



Evaluation of aquifer parameters through integrated approach of geophysical investigations, pumping test analysis and Dar-Zarrouk parameters in the central part of Bari Doab, Punjab, Pakistan

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Received: 18 May 2023 / Accepted: 27 October 2023 / Published online: 9 November 2023
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Abstract In the central part of Bari Doab in Punjab Province of Pakistan, the factors such as sporadic rainfall pattern, decrement of water in rivers, subsurface salinity and excessive mining of groundwater have badly affected the hydrogeology and recharge system of aquifer. The present research work is an endeavour to evaluate the characteristics and potential of aquifer for its future sustainable availability within the study area of central part of Bari Doab. The geophysical studies, pumping tests data, borehole logs and Dar-Zarrouk parameters were used integrally to evaluate the aquifer hydraulic and hydrologic parameters in the study area. VES technique of geophysical investigations using Schlumberger electrodes configuration was carried out at sparsely distributed 435 locations. Litho-logs and VES results altogether decipher that the subsurface alluvial succession is primarily composed of intermixed layers of sand, gravel, clay, silt and some kankar inclusions. The VES data allied with pumping test analysis of test wells in the

study area were used to evaluate the aquifer hydraulic properties. Comparatively low values of discharge rate, hydraulic conductivity and transmissivity were evaluated in two wells whilst relatively higher values of these parameters were evaluated in rest of six wells. The results of hydrologic parameters also confirm the results of hydraulic parameters in the wells. Finally, the Dar-Zarrouk parameters were used for the estimation of hydraulic parameters for whole study area and the aquifer zones of relatively high and low potential were delineated.

Keywords Doab · Vertical electrical sounding (VES) · Dar-Zarrouk parameters · Hydraulic conductivity · Transmissivity · Formation factor

Introduction to the study area

The socio-economic growth of an area is primarily related to the groundwater scenario of that area (WAPDA, 1980; Li et al., 2018). Punjab province is highly dense in terms of its population which holds about half of the total population of the country. The urban population of Okara, Pakpattan and Sahiwal cities of Punjab province has been crossed the figure of 10 million. Punjab province is known for a rapidly increasing demand of water to overcome the challenges such as population growth, agricultural and industrial development. Consequently, the groundwater issues are being observed to arise regionally and

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locally as well (I&P, 2005; MINFAL, 2008; World Bank, 2011; Hasan et al., 2017; Quraishi & Ashraf, 2019).

The central part of Bari Doab (latitude 29.90–31.20° and longitude 72.35–74.2°)

representing three adjacent districts of Pakpattan, Okara and Sahiwal in Punjab province, Pakistan, is selected as the study area (Fig. 1). The study area lies in Indus Plain within Punjab Province which is also known as Punjab Plains. The climatic condition of

