Case Study

Geospatial analysis of soil resistivity and hydro-parameters for groundwater assessment

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Abstract
Groundwater is a precious resource for irrigating the crops in developing countries. This research was governed in Faisalabad District of Pakistan to assess the groundwater strata using GIS cum geoelectric resistivity method approach. The IX1D computer model was calibrated with root mean square error (up-to 5%), to obtain true soil layers' resistivities and thicknesses model for each VES point based on apparent resistivity data collected by ABEM SAS 4000 Terrameter using the most common Schlumberger electrode array setting. Knowledge of geo-hydraulic parameters (hydraulic conductivity, transmissivity, and porosity) aids in identifying the quality and potential of groundwater repositories, estimated based on modeling results (soil layers resistivities and thicknesses). Most common interpolation (inverse distance weighted) method in ArcGIS Pro was used for mapping the soil aquifer layers resistivities/thicknesses and geo-hydraulic parameters. Transmissivity, Porosity, and hydraulic conductivity values ranged from 365.46 to 1888.503 m^2/day, 31.84 to 39.72% and 4.05 to 15.27 m/day for all surveys, respectively. Based on these results, aquifer layers with thicknesses 30 to 103.5 m, were distinguished as comprised of saline to low marginal quality (fine sand and clay formation), marginal to fresh quality (fine sand and gravel formation) and fresh quality groundwater (coarse sand and gravel formation).

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Graphical Abstract
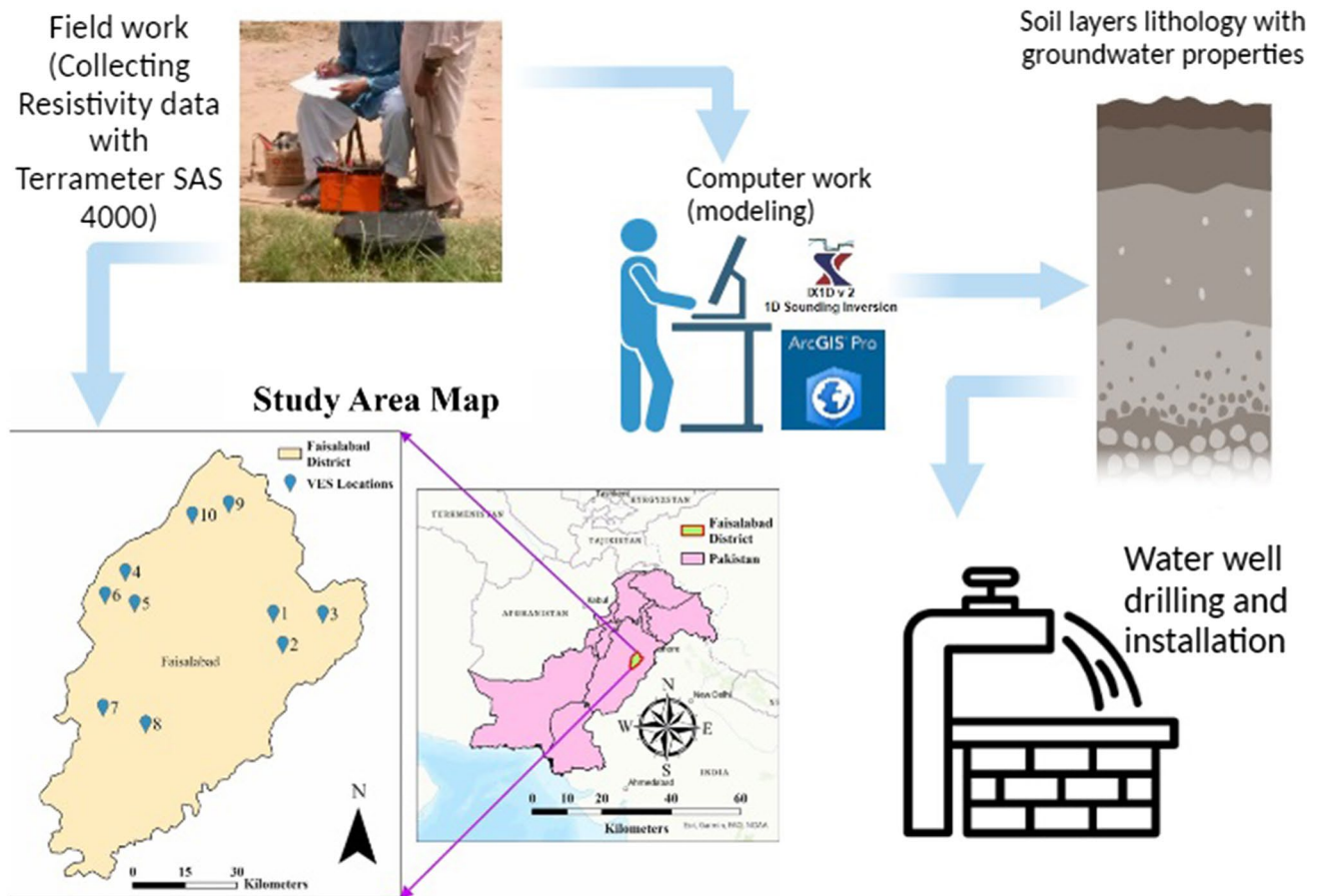
1 Introduction

