies and also in some places, it is not possible to inject current, and therefore, the arrangement of points is not in proper order.

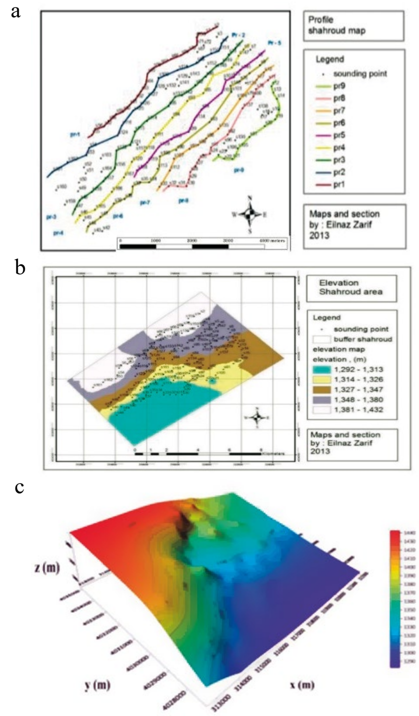


Figure 4. (a) Shahroud profile map; (b) Altitude map of the study area; (c) 3D elevation model with location of sounding points

In Figure 4(a), profiles from 1 to 9 are shown in different colors and the profiles are from left to right. In Figure 4(b) the areas shown in blue have the lowest elevations, mostly in the south and east. The areas marked in white have the highest altitude and are located in the northern and northwestern parts. As mentioned in the geomorphology of the study area, the north of the province is the highest region of the province and in the south, the lowlands have expanded which Figure 4(b) confirms. Sloping areas are spread in the northern regions of the province. In Figure 4(c), the location of sounding points was illustrated in the 3D elevation model.

3.2. Data Processing and Resistivity Interpretation

The VES data acquired were subjected to a series of processing steps to facilitate their interpretation, summarized in four steps. In the first step, the VES diagrams were first smoothed to eliminate all outliers. They were then inverted using IPI2WIN software, which allows each diagram to be broken down into well-defined electrical levels in terms of thickness and resistivity. In the second step, the geoelectric levels of the VES models of each profile were correlated horizontally. Consequently, four geoelectrical sections were drawn up to follow the evolution of the resistivity and the thickness of the formations crossed in both the vertical and lateral directions. Then, the third step was to interpolate the VES data using the inverse distance weighting (IDW) method. Several maps were produced, including four iso-resistivity maps, two iso- resistivity of the aquifer and bedrock maps, two iso- depth of water table level and bedrock maps, an iso- thickness of the aquifer map. Finally, based on the main geoelectrical characteristics extracted from the geoelectrical sections and R.T map, the fourth step concerned the elaboration of the groundwater prospectivity map.

Figure 5 shows the methodological flowchart applied in this work, described in the four steps above

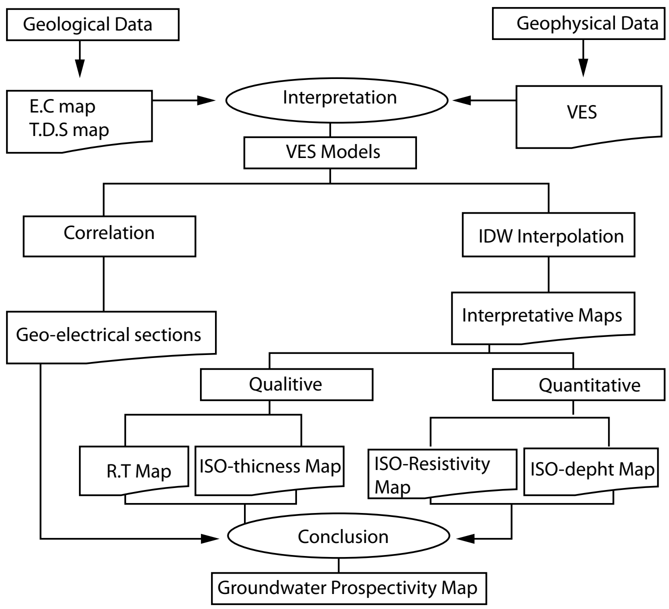


Figure 5. The methodological flowchart in this study.

3.3 Data inversion method

The geoelectrical data inversion method in the geoelectrical studies of the studied area is known as the T method. In this method, a large number of layers (in this case 29 layers) with constant thickness are selected for each geoelectric sounding curve. It has been shown that this method is more stable for solving matrix equations in inverse geoelectrical functions. Also, due to the use of a large number of layers, the error function takes significantly less values. Another advantage of using the T method is that according to the selected fixed depth, it is possible to draw electrical resistivity maps for each depth horizon (Dimitrev *et al.,* 1998).

