Hydrology
2023; 11(2): 33-42
http://www.sciencepublishinggroup.com/j/hyd
doi: 10.11648/j.hyd.20231102.12
ISSN: 2330-7609 (Print); ISSN: 2330-7617 (Online)

Geophysical Prospecting of Aquifer Hydrogeological Properties: Implications for Groundwater Resource Management in Parts of Indus Plain, Pakistan

Inayat Ur Rahman[1], Cui Yian[1, *], Shafqat Hussain[2], Akbar Ali[3], Mustafa Qasim[4], Idrees Khan[1], Musa Khan[4]

[1]School of Geosciences and Info-Physics, Central South University, Changsha, China

[2]Khyber Pakhtunkhwa Oil and Gas Co. Ltd. (KPOGCL), Peshawer, Pakistan

[3]National Centre of Excellence in Geology (NCEG), University of Peshawar, Peshawar, Pakistan

[4]Department of Geology, Bacha Khan University, Charsadda, Pakistan

Email address:

Cuiyian@csu.edu.cn (Cui Yian)

[*]Corresponding author

To cite this article:

Inayat Ur Rahman, Cui Yian, Shafqat Hussain, Akbar Ali, Mustafa Qasim, Idrees Khan, Musa Khan. Geophysical Prospecting of Aquifer Hydrogeological Properties: Implications for Groundwater Resource Management in Parts of Indus Plain, Pakistan. *Hydrology*. Vol. 11, No. 2, 2023, pp. 33-42. doi: 10.11648/j.hyd.20231102.12

Received: June 17, 2023; **Accepted**: July 7, 2023; **Published**: July 24, 2023

Abstract: Groundwater resource management is globally essential for sustainable development, as approximately 30% of Earth's total freshwater is accessible as groundwater. Additionally, the sustainability of groundwater resources in northeast Punjab province, Pakistan, is under threat due to several processes, including overexploitation, increasing pollution, and anthropogenic activities in the current Anthropocene era. Addressing this problem requires continuous hydrogeological exploration. Thus, extensive and adequate hydrogeological exploration is necessary to identify underlying geological layers, the aquifer layer, and aquifer hydrogeological properties. In this study, we conducted the resistivity technique, specifically vertical electrical sounding (VES), in conjunction with borehole lithological logs. The objective was to delineate the variations in depth, thickness, and resistivity of the underlying hydrogeological layers, as well as to evaluate the aquifer geohydraulic properties (e. g., depth, thickness, apparent resistivity, transverse resistance, longitudinal conductance, hydraulic conductivity, and transmissivity) and groundwater quality properties (e g., salinity distribution). This assessment aimed to gain insights into the potentiality of groundwater and the potential risks of groundwater contamination for effective groundwater resource management. We utilized the least-squares method of the IpI2Winv program to invert the calculated apparent resistivity, which was characterized by a dynamic range for smoothening and correcting outliers. The subsurface was divided into rectangular blocks, and the application automatically generated a 2D model. To reduce the discrepancy between the measured and computed apparent resistivity values, we repeatedly modified the resistivity of the blocks through computer iteration. This iterative process aimed to minimize errors and increase the goodness of fit. The relationship between the model response and the VES points' field data was frequently less than 8%. The comprehensive analysis of aquifer geohydraulic properties and groundwater salinity distribution provides valuable insights for groundwater resource management. In summary, this study will aid in developing a plan for drilling new productive wells to ensure drinking water, irrigation, and long-term plantation sustainability in the region and other areas within the Indus Plain, Pakistan.

Keywords: Vertical Electrical Sounding (VES), Aquifer Geohydraulic Properties, Groundwater Potential, Groundwater Salinity, Groundwater Resource Management, Indus Plain

1. Introduction

Groundwater is an extremely important natural resource that supports human livelihoods, economic development, and environmental health, but faces challenges such as over-exploitation, depletion, contamination, and climate change. Research seeks to address these challenges by developing strategies for sustainable use, protection, and conservation. Cooperation between local groundwater users, technical experts, and policy makers is essential for sustainable groundwater management to ensure their availability for future generations.

Aquifer characterization involve identifying and quantifying an aquifer's physical, hydraulic, and chemical properties. Characterizing an aquifer is essential for understanding its behavior, determining its recharge and discharge rates, and developing effective strategies for its management and protection [1]. Geophysical studies are always quantitative, relating to actual measurements based on the variation of response patterns or contrast of propagating waves passing through a non-homogeneous medium [2, 3]. The propagation parameters include seismicity, density, magnetic susceptibility, electrical conductivity, resistivity, and electromagnetic and radiometric radiance [4]. The shallow geophysics has demonstrated strong monitoring capabilities in hydrogeological characterization, hydraulic characteristics of aquifers, and groundwater contamination [5]. VES is a resistivity survey (geophysical method) used for aquifer characterizations and groundwater resource mapping, providing valuable information about the subsurface electrical resistivity distribution [6-9]. This technique measures electrical resistance of the subsurface materials, which varies with the moisture content, mineralogy, and porosity. The resistivity survey can be conducted using several configurations, such as the Wenner array, Schlumberger array, and dipole-dipole array.

The Indus Plain is a large alluvial plain in South Asia [10, 11] with 180 billion cubic meters of water available in Pakistan from the Indus River system, rainfall, and groundwater. Overuse of groundwater is causing surface salinity to rise, saltwater intrusion, and groundwater mining. In the Indus Basin, the total available surface water is 137 109 m3, with a total provided area of 16.7 million [12]. The geology of the Indus Plain has a significant influence on the distribution and availability of groundwater resources in the region. Domestic and industrial needs account for approximately 10% of overall groundwater exploitation in Pakistan. Groundwater contamination is a significant problem in Punjab, Pakistan, particularly in urban and industrial areas with inadequate sanitation infrastructure and improper waste disposal practices. In Punjab, the most populated province, almost 90% of the population relies on groundwater for daily household requirements. Groundwater resources in the study area are facing several problems, including groundwater depletion, groundwater salinity, climate change and groundwater contamination.