Water is essential for supporting all forms of life on our planet. However, many regions around the world are experiencing a growing issue of water scarcity. The excessive use of 70% of the accessible water for agricultural purposes is placing significant strain on this crucial resource [36]. Additionally, water plays a vital role in maintaining the balance of Earth's ecosystem. In developing countries with economies heavily reliant on agriculture, coping with seasonal and nationwide water shortages has become a major challenge [76]. The growing demand for freshwater resources emphasizes the need for effective water management in the agricultural sector which stands as the foremost global consumer for water [77]. Therefore, among the freshwater resources, availability of groundwater resource is of paramount importance to meet the demands of agriculture, households, and industries. Groundwater is an important component of water resource systems [4, 44] and it is a largest freshwater reservoir which is accessible [24]. With the enhancement of groundwater withdrawal, the quality of groundwater is continuously deteriorating with the passage of time [38].

   The Indus River Basin, a substantial transboundary river system, ranks among the largest in the Aisa concerning volumetric flow which sustains irrigation and hydropower systems in Afghanistan, India and Pakistan [34]. Indus basin system of Pakistan, plays a pivotal role in contributions for 90% of agricultural output and 25% of national GDP [9, 84]. In this system,

the anticipated rapid increase in population and impacts of climate change are expected to heighten the challenges interconnected with water resources and farm productivity [26, 72]. Owing to the challenges of water supply, Pakistan is at risk of confronting the severe food shortages. Current forecasts indicate a reduction of over 30% in water storage capacity by 2025 attributed to climate change impacts [84]. Moreover, canal irrigation water supply falls short of fulfilling the water demands for both present and past crops primarily due to an enlarged irrigated area [24]. So, the groundwater is utilized either directly or indirectly for irrigation to meet the crop water requirement and groundwater systems exhibit a slower response to short-term climate fluctuations compared to surface water systems, primarily because they serve as a crucial buffer against deficiencies in surface water [81]. The addition of groundwater can significantly contribute to sustaining crop yields at farm levels, potentially increasing them by 50–100% [37]. Therefore, the area under groundwater-based irrigation has seen a rise from 2.8 to 3.5 million hectares, while the area under canal irrigation has decreased from 7.9 to 6.9 million hectares. This shift in irrigated areas has been accompanied by a substantial increase in the number of water wells, underscoring the current heavy reliance of farmers on groundwater to ensure agricultural productivity [11]. Consequently, the exploration of groundwater is becoming increasingly crucial not only for Pakistan but also on a global scale due to the growing demand for irrigation water supplies.

Effective methods are essential for groundwater exploration [60]. Geophysics involves applying the principles of physics to study the earth with measurements taken either at or in near proximity of earth surface [43, 59]. So, there is an important role of geophysics in groundwater exploration, and it is very necessary to utilize cost-effective geophysical methods for locating the potential groundwater zones [20, 25, 53, 54, 59, 61]. Among the geophysical methods, the geoelectric resistivity method is being used mostly for investigating the groundwater strata because of has simple instrumentation and easy field operations as well as analysis of data than other methods [23, 66, 80]. Collected resistivity data can be employed to recognize and characterize the subsurface elements including identification and nature of aquifers viz quality of groundwater [48, 60]. Moreover, aquifer hydraulic parameters (hydraulic conductivity, transmissivity, and porosity) estimated from resistivity data of geophysical methods help in identifying the availability of potential groundwater repositories [6, 23]. A fundamental correlation was observed after the integration of hydraulic parameters attained from resistivity data [23, 41, 46, 49, 78].