3.4 Estimation of the relationship between the depth of exploration and the length of the current line

Geoelectrical-sounding curves show the values of apparent electrical resistance against different lengths of the current line (AB); as the distance between the current electrodes increases, the depth of penetration increases (Evien, 1938). But without interpreting these curves, it is not possible to determine what specific depth the apparent electrical resistances taken are related to (Barker, 1989; Apparao and Rao, 1974). The amount of penetration depth in each region and even each sounding differs from another sounding and depends on the thickness and electrical resistance of the layers. Schlumberger (1932) and Keller (1966) introduced the current penetration depth in their proposed array $AB/2$. But Bella (1932) and Hiellan (1938) considered it equal to $AB/3$. Barker (1989) estimated $AB/4$ as the penetration depth. Ayres (1989) obtained a penetration depth of 60 meters for $AB/2 = 215$ meters. Apparao and Rao (1973) calculated the current penetration depth for most of the current arrays and expressed this depth as $AB/4$ for the Schlumberger array. They also noted that the depth of current penetration in a specific area depends only on the distance between the current electrodes (AB), but the search volume depends on both the current electrode distance and the potential electrode distance.

Based on the calculations made for the studied area, this value follows the following relationship:

$$Depth = 0.5001\left(\frac{AB}{2}\right)^{0.998} \qquad (3)$$

Based on this relationship, the depth of exploration in our studied areas is about *AB*/4. In this study, maximum *AB*/2 of VES soundings is 464 meters and maximum penetration depth is 232 meters.

3.5 R.T map

RT map (Aquifer Resistivity multiply by Aquifer Thickness) that shows the potential of the aquifer for water resources and quality in the whole study area. From a geophysical point of view, the electrical resistivity factor can play an important role in determining the exact location of the excavation site (Lashkaripour and Nakhaei, 2005). Therefore, having the electrical resistivity of the aqueous layer (p) and considering its thickness (e), RT values are calculated according to the following formula.