To address this, a multifaceted approach is needed, including improving groundwater management practices and groundwater quality assessment. This study aims to evaluate VES data integrated with borehole lithological logs to assess aquifer geohydraulic properties and groundwater quality to understand the groundwater potential and risk of groundwater contamination. The current study will help to develop a plan for drilling new productive wells for drinking, irrigation and plantation longevity in the region and elsewhere. Overall, the current research is significant for ensuring the sustainable use and protection of groundwater resources and for addressing the complex challenges in its governance and management.

2. Study Area

2.1. Location and Climate

The study area is located in the southeast of Panjab Province, Pakistan covering about 200 km^2 [18] (Figures 1, 2). The study area is an important agricultural region that produces a variety of crops, including wheat, rice, sugarcane, and cotton. The region has a well-developed irrigation system, which relies on the rivers Ravi and Beas, as well as canals and tube wells, to provide water for crops (Figure 2). However, the region is also facing various challenges related to water management, including groundwater depletion, waterlogging, and salinization. The study area is a semi-arid to arid region in Pakistan, with hot summers and cool winters [17]. It receives most of its rainfall during the monsoon season, with the highest amounts in the foothills of the Himalayas. The prevailing winds are from the west and northwest, bringing dry and hot air during the summer months and cooler and moister air during the winter months [18].

2.2. Hydrological and Hydrogeological Setting

The study region is bounded by two major rivers - the Ravi and the Chenab - which provide significant surface water resources for the region. These rivers are fed by the Himalayan snowmelt and provide irrigation water for agriculture, as well as serving as important sources of drinking water and hydropower. The study region is prone to flooding, particularly during the monsoon season from July to September. The floods are caused by heavy rainfall and can result in damage to crops, property, and infrastructure. The hydrological characteristics of the Bari Doab region are complex and include significant surface water and groundwater resources, extensive irrigation systems, and a risk of floods.

The geology of the study region plays an important role in controlling the distribution and availability of the area's groundwater resources. The geology is dominated by alluvial deposits that have been deposited by the rivers Ravi and Beas. These alluvial deposits consist of sand, silt, and clay, and they are relatively young in age, dating back to the Quaternary period. The alluvial deposits are generally unconsolidated and have high porosity and permeability, making them excellent aquifers for groundwater storage and extraction. However, these deposits also have a high susceptibility to erosion, which can result in land degradation and soil erosion in some areas. The alluvial deposits are underlain by older sedimentary rocks, including sandstones, shales, and limestone. These rocks are part of the Siwalik and Murree formations, which were deposited during the Paleogene period.

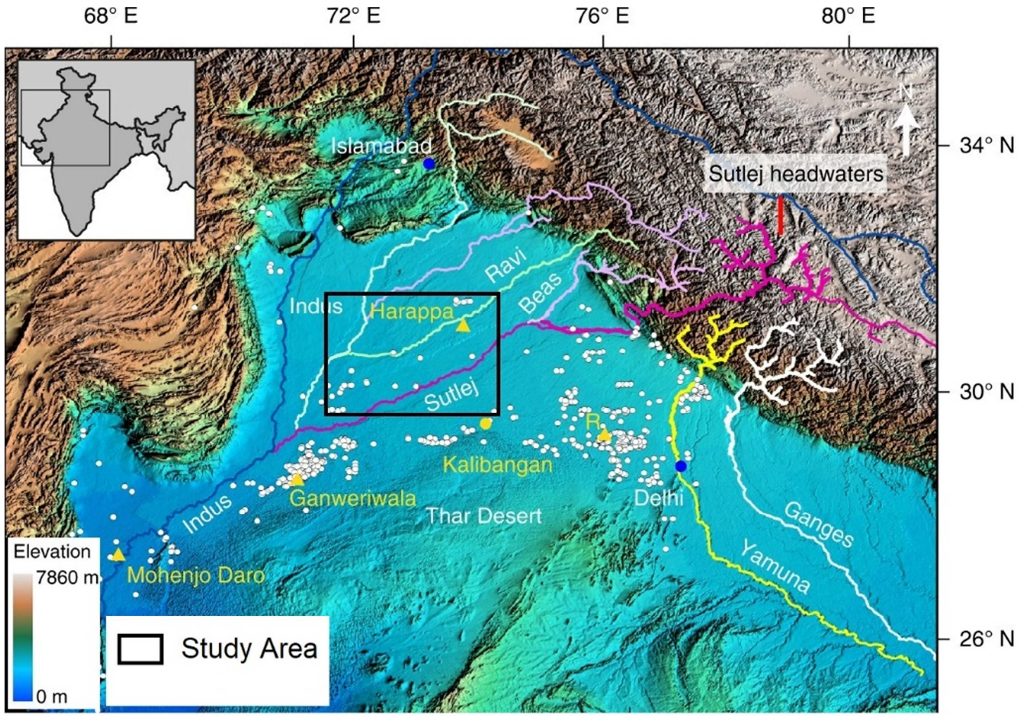


Figure 1. Location of the Indus Plain. Pakistan's topography borders with other countries. The rectangle shows the study area locations. Counter-intuitive influence of Himalayan river morphodynamics on Indus Civilization urban settlements, modified from [15].