GIS coupling with other models is largely being used in now a day research such as GIS method along resistivity profile together was used to locate the deep water well sites and groundwater potential zones [3, 16, 30, 50] which indicates the effectiveness of GIS usage in assessment, monitoring and management of groundwater [1, 5, 8, 21, 50, 75]. For mapping the groundwater strata and properties, it is essential to know in depth about groundwater and soil layer lithology and GIS can play a great role in achieving this goal [5, 8]. GIS coupled electric resistivity meter method was used for estimation and mapping of soil layers resistivities as well as geo-hydraulic parameters to differentiate the soil lithological layers and groundwater potential zones [23]. GIS analysis was used for delineating the hydrogeological zones by integration of vertical electrical sounding data collected by electric resistivity meter at field [31]. Unfortunately, continuous decrease in surface water resources in Pakistan is leading to excessive extraction of groundwater resources [22] and excessive usage of water resources by mismanaging leads to that quality resource depletion along with water quality deterioration and environmental issues [58]. That is why the groundwater exploration along with soil layers lithology determination prior to the well drilling is very essential which leads to the groundwater management, and it is dire need of the time [79]. Some studies identified only the groundwater quality zones with formations characteristics based on layers resistivity and thicknesses data [25, 32, 40, 67] but in this research study we calculated also the geo-hydraulic parameters from resistivity layers thicknesses and resistivities to better understand not only the groundwater quality but also the groundwater potential zones. Integrated electrical resistivity and GIS approach was potentially applied to find out the hydrogeological zones in a study [31]. Moreover, declining in water table was assess through GIS by deploying the interpolation method in study conducted in desert area of Iran [5]. Continuous decline in surface water resources of country putting the enormous pressure on groundwater resource and without proper management and prior investigation, it led towards depletion of this quality resource (groundwater). Keeping in view the water security and sustainability [42], there is a dire need to properly manage the groundwater extraction by assessing its quality and potential properly which will also be very effective in policy making process to save for future generations. In this study, an integrated approach of resistivity surveys along with ArcGIS Pro's interpolation methods was used for estimation and mapping of soil layers resistivities/thicknesses and calculated geo-hydraulic parameters to evaluate the groundwater quality and potential zones, respectively. Points suitable for well installations to attain fresh quality of groundwater were identified. This study also tried to mitigate the bore hole failures trend and could also be quite effective in policy making steps for resource management in Pakistan [42, 58].
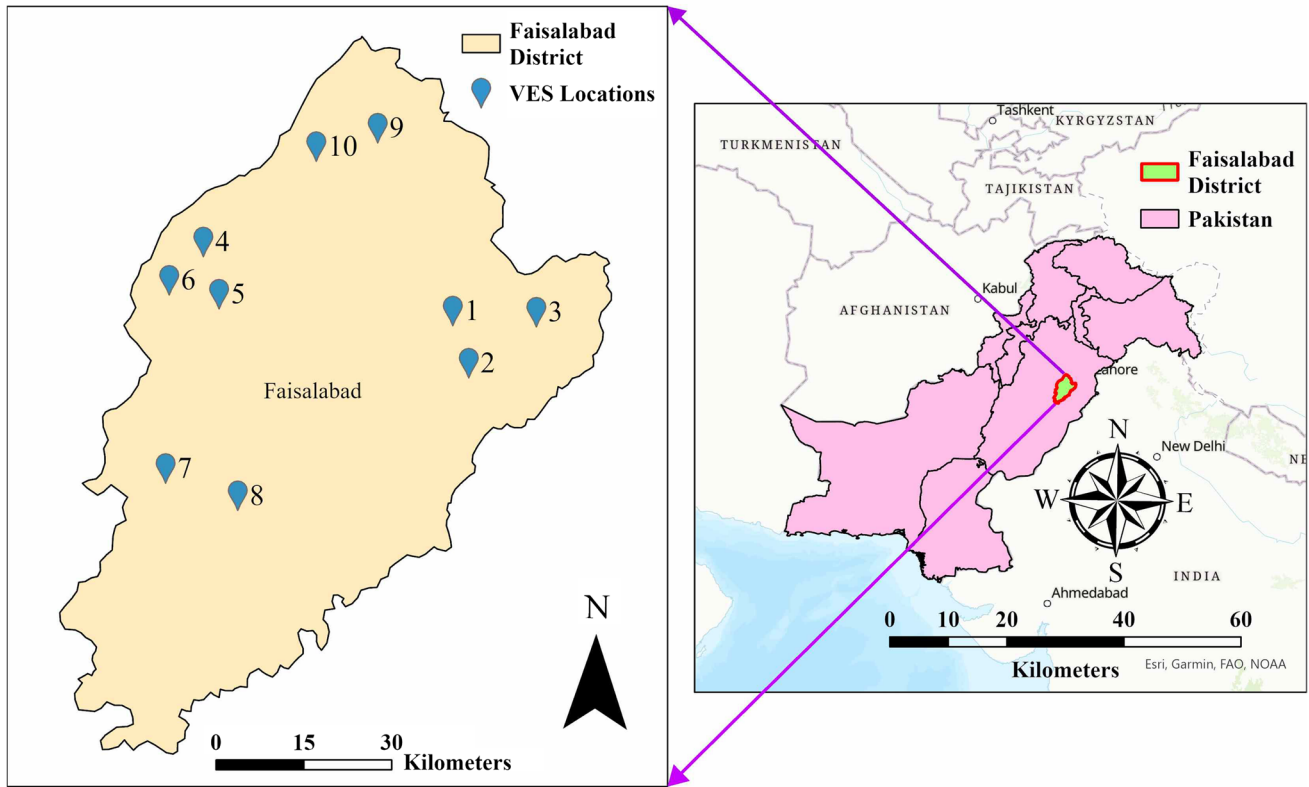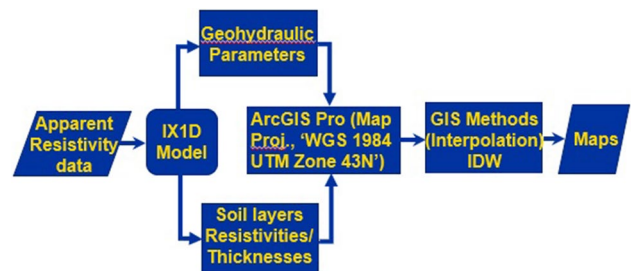
Study Area Map