$$RT = p.e \qquad (4)$$

In this regard, *p* in addition to the characteristics of the hydrous formation also depends on the concentration of solutes. Thus, using the data obtained from geophysics and modeled layers and the obtained resistances for each model, finally, an R.T map was prepared for the study area.

3.6 Geophysical cross section and pseudo-section maps:

To determine the stratification of the subsoil in the area, the geoelectric sections must be examined. Geoelectric sections after interpretation of sounding curves for each profile, and considering the true electrical resistance of the subsurface layers, topographic changes along with the profile, the trend of electrical resistance changes in depth, and field information has also been obtained. To observe changes in subsurface apparent electrical resistivity that reflect qualitative changes in subsurface structures, pseudo-section maps of apparent electrical resistivity were drawn using Arc GIS software. Geoelectric pseudo-section maps show the apparent electrical resistivity distribution in a deep section along with a profile.

4. Results

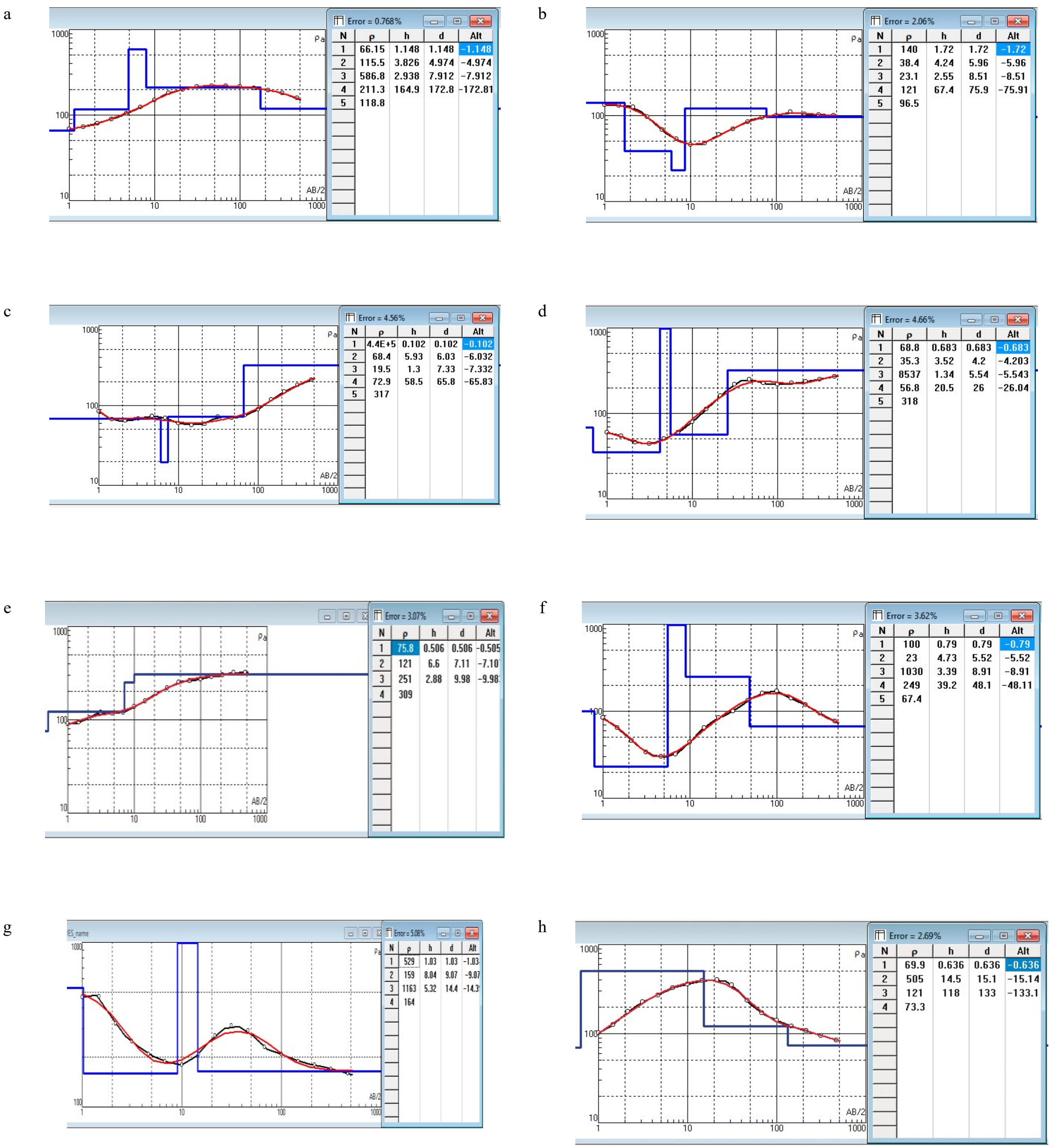
The purpose of interpreting the data obtained from vertical electrical sounding in an area is to obtain an acceptable and logical geoelectric image or model that is consistent with the results of geological studies in that area. First, to investigate the quality of alluvial sediments of the plain and how the bedrock changes interpretation of qualitative form is done. In qualitative interpretation, the apparent electrical resistivity changes obtained from maps and related sections are evaluated. To get the real model of the earth, interpretation must be done quantitatively. In quantitative interpretation, raw data from electrical soundings are usually presented on a curve with logarithmic axes. In these axes, the value of ρ_a is a function of the length AB / 2 (Half distance of current electrodes) is drawn. Using logarithmic axis systems, it is easier to interpret the results with the help of standard curves or abacuses (Reynolds, 1997).