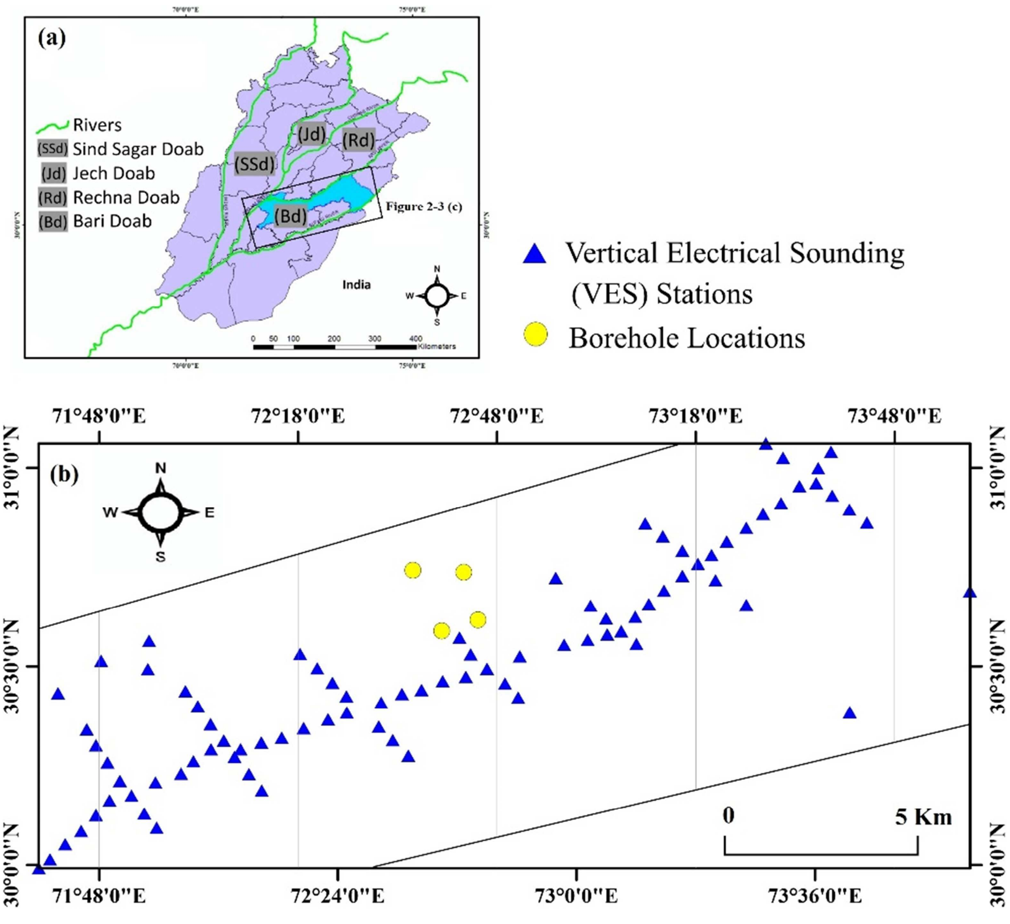


Figure 2. Location map of the study area and location of VES and boreholes (a) the location of Panjab province and the location of the Punjab Doabs (the regions located between the five rivers of the Punjab region). The study area lies in the Bari Doab. (c) A map depicting the location of the researched region, including VES stations and boreholes.

3. Materials and Methods

3.1. Datasets

Vertical electrical sounding (VES) was performed at 87 sites throughout the research area (Figure 2b) using the Schlumberger electrode configuration. Four electrodes were positioned for the Schlumberger electrode configuration in such a way that the distance between the two potential electrodes was kept significantly lower than the distance between the current electrodes while ensuring that all four electrodes were placed along a straight line. During the VES survey, the spacing between the potential electrodes was also kept to one-fifth of the distance between the current electrodes. Thus, VES surveys were conducted following standard procedures (Figure 4). In addition, lithological data from several boreholes in the study area were used. The geological data obtained from boreholes were used to calibrate the geoelectrical models obtained from the apparent resistivity curves.

3.2. Workflow

The workflow chart is shown in Figure 3. The first stage involves acquiring and collecting vertical electrical sounding (VES) data and borehole lithological data, respectively. Subsequently, Eighty-seven (87) vertical electrical sounding (VES) points were acquired using the Schlumberger array, with half maximum current electrode separation (AB/2) of 100 m. In general, identifying aquifer horizon and aquifer hydrogeological properties requires more extensive and adequate hydrogeological exploration. Subsequently, in the second stage, the result of VES inversion based on least square optimization coupled with borehole lithological logs were used to evaluate aquifer hydrogeological properties. These hydrogeological properties include depth, thickness, resistivity, Longitudinal conductance (Sc), Transverse resistance (Tr), Hydraulic conductivity (K), and Transmitivity (T), which are important for understanding the aquifer's behavior and capacity to store and transmit water as well as aquifer zones not contaminated by the extension of the salinity and determining the potentiality of the existing aquifer. The third stage involve the assessment of groundwater salinity distribution. The last stage involves combining the information and results obtained from several hydrogeological properties to develop strategies for sustainable groundwater resource management. It will help in enhancing our understanding to develop a strategy for drilling new productive wells for drinking, irrigation and plantation longevity in the region.