Fig. 1 Study Area Map -VES Locations

Fig. 2 Flowchart for data processing in methods

2 Methods

2.1 Study area

This study was conducted in Faisalabad district of Pakistan covering an area of 2261.014 sq. miles. Geographically, Faisalabad is situated at an elevation of 604.134ft above sea level and with coordinates (30.68°N 72.85°E to 31.76°N 73.21°E) as shown in Fig. 1. The climate is arid to semi-arid characterized by extremely hot summers (69.8–123.8°F) and milder winters (44.6–80.6°F) [29].

2.2 Data processing steps

In Fig. 2, data processing steps are shown. Firstly, apparent resistivity data collected in field by using ABEM SAS 4000 Terrameter [7, 12, 47, 52, 68], was processed using IX1D model. The model calculated true resistivities and thicknesses

of soil layers which were then utilized to determine geo-hydraulic parameters [15, 52]. ArcGIS Pro, with a suitable projection for Faisalabad, was employed for mapping true resistivities-thicknesses and calculated geo-hydraulic parameters. The interpolation method IDW in ArcGIS Pro was applied for mapping following recommendations from various researchers [65, 70, 83, 85] as shown in Fig. 2.

2.3 Investigation method

Electric resistivity surveys with most commonly being used Schlumberger electrode array [2, 3, 7, 18, 22] were conducted in the research area. Schlumberger electrode array configuration was chosen and employed because of simple layout and high efficiency in groundwater exploration [22, 25, 40, 68]. Specific parameters, including current electrode partition (AB/2) of 2–180 m and potential electrode (MN/2) partition of 0.5–20 m, were employed during the survey [39, 40, 52, 68, 74]. Geometric constant (K), derived from respective positions of current and potential electrodes, was utilized to calculate apparent resistivity [47, 73].

$$\mathrm{P}a = K * R$$

ρa represents the apparent resistivity measured in Ω-m, R is the resistance measured in Ω, and K is Constant of proportionality [47].

2.4 Modeling

The IX1D computer software generated resistivity models (soil layers resistivities and thicknesses) for selected VES points, minimizing the root mean square (RMS) error between the model's generated data and actual field data [40, 68]. RMS is the estimation of closeness of theoretical to observed field curves. The acceptable range for RMS (5–8%) was followed, with three iterations performed until the RMS reached 5% [39, 47].

2.5 Geo-hydraulic parameters

Hydraulic parameters (hydraulic conductivity, transmissivity and porosity) were interrelated in determining groundwater potential zones. Understanding these parameters is crucial for effective groundwater management [51]. Hydraulic conductivity, indicating how water moves through material [13, 62] and transmissivity, obtained by multiplying hydraulic conductivity with aquifer layer thickness, play significant roles [17, 33, 69]. For two alike sandy aquifers, if one has high porosity then it will have high hydraulic conductivity as well. On the other hand, clay with low hydraulic conductivity will have higher porosity because clay is a more saturated material which holds substantial amounts of water but doesn't release it quickly [19].

2.6 Map projection and interpolation (ArcGIS Pro)

A projected map projection (WGS 1984 UTM Zone 43N) was used under 'WGS 1984' as the datum for measuring the locations and creating maps. Inverse distance weighted (IDW) interpolation in ArcGIS Pro was chosen as one of the most common spatial analysis methods for mapping values in uncalculated places [4, 65, 83]. This approach involves applying a linear weighted combination of sample points for calculating cell values [45]. It was concluded that IDW works to forecast the values for any uncalculated place, by estimating the surrounding value's foreseen locations [14]. There are two assumptions behind its procedure: firstly, the effect of untold value of a location is expanded with respect to the close commanded locations as compared to distant spots. Secondly, the impact degree of location has directly proportionality with inverse of the distance between the locations [27].