Because in this study, the identification of alluvial thickness and depth of resistant bedrock was considered, therefore, the interpretation with details of different layers, and further separation of these layers is avoided.

4.1 Sounding Curves and Error Sections

For Schlumberger sounding curves, the apparent resistivity values were drawn against half current electrode space on a log-log graph and a smooth curve was plotted for each of the soundings. Then, the sounding curves were interpreted by the well-known method of curve matching with the aid software IPI2win to determine the true resistivity and thicknesses of the subsurface layers. Finally, the error sections are plotted and interpreted for the profiles (Loke, 1999). Due to the high volume of diagrams, only the error sections and VES curves of profile 5 are described and explained while the rest can be found in the appendix section. ρ, h, d are resistivity, thickness and depth of each layer, respectively.

Profile 5 Error Section and sounding curves



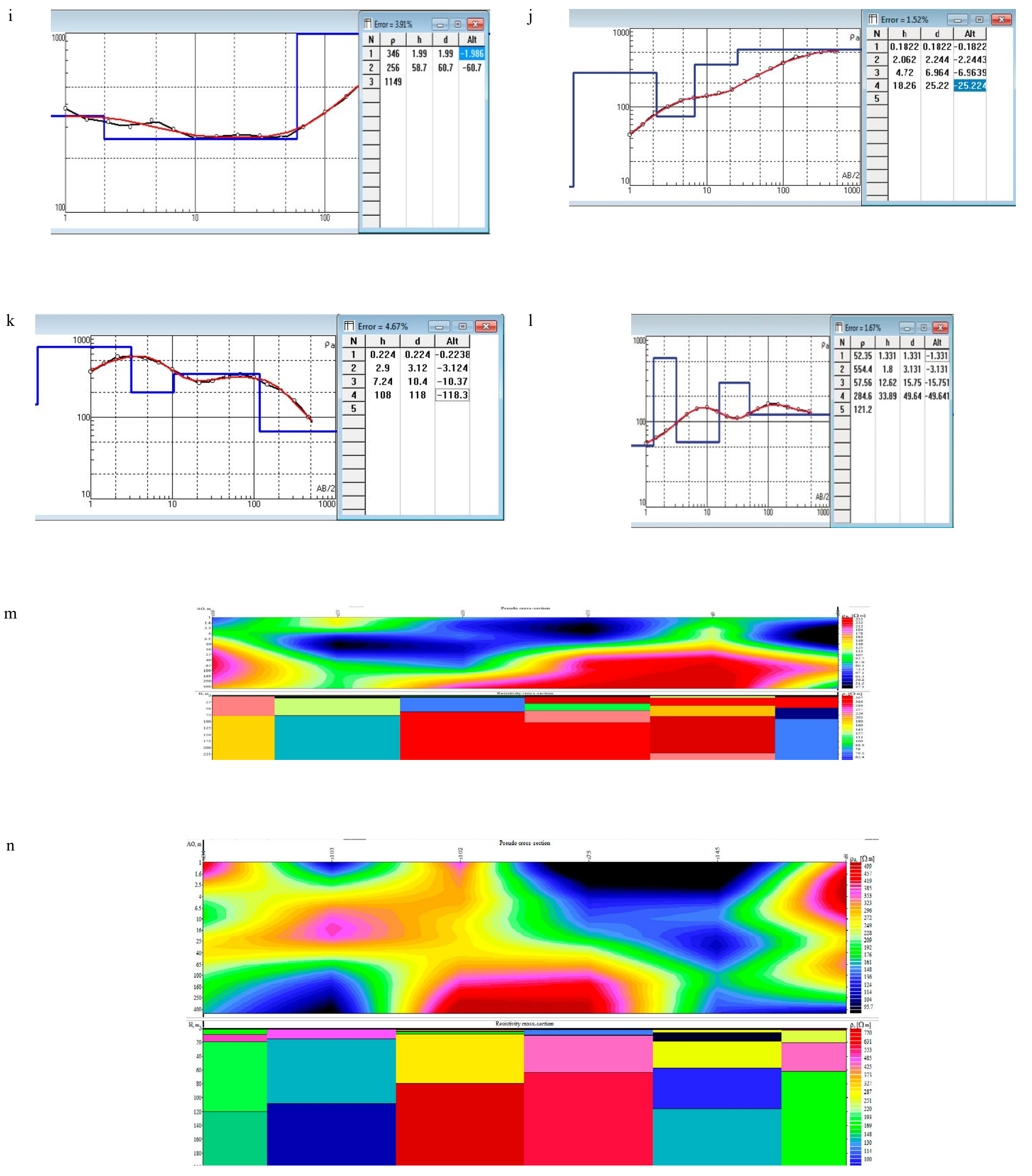


Figure 6. Representative of the iterated VES curves showing the inverse models of the geoelectrical parameters for profile 5 (a) S168, (b) S119, (c) S109, (d) S110 (e) S89, (f) S134, (g) S84, (h) S103, (i) S102, (j) S75, (k) S145, (l) S8, (m) error section for sounding S168-S134, (n) error section for sounding S84-S8.

The information obtained from the above diagrams along with the lithological and geological information of the area can be seen in the Table 1.

4.2 Geophysical cross section and pseudo-section maps:

In this paper, for the sake of brevity, only the results of processing and interpretation of the resistivity data collected along profile 5 are discussed and the maps of geophysical cross section and pseudo-sections of the other profiles are given in the appendix.

As shown in the pseudo-section of Figure 7(b), the highest apparent electrical resistivity in surface sections is attributed to the location of soundings 26, 28, 137, and 79, this is due to the presence of rocky structures or coarse and dry alluvium on the surface. In the deeper parts, due to the wetting and hydration of the alluvium and the small size of the sediments or the low water quality, their apparent electrical resistivity decreases, and with increasing depth of study, the apparent electrical resistivity increases again due to the impact of the resistant bedrock. Sudden changes in apparent electrical resistivity between 30 and 28 soundings indicate a rupture of the formation or fault zone. In the middle and left of the profile, there are areas with lower electrical resistivity (areas under soundings 82, 97, and 32) which indicates sedimentary formation or water saturation zone in these areas.

From Figure 7, the distribution of fine-grained and coarse-grained zones in the surface horizons can be deduced. The heterogeneous sedimentation situation in Shahroud sedimentary basin is also estimated at a glance. Zones with a high electrical resistance that represent coarse-grained deposits can be seen in these figures.

4.3 Iso- Resistivity maps

In order to understand how to spread deep layers with the same electrical resistivity and determine the extent of expansion of zones with equal granulation, Saturated or unsaturated as well as the bedrock of the area were designed iso-resistivity maps for different depths.