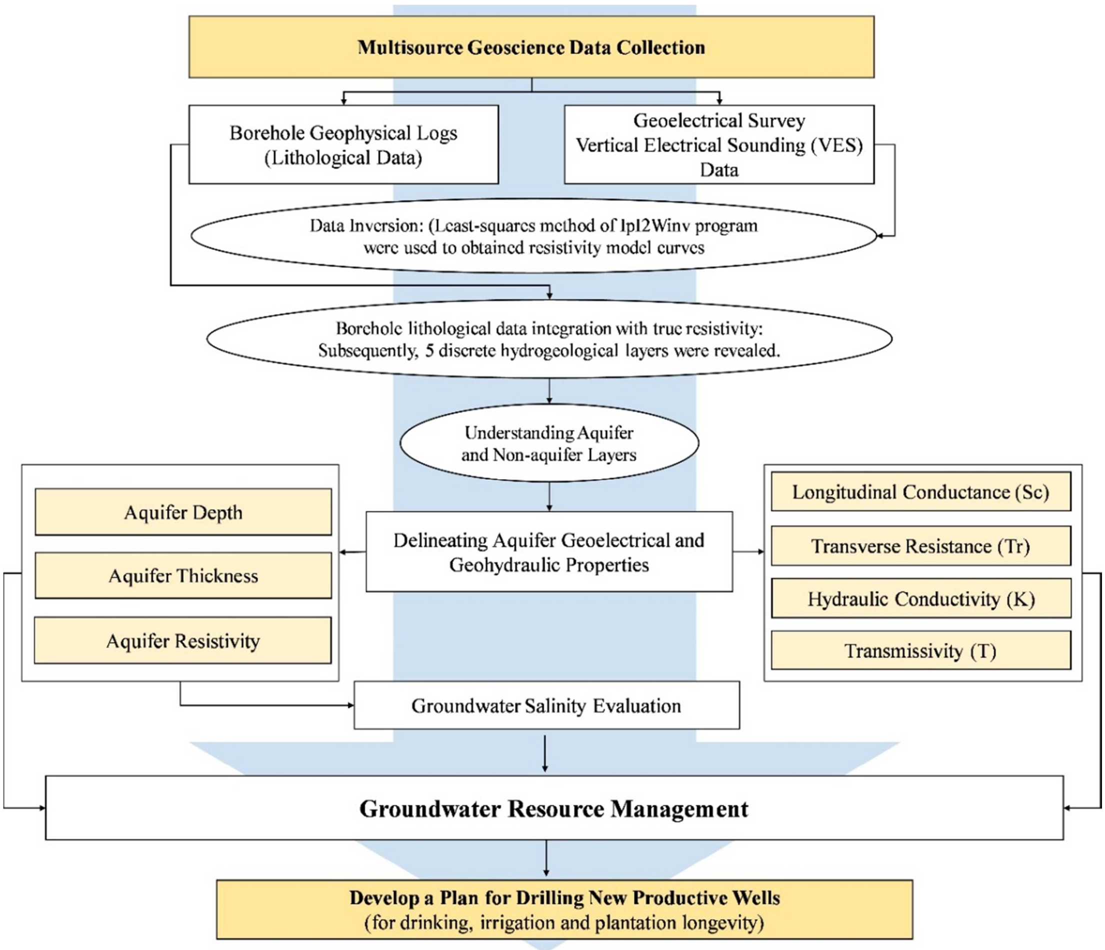


Figure 3. *Flowchart of the proposed method in this study.*

3.3. Vertical Electrical Sounding (VES) Data Inversion

Vertical Electrical Sounding (VES) is based on the principles of electrical resistivity, which refers to the ability of geological materials to resist the flow of electrical current (Figure 4). In VES, a current is passed into the ground through two electrodes, and the potential difference is measured by another pair of electrodes at a distance from the current electrodes (Figure 4). By varying the distance between the current and potential electrodes and measuring the resulting potential difference, a series of apparent resistivity values are obtained at different depths. The resistivity model curves were obtained in this study by fitting the field data with the least root mean square (RMS) error between the synthetic data generated from the model and the field data using the least squares approach of the IpI2Winv inversion tool. Iteration of the solution was utilized until the fitting errors were constant. IpI2Winv is an application that allows for the automatic and manual interpretation of VES curves in 1D. The key advantage of this program is the ease with which it may be manually interpreted. The IpI2Winv program's least-squares method is a prominent methodology in geophysical inversion for estimating the parameters of an assumed Earth model from provided observations. This method estimates the solution of an inverse problem by locating the optimal model parameters that minimize the Euclidean length, a measure of prediction error length.

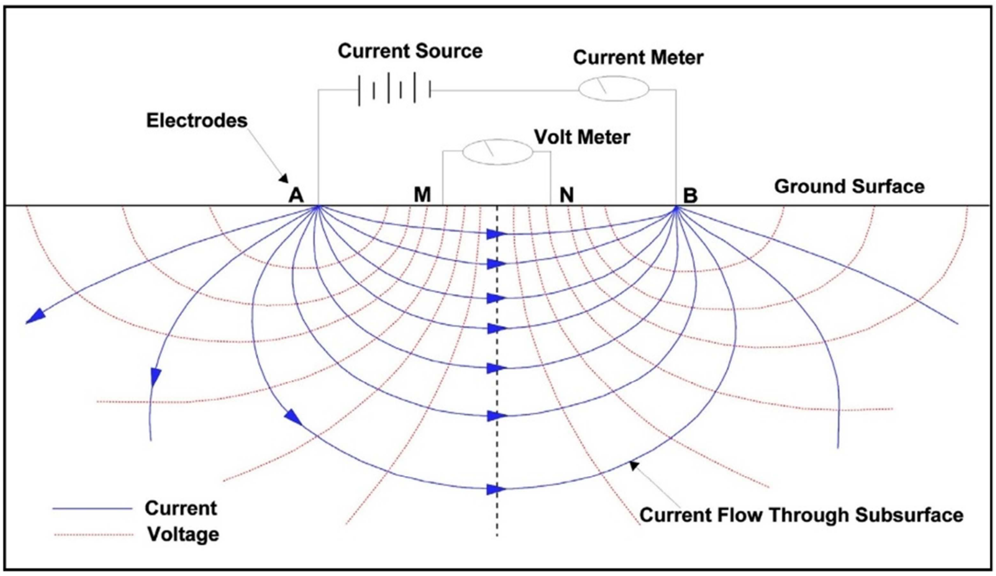


Figure 4. *Fundamental concepts for resistivity measurements (modified after [16] Schlumberger array configuration.*

3.4. Aquifer Geohydraulic Properties Assessment

Evaluation of aquifer hydrogeological properties is essential for understanding the characteristics and behavior of groundwater systems, and for managing and protecting these resources. Some of the important properties that can be evaluated includes, depth, thickness, resistivity, Longitudinal conductance (Sc), Transverse resistance (Tr), Hydraulic conductivity (K), and Transmitivity (T).