3 Results and discussions

3.1 Data collection and modeling

For this study, vertical electrical sounding data was acquired at selected VES locations using a Resistivity meter (ABEM Terrameter SAS 4000). The 'IX1D' computer model facilitated the determination of soil layers' resistivities and thicknesses. Geo-hydraulic parameters (transmissivity, hydraulic conductivity, and porosity) were subsequently derived from these properties [15, 19, 53–56]. Using the newly developed GIS software 'ArcGIS Pro', resistivities/thicknesses of soil aquifer layers and assessed geo-hydraulic parameters were mapped for interpreting the soil layers lithology and groundwater quality and potential zones.

Here, h_{aq} represents the aquifer layer thickness calculated in meter, K represents the hydraulic conductivity calculated in m/day, ρ_{aq} is the aquifer layer resistivity measured in Ω-m, Φ is the porosity measured in % and T_r is the transmissivity measured in m^2/day [15, 53]. A graph was employed to illustrate geo-hydraulic parameters and resistivities-thicknesses of soil aquifer layers at all VES points. Notably, the 7th and 8th VES points displayed low aquifer layer thickness, while 9th and 10th VES points exhibited higher resistivity values indicating hard formations at these locations in aquifer layers [74]. This led to lower hydraulic conductivity, transmissivity and porosity values at these locations compared to others. On the other hand, resistivity values are very low at 4th, 5th, and 6th VES points but the layers thicknesses, hydraulic conductivities, transmissivities, porosities are higher at these locations than others. Aquifer layers resistivity values at 1st, 2nd and 3rd VES points are in good range with high aquifer layers thicknesses (up to 100 m) and promising values of hydraulic conductivity, transmissivity and porosity, declaring these points suitable for extraction of groundwater from aquifer layers.

3.2 GIS mapping and analysis

3.2.1 Groundwater quality zones

Groundwater quality zones and aquifer layer thicknesses maps were depicted in Fig. 4a and b based on resistivities and thicknesses of aquifer layers for identifying the groundwater quality zones along with their respective thicknesses together with reference to each VES point. Based on layers' resistivities and thicknesses, we can assess and define the groundwater quality zones depending mainly on range of resistivity values in geophysical settings [32, 40, 71]. VES points 4th, 5th, and 6th were identified as having aquifer layers with clay and find sand, up to 90-m and saline to low marginal quality groundwater based on low resistivity values ranging from 20 to 30 Ωm as shown in Figs. 3 and 4a. In calibrated true resistivity models of geophysical surveys, resistivities of clay formation are generally shown less than that of sand which is less than that of gravel in humid environmental conditions as it was reported in some recent studies [2, 32, 40, 71]. Points 9th and 10th exhibited hard formations with higher resistivity values ranging from 400 to 800 Ωm as shown in Fig. 3 and thicknesses up to 103.5 m. Higher resistivities displayed by calibrated layered resistivity model in the soil profile, indicate top surface materials or hard formations which depends mainly on the depth within profile whether it is above or below water level which was declared in some past and recent studies as well [2, 22, 40, 71, 74]. On the other hand, aquifer layers at 1st, 2nd, 3rd, 7th, and 8th VES points consist of coarse sand and gravel materials where groundwater