a

b

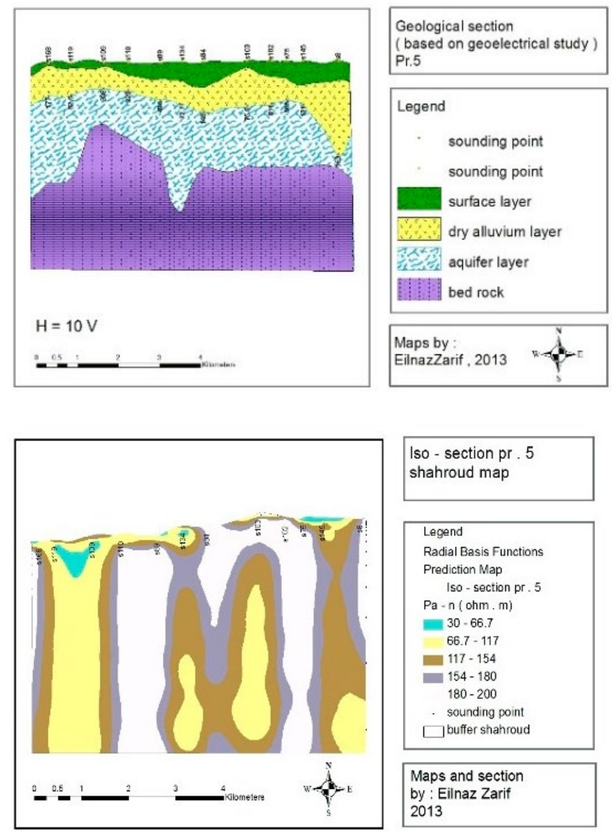


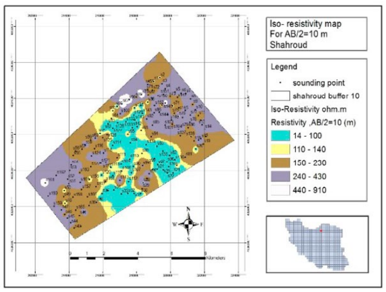
Figure 7. Profile 5 (a) Geoelectric cross section map, (b) 5 pseudo-section map

Table 1. The VES correlation of the layer models obtained from the apparent resistivity and their lithology for profile 5.

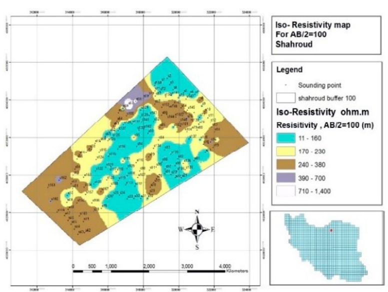
layer	1			2			3			4		Geographical coordinates		
lithology	Surface alluvial sediments			Coarse and dry alluvial sediments			Course sand (Aquifer layer)			Bed rock				
Location	*Resistivity (Ω.m)*	Thickness (m)	Depth (m)	Resistivity (Ω.m)	Thickness (m)	Depth (m)	Resistivity (Ω.m)	Thickness (m)	Depth (m)	Resistivity (Ω.m)	Depth (m)	Latitude (X)	Longitude (Y)	Altitude (Z)
S168	107.5	3.3	3.3	228	74.4	77.7	177	174	251.1	102	350	316149	4029410	1306
S119	87.8	10.8	10.8	130	64.8	75.6	82.6	200	275.6	138	350	316590	4029733	1311
S109	72.52	8.02	8.02	72.5	54.2	62.22	308	187.8	250.02	308	350	317079	4030360	1320
S110	170.82	57.8	57.8	223	46	103.8	329	146	249.8	329	350	317605	4030659	1323
S89	185.36	39.3	39.3	183	41.1	80.4	494	141	221.4	224	350	318316	4030967	1319
S134	149.93	46.9	46.9	44.3	41.9	88.8	72.7	161.2	250	72.7	350	318573	4031450	1340
S84	387.66	19.1	19.1	181	101	120.1	148	130	250.1	148	350	318856	4031873	1339
S103	267.95	14.9	14.9	131	93	107.9	75.6	142	217.6	75.6	350	319699	4032541	1370
S102	298	7.65	7.65	287	71.5	79.15	811	170.8	250	811	350	319844	4033105	1357
S75	157.13	10	10	432	53.5	63.5	565	186.5	251.5	565	350	320223	4033189	1359
S145	155.62	57.4	57.4	100	58.9	116.3	131	134	250.3	131	350	320493	4033474	1359
S8	431	20.3	20.3	454	41.2	61.5	163	159	220.5	41.7	350	321194	4033971	1358

For the preparation of these sections, the values of apparent electrical resistivity in relation to the effective penetration depth of the relevant current are considered and then the iso- resistivity maps are plotted. In each map, you can see how the electrical resistivity changes in the relevant effective depth in the area. By comparing iso-resistivity maps for different AB lengths, we can qualitatively understand the trend of changes in resistivity with depth. To qualitatively study the alluvial sediments of the plain and how the bedrock changes, maps of iso-resistivity have been drawn in current transmitter electrodes 10, 100, 215, and 464 meters.

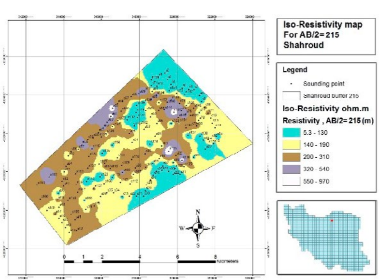
a



b



c



d

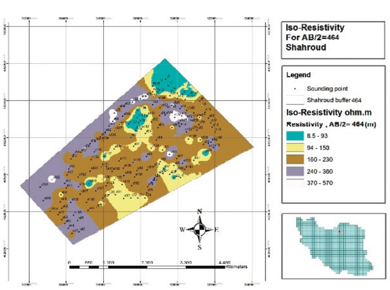


Figure 8. Iso resistivity map for (a) AB/2=10 (m), (b) AB/2=100 (m), (c) AB/2=215 (m), (d) AB/2=464 (m)

In figure 8(a), the central and southern regions have the lowest electrical resistivity of about 100 to 150 ohm-meters and separate the two high electrical resistivity sections northeast and southwest. In the center, low electrical resistivity zones can be tracked locally and separately, in these points, the resistivity reaches 110 ohm-meters. Due to the depth of exploration in these maps (AB/2=10), the greatest effect on electrical resistivity is moisture and grain size of surface deposits. In figure 8 (b), the prevailing electrical resistivity at AB/2=100 meters in the area are about 100 to 200 ohm-meters. High electrical resistance bands can be seen in the northwest and southwest. The area to be considered at this depth is the low electrical resistivity zone that appears in the north of the area and has an electrical resistivity of about 50 to 100 ohm-meters.