3.4.1. Longitudinal Conductance (Sc)

Longitudinal conductance (Sc) is an important parameter in hydrogeology that describes the ease with which groundwater flows through an aquifer [17]. It is directly related to the hydraulic conductivity of the aquifer and is used to estimate the rate of groundwater flow through the aquifer. Sc is related to the subsurface resistivity and thickness of the formations. In this study, longitudinal conductance (S) were calculated using equation (1).

$$s = {}^{h}\!/_{p} \tag{1}$$

where h is the layer thickness in meters and p is the electrical resistivity of the layer in ohmmeters.

3.4.2. Transverse ResistaSnce (Tr)

In this study, transverse resistance (Tr) were calculated using equation (2).

$$T_r = hp \tag{2}$$

where h is the layer thickness in meters and p is the layer's electrical resistivity in ohmmeters.

3.4.3. Hydraulic Conductivity (K)

Aquifer hydraulic conductivity, often denoted as K, is a measure of the ability of an aquifer material to transmit water through its pore spaces under a unit hydraulic gradient [18]. Hydraulic conductivity is typically measured in meters per second, although it can also be expressed in other units such as centimeters per day or feet per hour. In this study, hydraulic conductivity (K) was calculated using equation (3).

$$K = 386.40R_{rw}^{-.93283} \tag{3}$$

where R_{rw} is the resistivity of the aquifer.

3.4.4. Transmitivity (T)

In this study, the aquifer transmissivity (T) was estimated using equation (4).

$$T = K\sigma T = \frac{KS}{\sigma} = Kh \quad (4)$$

where S is the longitudinal conductance, T is the transverse resistance, and σ is the electrical conductivity (inverse of resistivity).

3.5. Groundwater Salinity Assessment

Geophysical methods can be used to evaluate groundwater salinity by measuring the electrical conductivity of the subsurface. Electrical conductivity is directly related to the concentration of dissolved salts in the groundwater, so high electrical conductivity values indicate high levels of salinity. In this study, Archie's formula was used to calculate the TDS. Because of a known proportional relationship between the TDS level in groundwater and water resistivity, the TDS level was determined from connate water resistivity. [17] The following formula relates groundwater resistivity Rw to formation resistivity Rb of sandy aquifers.

$$F = \frac{Rb}{Rw} \quad (5)$$

F is the porosity-dependent formation factor (ϕ) [19] as shown below.

$$F = \frac{a}{\phi m} \quad (6)$$

Using F = 5.4 in equation (5), Rw can be calculated from measured formation resistivity Rb. TDS in mg/L was calculated using the equation below.

$$TDS = \frac{1000 * 0.64}{Rw} \quad (7)$$

4. Results and Discussion

4.1. Geohydraulic Properties

4.1.1. Depth Variation

In general, the depth variations of hydrogeological layers are important to understand the structure and characteristics of groundwater systems. The depth of an aquifer refers to how far below the ground surface it is located. Aquifers can vary in depth, and this variation can have important implications for the way they function and the water they contain. Moreover, the depth of aquifer variation can have important implications for its recharge rate, storage capacity, vulnerability to pollution, and resilience to short- and long-term changes in precipitation and land use. The aquifer layer with depth value ranging from 0 to 135.9689 (m) corresponds to Sand containing fresh water (saturated zone) is shown in (Figure 5a).

4.1.2. Thickness Variation

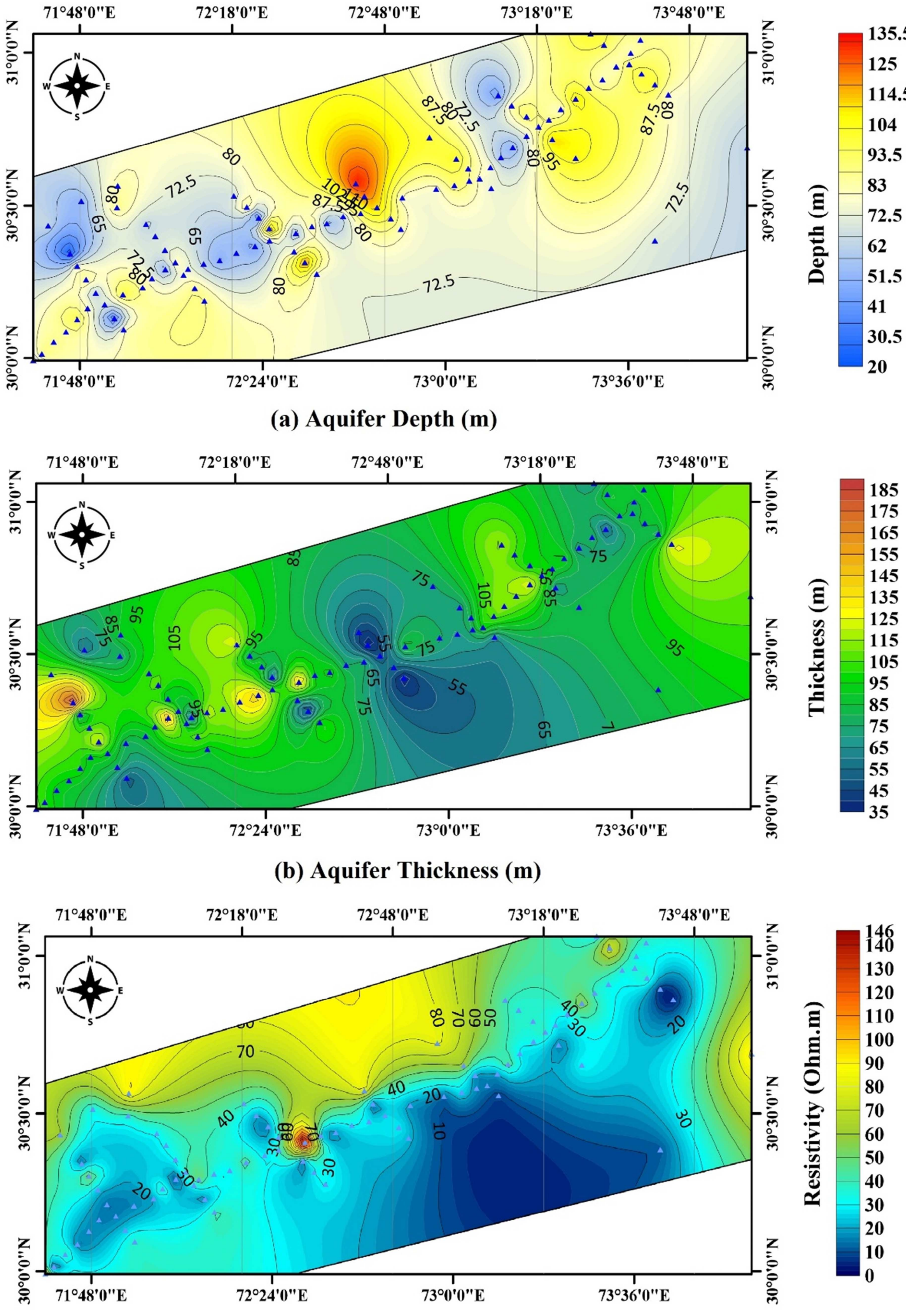
The aquifer thickness varies from 35 to 185 m, as illustrated in the image map (Figure 5b). The image map shows that the northwest and northeastern areas of the study area have very high aquifer thickness, while the central part of the study area has low thickness. It can be deduced that these aquifer-thickened zones have a large groundwater potential. High thickness of the aquifer can indicate that there is a large volume of water stored in the aquifer, which can potentially provide a sustainable source of groundwater for various uses such as drinking, irrigation, and industrial purposes. A high thickness can also indicate that the aquifer has good potential for recharge, meaning that it can be replenished with water over time. However, the quality and availability of the water in the aquifer can be influenced by various factors such as geological formations, land use practices, and climate conditions.