Fig. 3 Graph summary of soil aquifer layers resistivities/ thicknesses and geo-hydraulic parameters
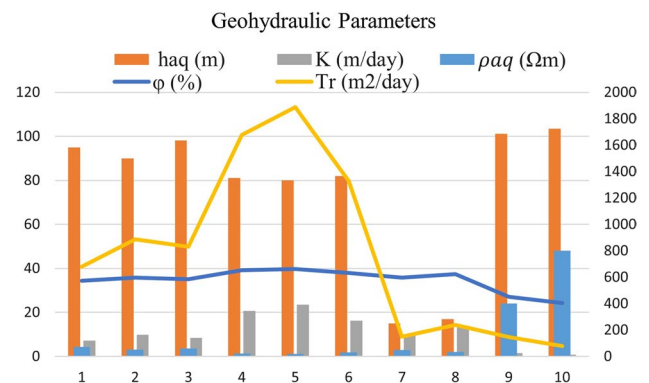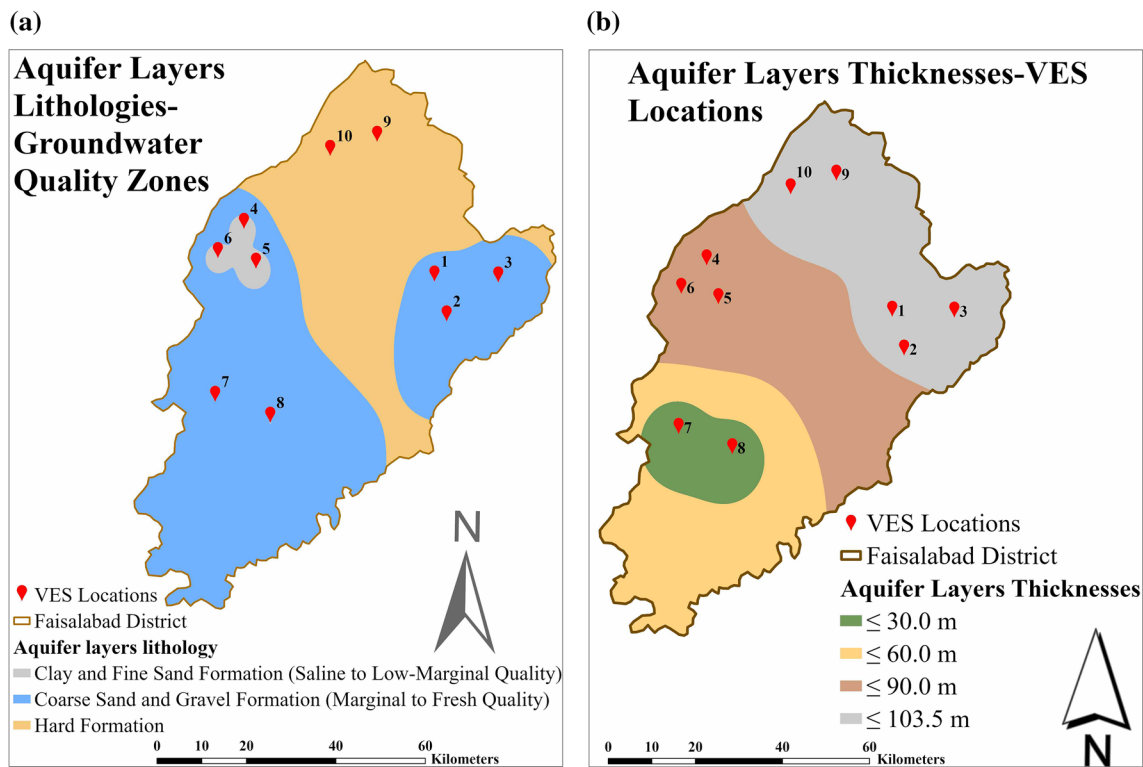
Fig. 4 **a** Groundwater quality zones Map. **b** Aquifer layer thicknesses Map

quality is marginal to fresh based on higher aquifer layer resistivity values ranging from 35 to 72 Ωm as shown in Fig. 3 while thickness of aquifer layer at 1st, 2nd and 3rd points is high as up to 103.5 m as compared to the 7th and 8th points where aquifer layer thickness is only up to 30 m. Keeping in view these results, the resistivity inverse model also showed the freshwater zones very clearly in research conducted by [32]. Moreover, resistivity ranges of < 25 Ωm, 25 to 50 Ωm 50 to 100 Ωm were declared for poor, marginal and good/fresh quality groundwater layers based on calibrated model results [2, 22, 40, 68].
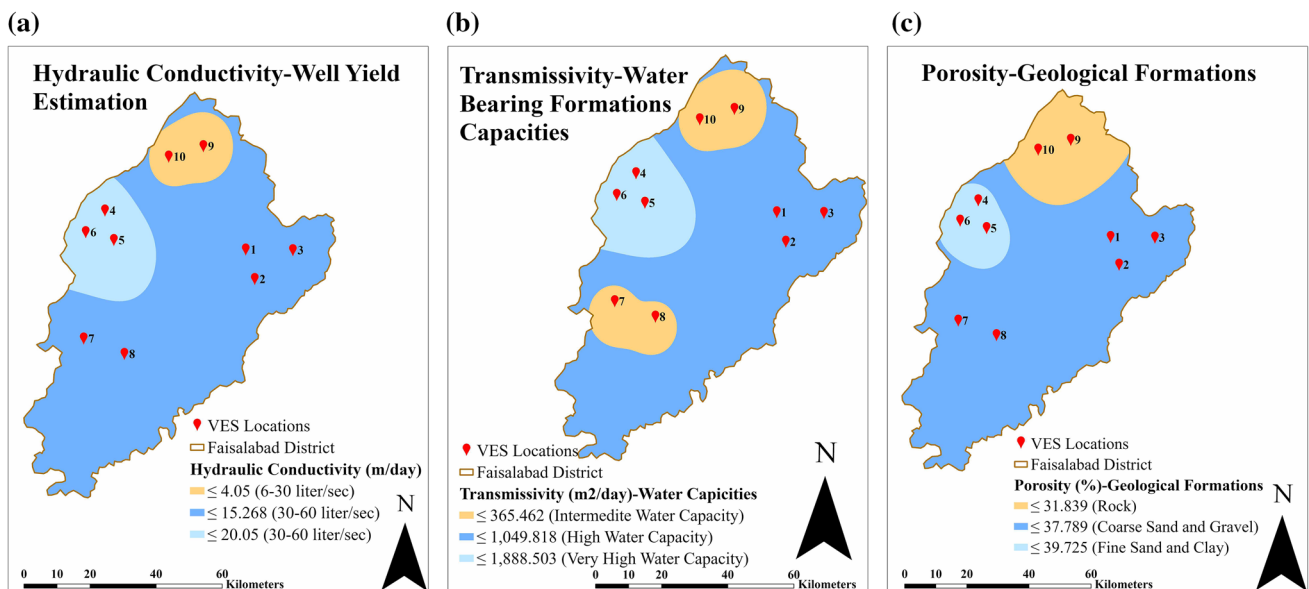