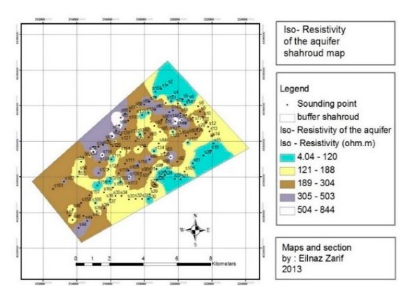
On AB/2= 215 meters, a low electrical resistivity zone in the north of the region is visible, which is expanding to the east of the region. The presence of this zone at greater depths can be due to the presence of water in these areas. Elsewhere in this depth, the trend of changes in electrical resistivity follows the map of AB/2=100 meters. At AB/2= 464 meters, as in previous maps, the predominant electrical resistivity of the area is about 100 to 200 ohm-meters. At the border between the northwestern heights of the region and the adjacent plain, a high electrical resistance band of about 200 to 300 ohm-meters, which extends from the north and northwest to the southwest of the region. Detection and fading of halos with low or high electrical resistance index at different depth horizons and in order from surface to depth, indicates granulation changes in dry to wet alluvial deposits of Shahroud area. This sedimentary sequence is consistent with the location of Shahroud at the foot of the heights and the presence of river and flood deposits. A low electrical resistance zone in the north of the region at AB/2= 464 meters has also been observed and has spread to the east of the region up to the range of soundings 1, 2, 3, 4, 5 and 6 which can be a sign of water in this region.

Comparing these four maps, it can be concluded that by increasing the length of the flow line as a result of increasing the depth of exploration, the apparent electrical resistivity decreases. Also, the amount of electrical resistivity measured in the north of the plain is much higher than in its south, which indicates the difference in the geophysical properties of the northern and southern layers of the plain. This difference in the geophysical properties of the layers actually refers to the coarser alluvial granulation in the north of the plain, due to the presence of coarse-grained sediments and the effect of better water quality. Also, the values of electrical resistivity in some areas in the map AB / 2 = 464(m) are slightly higher than the map AB / 2 = 215(m), this is because the electric current for the distance AB / 2 = 464(m) penetrated the bedrock which has a higher resistance than the aqueous layer, and the amount of apparent resistivity has increased. In addition, it can be concluded that the bedrock in the northwest of the region is higher than in other areas.

4.4 Iso- resistivity of the aquifer and bedrock maps

Iso- resistivity map of the aquifer is suitable for aquifer transfer capability to determine areas with high discharge potential in the aquifer and the best location for drilling wells in the area.

a



b

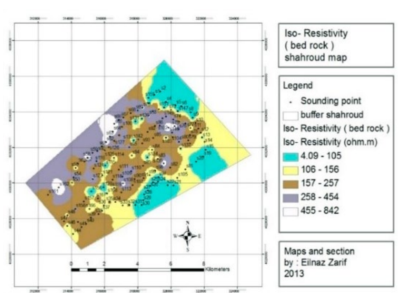


Figure 9. (a) Iso resistivity of the aquifer map, (b) Iso resistivity of bedrock map

Figure 9(a) shows the variation of the resistivity in the study area. Low electrical resistivity indicates the presence of various salts in water. In the central and northern areas of the region, the electrical resistance of the aqueous layer is high and in the southeast, southwest, and northeast of the city, the electrical resistance is lower. According to figure 9(a), it can be concluded that the central and northern areas of Shahroud have more suitable groundwater quality than its southern and northeastern areas. In figure 9(b), the bedrock electrical resistivity values obtained during the interpretation process have been used to draw an iso-resistivity map of the bedrock below the study area. The bedrock resistivity values range from 4.09 to 842 ohm.m. A major part of this layer is characterized by resistivity values between 4 and 156 ohm.m, which is representative of fractured and fluid-saturated bedrock and is mainly visible in the southern and eastern parts of the region. In places where the electrical resistance of the bedrock is higher, it is geologically more suitable for forming an aquifer layer, which can be seen in the northwestern and central areas of the region.