4.1.3. Apparent Resistivity

The resistivity of an aquifer layer is an important property that has significant implications for the exploration and management of groundwater resources. In this study, the minimum, median and maximum aquifer resistivity values are 3.3 (ohm's), 35 (ohm's), and 169. 7 (ohm's). The variation in aquifer resistivity values (Figure 5c) shows that the northern and northeastern parts of the study area are made of highly resistive materials, implying a low concentration of conducting fluid and thus a high groundwater quality, whereas the southeastern and southwestern areas show the presence of low resistive fluid and thus a high concentration of conducting materials. Furthermore, the zone beneath high resistive aquifer materials may not be suitable for drilling boreholes with high production expectations. The resistivity of an aquifer layer can vary widely depending on the type of soil or rock that makes up the aquifer. In general, aquifers with higher porosity and permeability tend to have lower resistivity, while those with lower porosity and permeability have higher resistivity.

4.1.4. Aquifer Longitudinal Conductance (Sc)

Longitudinal Conductance (Sc) is an important parameter in groundwater flow modeling, as it controls the rate of groundwater flow along an aquifer. A high value of Sc indicates that the aquifer is highly conductive and that groundwater can flow rapidly through it, whereas a low value of Sc indicates that the aquifer is relatively impermeable and that groundwater flow is slower. Moreover, longitudinal conductance (Sc) is an important property of an aquifer because it directly affects the rate at which groundwater flows through the aquifer. Aquifers with high Sc values have a greater capacity to transmit water along their length, which means that they can supply more water to wells and streams, and can recharge more quickly from precipitation. In contrast, aquifers with low Sc values have limited ability to transmit water along their length, which can result in slow or stagnant groundwater flow. Sc is a key parameter in groundwater flow modeling, which is used to predict the movement of groundwater within aquifers. The longitudinal conductance calculated for the aquifer unit (Figure 6a) in this investigation ranges between 0.0005 and 9 Ω^{-1}. This demonstrates that the studied area has high permeability and a low volume of clay, making the aquifer vulnerable to pollution as a result of surface pollutant liquid infiltration into the aquifer.



(a) Aquifer Depth (m)

(b) Aquifer Thickness (m)

(c) Aquifer Resistivity (Ohm.m)

Figure 5. *(a) Spatial depth variation of the aquifer layer; (b) Thickness variation; (c) and aquifer resistivity variation.*

4.1.5. Aquifer Transverse Resistance (Tr)

Transverse resistance is an important parameter in groundwater flow modeling, as it affects the rate at which water can flow through an aquifer. In this study, the transverse resistance (Tr) computed for the aquifer unit is typically between 150.762 and 10400.6516 Ωm2. (Figure 6b) depicts the distribution of aquifer transverse resistance. Maximum transverse resistance is recorded in the area's eastern and northwestern corners. This shows that the eastern and northwestern parts of the land are thick, and it may be assumed that these areas have high transmissivity and aquifer unit yield.

4.1.6. Aquifer Hydraulic Conductivity (K)

Hydraulic conductivity (K) is a measurement of how easily a fluid moves through a medium. It ranges from 4 to 225 m/day and is attributed to the aquifer sand repository's heterogeneity. Knowledge of hydraulic conductivity is important for groundwater management, prediction of flow, and assessment of potential contamination. (Figure 6c) demonstrates the range in hydraulic conductivity, with maximum values observed in the extreme northern and central regions of the study area and lowest values observed in the south eastern zone Aquifers have a wide because of the variability of the aquifer sand repository, the range of hydraulic conductivity, which is important for groundwater management and other aquifer properties.

4.1.7. Aquifer Transmitivity (T)

Aquifer transmissivity (T) is a measure of an aquifer's ability to transport water. It is an important parameter in groundwater modeling, as it determines how much water can flow through the aquifer and how quickly it can be pumped out. In the current study, the transmissivity values of aquifer layer in Figure 6d range from 3 to 15600 m^2/day, which have a medium to high groundwater potential. The findings indicate that the groundwater potential in the research area's eastern and northern regions is high due to strong aquifer transmissivity, making it appropriate for the development of productive boreholes.