Fig. 5 **a** Well yield Map. **b** Formations' water capacities Map. **c** Porosities Map

3.2.2 Groundwater potential zones

3.2.2.1 Hydraulic conductivity and transmissivity Figure 5a and b showcased groundwater potential zones (well yield based on hydraulic conductivities and water capacities of the formations based on transmissivities) of aquifer layers. In groundwater management science, hydraulic conductivity and transmissivity are the important factors aiding in the understanding of groundwater exploration properties [15, 22, 28]. Aquifers play a crucial role in supplying the water to wells after activation of pump, water level declines which stimulate the groundwater flow from aquifer as it initially comes from storage within the aquifer, so aquifers possess at least two vital properties: capacity to store and capability to transmit the water. Therefore, these two properties are essential to know about groundwater storage and transmitting potential in groundwater management [17, 63]. Both maps look similar, but these are different in defining the hydraulic properties and we can identify the high groundwater potential zones by finding out high well yields and water capacities in these both maps. When we refer to hydraulic conductivity, we are discussing a parameter which governs the average characteristics of groundwater flow through aquifer layer. Hydraulic conductivity is the measure of how water moves through the soil particles [62]. The idea of transmissivity bears similarity to hydraulic conductivity. The primary distinction lies in the fact that transmissivity is the measure that extends over the vertical thickness of aquifer layer [17]. There is a linear relationship between hydraulic conductivity as well yield would be higher if hydraulic conductivity increases. Well yield as well was estimated based on hydraulic conductivity. Well yield could be attained as 6–30 l/s through medium well sorted sand and porous limestone, if K is moderate 0.3–3 m/day. It was reported that well yield would be higher 30–60 l/s through the coarse sand and gravel formation, based on higher K 3–20 m/day [64]. Transmissivity is also connected with the water bearing formations based on findings of [35]. Water bearing formations capacities would be very low, low and intermediate based on transmissivities of 0.1–1, 1–10, and 10–100 m^2/day respectively [35]. So, keeping in view these previous studies' findings, 9th and 10th points have low hydraulic conductivity (up to 4.05 m/day) and low transmissivity (up to 365.462 m^2/day) which shows that aquifer layers at these points have low well yield (6–30 L/sec) and intermediate water capacities respectively. In both maps, aquifer layers at 4th, 5th, and 6th VES points consist of high well yield (30–60 L/sec) and very high-water capacities by having higher hydraulic conductivity (up to 20.05 m/day) and higher transmissivity (up to 1888.503 m^2/day) respectively. It can be clearly seen from both maps that 1st, 2nd, and 3rd VES points have high groundwater potential aquifer layers in which well yield is 30–60 L/sec indicating the high-water capacities of that formation layers based on intermediate to higher hydraulic conductivity (up to 15.268 m/day) and intermediate transmissivity value (up to 1049.818 m^2/day) respectively. On the other hand, 7th, and 8th VES points have intermediate to higher hydraulic conductivity (up to 15.268 m/day) indicating high groundwater potential zones where well yield is 30–60 L/sec while these points show intermediate water capacities by having low transmissivity value (up to 365.462 m^2/day) because these points have very low thicknesses of aquifer layers.

3.2.2.2 Porosity Figure 5c displayed the porosity map which complemented the groundwater quality zones map, aiding in the illustration of geological formations within aquifer layers. Aquifers play a crucial role in supplying the water to wells and one of the aquifer's important attributes is its capacity to store water [17]. Porosities values are used to differentiate the geological formations in the aquifer layers by storage and retention of water within a geological formation. Assessment of porosity is especially important to validate the occurrence of aquifer layer in the geological formation [18, 19]. Map shows that 9th and 10th VES points consist of rock formations based on low porosity value (up to 31.839%), aligning with the groundwater quality zones map (Fig. 4a). So, the porosity map is aiding in explaining the geological formations as discussed by [19]. Similarly, VES points (1st, 2nd, 3rd, 7th, and 8th), consist of coarse sand and gravel formations by having intermediate to higher porosity value (up to 37.789%) aligning with the results of groundwater quality zones map (Fig. 4a). On the other hand, 4th, 5th, and 6th VES points consist of clay and fine sand materials by showing the higher porosity value (up to 39.725%).