4.5 Iso- depth of water table level and bedrock maps

To prepare these maps, the depth of the water table and bedrock in different parts of the region were measured from electrical resistivity method and then the obtained numbers on a map with a suitable scale were drawen and act similar to the height level maps in mapping. Using the three components of latitude and longitude and depth of aquifer and bedrock in each sounding, maps of the depth of the resistant aquifer and bedrock with white to green color spectrum in order from low to high, respectively are drawn.

a

b

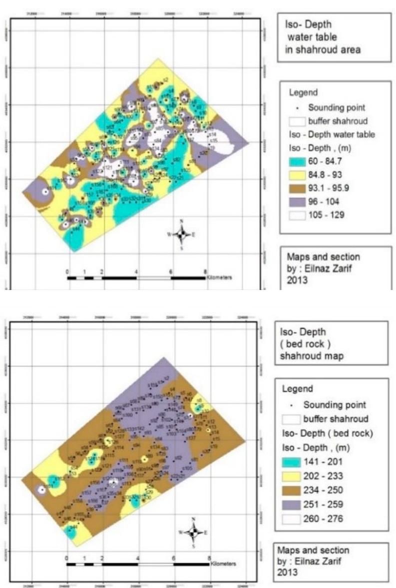


Figure 10. (a) Iso- Depth of water table, (b) Iso- Depth of bedrock map

The variation of aquifer depth in the study area is shown in Figure 10 (a). Wherever the aquifer starts from a shallower depth, it is closer to the ground and is better for drilling wells. Shallow aquifer depth values dominate in and around the northern and southern parts and reach about 84 meters. Deeper aquifers are distributed at depths between 105 and 129 meters within the central, southeastern, and northwestern parts of the study. In Figure 10(b), the depth of the bedrock in the north and northeast and the initial soundings of profiles 1, 2, 3, and 4 and the end of profile 9 have the maximum depth and in the northwestern and southwestern heights of the region, especially at the end of profiles 2, 4 and 8 has a minimum depth that can be seen with the yellow and green color spectrum.

According to the results, the minimum depth of bedrock is 141-201 meters. Bedrock at high depths had high electrical resistivity and low fracture. However, in some cases at great depths, the electrical resistance decreases, which can be due to the presence of hydrated cavities or alteration of the formation, this can be seen in the northeast and the central part of the map in soundings 156 and 164. In general, the deeper the bedrock starts, the thicker the aquifer layer, the bedrock has a relatively good depth in the whole area except the southwest and northwest.

4.6 Iso- thickness of the aquifer map

To prepare this map, the thickness of the alluvial layer at the location of each electric sounding is measured from the geoelectric sections. Then, by inserting numbers in the location of each sounding, using the interpolation method, curves of equal thickness of the sediments are drawn in GIS software.

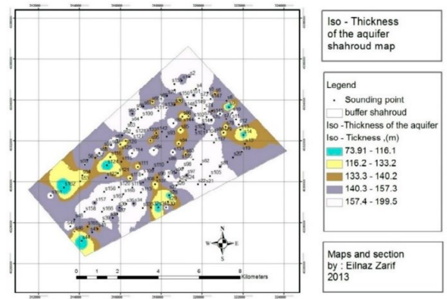


Figure 11. Iso-Thickness of the aquifer map

Figure 11 shows the distribution of the aquifer thickness in the shahroud, where a minimum thickness of 73.91 m is observed in sounding 9, 14, 124, 28, 32, 162, 44 and the southwestern and the northeastern part of the study area appear to have the thickest aquifers, which range from 157.4 to 199.5. In general, the thicker the water layer, the better the place to drill the well, and it can be said that except for a few low-thickness areas that are scattered, the aquifer layer has a good thickness in the whole area.

4.7 R.T map

The greater the thickness of the aqueous layer and its electrical resistivity, the greater R.T which leads to finding the best place to dig wells. As it is clear from Figure 12, the RT value increases towards the north and the central part of the study area, which means the north and center of Shahroud City, where there is high potential for development and operation. These areas have high hydraulic permeability. As expected, the amount of R.T in the southern and eastern regions decreases sharply.

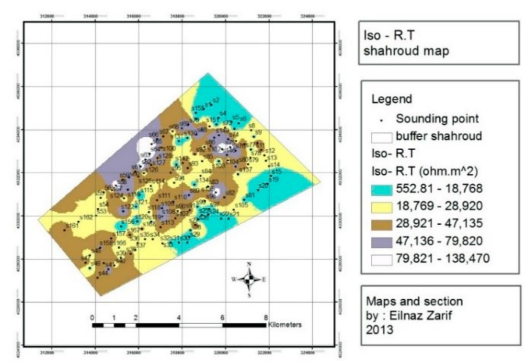


Figure 12. R.T map

5. Discussion

Subsurface water quality is measured by various factors obtained from hydrochemistry or water physics. Based on the available information on the deep wells of Shahrood and its surroundings, the Electrical Conductivity of water (E.C.) map and Total Dissolved Solids (T.D.S) map in the water of the region, have been prepared. High electrical conductivity or low electrical resistance indicates the presence of various solutes in water. (Ahmed et al., 2020). Figure 13(a) shows the EC map of underground water in Shahrood city. It can be seen that the electrical conductivity is high in the central, north, and northeast areas of the region, and it can be said that these areas have better underground water quality than the southwest and southeast areas. It is expected that T.D.S. map with E.C. map. to have a good match, because the amount of solution in water increases its electrical conductivity, and with the increase of T.D.S., electrical conductivity also increases. This fact is proven by comparing Figures 13(a) and (b) and the two prepared maps correspond quite noticeably. As can be seen in Figure 13(b), the amount of TDS in the central, north, and northeast areas of the region is around 600 mg/liter, and in the southeast and southwest of the city, it reaches 1300 mg/liter. Therefore, according to Carroll's classification (Carroll, 1962), the north, northeast and center of the city have fresh water, and the southwest and southeast have semi-saline water. Quantities such as TDS and EC are important in subsurface studies, based on which the electrical resistance factor changes in addition to the grain size effect. By considering the effect of these parameters, a more realistic estimate of the aquifer's granularity can be obtained. (Ahmed et al., 2020).