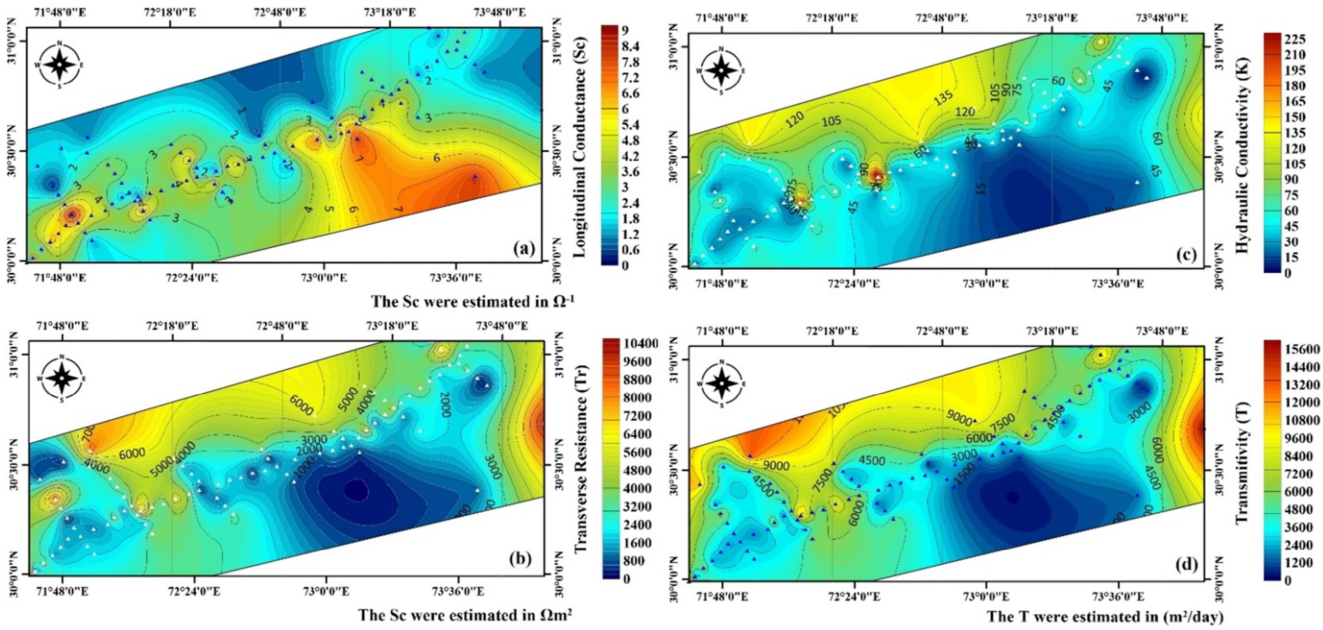


Figure 6. *(a) Longitudinal conductance (Sc) of aquifer layer; (b) Transverse Resistance (Tr) of aquifer layer; (c) hydraulic conductivity (m/day) of aquifer layer; (d) and transmitivity (T) of aquifer layer.*

4.2. Groundwater Salinity Distribution

Understanding groundwater salinity distribution by geophysical approaches is essential for long-term groundwater resource management and contamination prevention. High TDS levels can have a severe impact on water quality, so methods to mitigate the effects of high salinity are needed. Groundwater salinity in the form of TDS is measured in milligrams per litter (mg/L) or parts per million (ppm). TDS levels above 500 mg/L are considered unsuitable for drinking, while levels above 1,000 mg/L can affect crop growth and yield. Figure 7 revealed that the south-eastern and western parts of the study area have high TDS variation; As a result, these zones will have insufficient water-bearing potential. This indicates that high TDS levels in groundwater can have negative effects on water quality and make the water unsuitable for drinking or irrigation. The results of this study, which evaluated groundwater salinity distribution using resistivity techniques coupled with borehole lithological logs, can have several implications for groundwater resource management. By identifying areas with high salinity levels, water managers can develop appropriate strategies to minimize the impact of high salinity on groundwater use. This could include the development of desalination technologies, groundwater treatment facilities, or the use of alternative water sources.