Combining analysis from groundwater quality zones, layers thicknesses and geo-hydraulic parameters maps, it is recommended, not to install wells at 9th and 10th points due to hard formations [74] as shown in Fig. 4a and low groundwater potentials as shown in Fig. 5a–c. 4th, 5th, and 6th points are unsuitable to install wells for fresh groundwater extraction due to saline to low marginal quality aquifers despite having good hydraulic conductivity, transmissivity and porosity values as shown in Figs. 4a and 5a–c. On the other hand, 1st, 2nd, and 3rd VES points are suitable for well installations, offering fresh groundwater through coarse sand and gravel formations based on high groundwater potentials as shown in Fig. 4b but 7th, and 8th VES points are suitable for shallow well installations only based on less aquifer layers thicknesses and low transmissivities as shown in Figs. 4b and 5b) despite having coarse sand and gravel materials formations (marginal to fresh groundwater) aquifer layers as well as good hydraulic conductivities and good

porosities as shown in Figs. 4a and 5a–c. Likewise, the shallow thickness aquifers were also identified recently in the same region study conducted by [40].

4 Conclusion

Affordable geophysical surveys are often suggested prior to the costly process of borehole drilling for groundwater resource [20, 25, 53, 54, 59]. This precaution is essential to enhance productivity and prevent potential inefficiencies that may arise from improper sitting. In this study, GIS cum geoelectric resistivity method approach was used to assess the groundwater strata at selected VES points in Faisalabad District of Pakistan, and this approach is proved as very useful in recommending the groundwater quality and potential zones locations. 9th, and 10th VES points containing hard formations of thicknesses (≤ 103.5 m) were not suitable for well installations based on very low hydraulic conductivity (≤ 4.05 m/day), low transmissivity (≤ 365.462 m^2/day), and low porosity ($\leq 31.839\%$) values while 4th, 5th, and 6th VES points were declared as unsuitable for well installations because of having saline to low marginal quality groundwater aquifer layers despite of having good hydraulic conductivity (≤ 20.05 m/day), very high transmissivity (≤ 1888.503 m^2/day) and high porosity ($\leq 39.725\%$). On the other hand, 1st, 2nd, and 3rd VES points were suitable for well installations to extract fresh groundwater through coarse sand and gravel formations of greater thicknesses (≤ 103.5 m) based on good hydraulic conductivities (≤ 15.268 m/day), high transmissivities (≤ 1049.818 m^2/day), and intermediate to higher porosities ($\leq 37.789\%$) but 7th, and 8th VES points were suitable for shallow well installations only based on less aquifer layers thicknesses (≤ 30 m) and low transmissivities (≤ 365.462 m^2/day) despite having coarse sand and gravel materials formations (marginal to fresh quality) aquifer layers as well as good hydraulic conductivities (≤ 15.268 m/day) and porosities ($\leq 37.789\%$). This study helped to mitigate the borehole failure trend in this region.

5 Study limitations

Though, accuracy of resistivity surveys is beyond 80% as most being seen in the literature and field experiences' results but in this type of study, the number of resistivity surveys should be increased as much as when covering the larger area. As, in this study, the number of surveys is quite less to assess the groundwater quality and potential in the larger area as well. That is why we used the most widely used interpolation method in GIS to estimate the groundwater potentials and formations at unknown locations by mapping the actual points and nearby locations as zones for understanding in an uncomplicated way. Economic constraints could be an issue for conducting the resistivity surveys in the large area coverage while other geophysical methods are quite expensive. Moreover, there could also be hindrances to limit the specific selected electrode array in the resistivity survey at a point in the field. So, selecting the appropriate point to cover the whole straight distance of 180 m at both sides is also necessary for conducting survey in an efficient way. In Asian and African developing countries, mostly farmers cannot afford the installation costs of well even up to and beyond 150 m depth.

5.1 Future research recommendations

Based on results, it is recommended that surface electrical resistivity methods have immense potential and are quite affordable in assessing combinedly the groundwater quality and potential zones than other alone surface (gravity, seismic, magnetic, and nuclear methods etc.) and subsurface (borehole test) geophysical methods [10, 23, 57, 82]. Due to declining status of groundwater, mismanagement in withdrawal and growing population demands on agriculture, it is direly needed to expand the research areas by deploying the cost-effective electrical resistivity method to properly investigate them prior to install the well in the developing countries like Pakistan.

Data availability Data generated during this study is not publicly available as the resistivity surveys were conducted over the Farmers fields through the Govt. Department where online data publishing in repository form is not allowed. However, data processed can be made available upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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