a

b

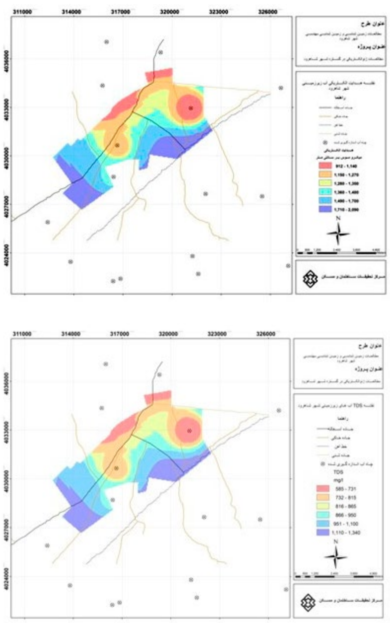


Figure 13. (a) E.C map of subsurface waters of the region; (b) T.D.S map of subsurface waters of the region

The higher the electrical resistance of the aqueous layer, the higher the quality of the water and the amount of salts in it is less (Corwinand Yemoto, 2017; Rusydi, 2018). According to figures 8 and 9 (a), it can be concluded that the central and northern areas of Shahroud have more suitable groundwater quality than its southern and northeastern areas. Moreover, wherever the aquifer starts from a shallower depth, it is closer to the ground and is better for drilling wells. According to Figure 10(a), Shallow aquifer depth values dominate in the northern, northeastern, southern and southwestern parts and reach about 84 meters. On the other hand, the thicker the water layer, the better the place to drill the well, and it can be said from fig. 11 that except for a few low-thickness areas that are scattered, the aquifer layer has a good thickness in the whole area especially in northern, southern and central of the area.

The greater the thickness of the aqueous layer and its electrical resistivity, the greater R.T which leads to finding the best place to dig wells. As it is clear from Figure 12, the R.T value increases towards the north and the central part of the study area, which means north and center of Shahroud city where high potential for development and operation have. These areas have high hydraulic permeability. RT levels are lowest in the northeast, southern and southeastern.

In places where the electrical resistance of the bedrock is higher, it is geologically more suitable for forming an aquifer layer, which can be seen from Figure 11 (b) in the northern, northwestern and central areas of the region. While, the bedrock in the southern, southeastern and northeastern regions has a lower resistance.

In general, the deeper the bedrock starts, the thicker the aquifer layer; according to Figure 10(b), the bedrock has a relatively good depth in the whole area except the southwestern and northwestern.

Although in the southern and northeastern regions the depth of the aquifer is less and closer to the ground, the water quality is lower and the depth and resistivity of the bedrock and the amount of RT is the lowest. Consequently, these areas cannot be suitable targets for groundwater exploitation.

In the northwestern region, the thickness of the aquifer and the electrical resistivity of the bedrock is high, but due to the low electrical resistance of the aquifer in this area, it is recommended that wells not be drilled in these areas for drinking water because of the low-quality water and only used for agricultural purposes.

6. Conclusion and Suggestion

Given that today underground water flow modeling and pollution transmission is one of the most effective and the most important tools used in the management of water resources, evaluation of aquifer hydraulic variables to provide the information needed in Groundwater modeling is of great importance. Drilling exploratory wells to determine variables aquifer hydraulics is often costly and time-consuming. On the other hand, because in the calibration stage of modeling, the evaluated hydraulic variables can be corrected, therefore, estimating these variables using vertical electrical sounding (VES) information as an initial value can be useful.

According to the explanations provided in the discussion section, the northern and central parts of the region have the best position for drilling wells.

Finally, 6 proposed groundwater exploration areas are suggested, as shown in Figure 14.

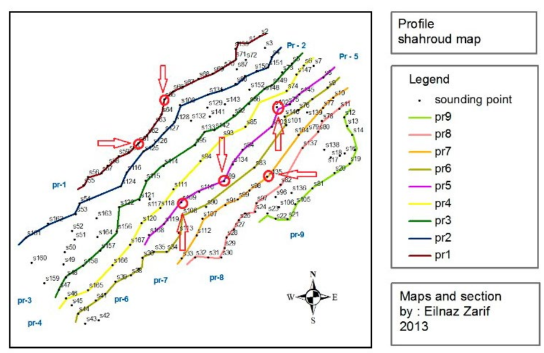


Figure 14. Map of proposed locations for drilling wells

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