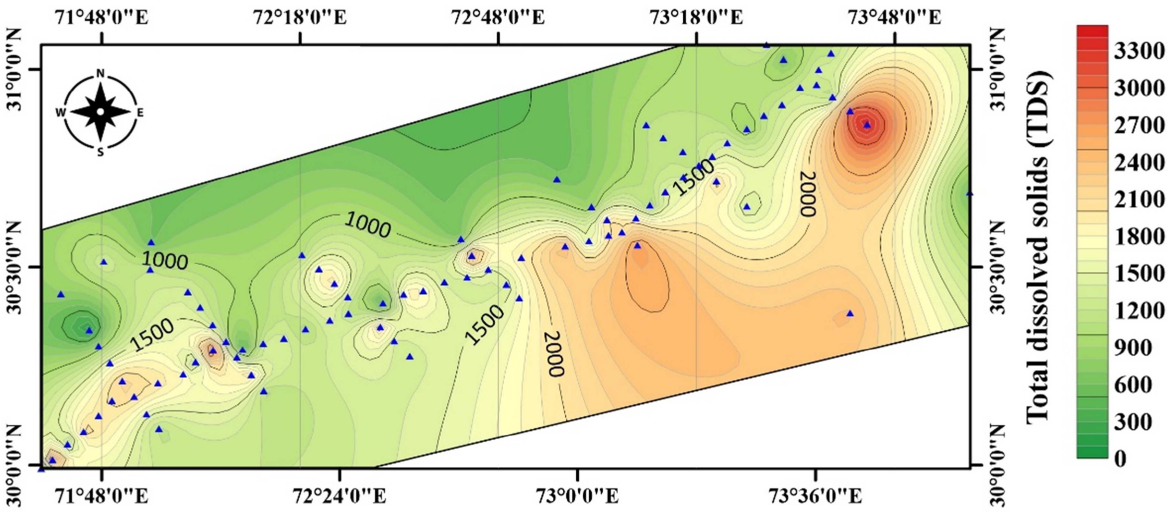


Figure 7. *Groundwater salinity distribution in the form of TDS.*

5. Conclusion

The current study innovatively attempts to synergistically process VES and borehole lithological logs data to identify aquifer geohydraulic properties as well as groundwater quality property (such as salinity distribution). The geohydraulic properties were used to construct various contour maps to understand the groundwater potentiality and potential risk of groundwater contamination for groundwater resource management (e. g., to develop a plan for drilling new productive wells for drinking, irrigation and plantation longevity in the region). According to the predicted aquifer parameters, the hydraulic conductivity values range from 4 to 225 m/day whereas transmissivity ranges from 3.00907 to 15600.563 m^2 /day. The transmissivity map delineated that the eastern and northern parts of the study area to have high aquifer transmissivity; As a result, these areas will have high water-bearing potential. Moreover, the longitudinal conductance (Sc) ranging between 0.0005 and 9 Ω^{-1}. This demonstrates that the studied area has high permeability and low volume of clay, making the aquifer vulnerable to pollution as a result of surface pollutant liquid infiltration into the aquifer. Moreover, the salinity distribution help identifies areas where there is a potential risk of groundwater contamination. The detailed information can be used to guide the development of new wells in areas with high potential for productive aquifers, leading to increased access to clean water for local communities. This is particularly important in arid and semi-arid regions where surface water is scarce, and groundwater is the primary source of water for residential, agricultural, and industrial uses.

Acknowledgements

This study was funded by the National Natural Science Foundation of China (No. 42174170, No. 42130810). The authors thank Mr. Imad Khan (Geophysical Services, Peshawar, Pakistan) for providing the dataset.

References

[1] Hubbard, S. S. and Y. Rubin, Hydrogeological parameter estimation using geophysical data: a review of selected techniques. Journal of Contaminant Hydrology, 2000. 45 (1-2): p. 3-34.

[2] Khalid, P., S. Ullah, and A. Farid, Application of electrical resistivity inversion to delineate salt and freshwater interfaces in quaternary sediments of northwest Himalaya, Pakistan. Arabian Journal of Geosciences, 2018. 11: p. 1-11.

[3] George, N. J., Integrating hydrogeological and second-order geo-electric indices in groundwater vulnerability mapping: A case study of alluvial environments. Applied Water Science, 2021. 11 (7): p. 123.

[4] Khalid, P., et al., Estimating active storage of groundwater quality zones in alluvial deposits of Faisalabad area, Rechna Doab, Pakistan. Arabian Journal of Geosciences, 2019. 12: p. 1-9.

[5] Hasan, M., et al., Assessment of aquifer vulnerability using integrated geophysical approach in weathered terrains of South China. Open Geosciences, 2019. 11 (1): p. 1129-1150.

[6] Yadav, G. and H. Abolfazli, Geoelectrical soundings and their relationship to hydraulic parameters in semiarid regions of Jalore, northwestern India. Journal of Applied Geophysics, 1998. 39 (1): p. 35-51.

[7] Abdulrazzaq, Z. T., R. H. Hasan, and N. A. Aziz, Integrated TRMM data and standardized precipitation index to monitor the meteorological drought. Civil Engineering Journal, 2019. 5 (7): p. 1590-1598.

[8] Aziz, A., et al., Biological wastewater treatment (anaerobic-aerobic) technologies for safe discharge of treated slaughterhouse and meat processing wastewater. Science of the total environment, 2019. 686: p. 681-708.

[9] Srivastava, P., et al., Soils of the Indo-Gangetic Plains: a pedogenic response to landscape stability, climatic variability and anthropogenic activity during the Holocene. Earth-Science Reviews, 2015. 140: p. 54-71.

[10] Irfan, M., et al., Vulnerability of environmental resources in Indus Basin after the development of irrigation system. Irrigation-water productivity and operation, sustainability and climate change, 2019.

[11] Muhammad, S., et al., Hydrogeophysical modeling and physio-chemical analysis of quaternary aquifer in central part of Bari Doab, Punjab, Pakistan. Modeling Earth Systems and Environment, 2022: p. 1-17.

[12] Loke, M. and R. Barker, Practical techniques for 3D resistivity surveys and data inversion1. Geophysical prospecting, 1996. 44 (3): p. 499-523. 27.

[13] Archie, G. E., The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the AIME, 1942. 146 (01): p. 54-62.

[14] Winsauer, W. O., et al., Resistivity of brine-saturated sands in relation to pore geometry. AAPG bulletin, 1952. 36 (2): p. 253-277.

[15] Aweto, K., Resistivity methods in hydro-geophysical investigation for groundwater in Aghalokpe, Western Niger Delta. Global Journal of Geological Sciences, 2013. 11: p. 47-55. 31.

[16] Singh, A., Thomsen, K. J., Sinha, R., Buylaert, J. P., Carter, A., Mark, D. F., Mason, P. J., Densmore, A. L., Murray, A. S., Jain, M. and Paul, D., 2017. Counter-intuitive influence of Himalayan river morphodynamics on Indus Civilisation urban settlements. Nature communications, 8 (1), p. 1617.

[17] Qureshi, A. S., McCornick, P. G., Sarwar, A. and Sharma, B. R., 2010. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. Water resources management, 24 (8), pp. 1551-1569.

[18] Van Steenbergen, F., Basharat, M. and Lashari, B. K., 2015. Key challenges and opportunities for conjunctive management of surface and groundwater in mega-irrigation systems: Lower Indus, Pakistan. Resources, 4 (4), pp. 831-856.