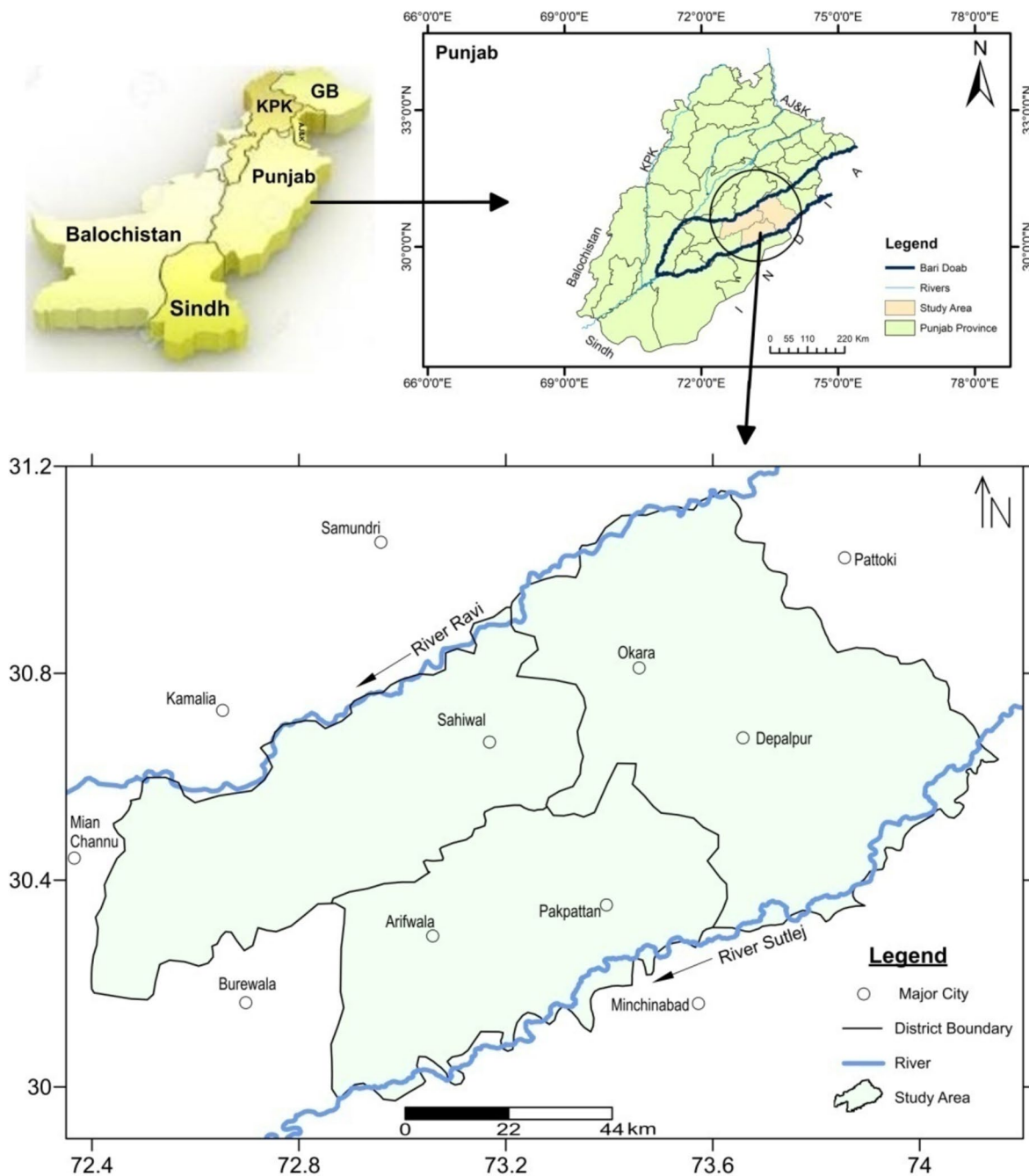


Fig. 1 Location map of the study area

this region is mostly semi arid with three distinctive seasons. An oppressive summer season is observed with late monsoon followed by cool winter. The cool winter is occasionally accompanied by rain-falls (Kazmi & Jan, 1995; Sayal, 2015; Quraishi & Ashraf, 2019). Geographically, southern and northern boundaries of the study area are represented by Sutlej and Ravi Rivers respectively (Fig. 1). The study area is mainly comprised of vast cultivated lands which are heading towards rising demand of groundwater abstraction. The adjacent rivers of the study area act as primary source of groundwater recharge. However, the canals and rainwater are the secondary sources (Kazmi & Jan, 1997; Butt, 2017). The depletion of these surface water resources is being observed whilst the water demand is increasing day by day. The insufficiency of surface water resources is causing the over-withdrawal of groundwater. Eventually, the over abstraction of groundwater is being observed in all over the Doab as well as in the study area to overcome the water needs for swift increment of population, industry and agriculture setup (Haq, 2002; I&P, 2005; Hasan et al., 2017; Quraishi & Ashraf, 2019; Hasan et al., 2020).

The Indus Basin of Pakistan holds one of the world's best canal systems for irrigation with about 30 to 31 million hectare of irrigated land (MINFAL, 2008). According to World Bank report, Pakistan is going to become a water scarce state rapidly. Excessive abstraction of fresh water reserves through brisk installation of pumping boreholes with lack of scientific techniques has caused a decline in water table as well as the saline water intrusions into fresh groundwater (Bakhsh & Awan, 2002; Pakistan Bureau of Statistics, 2011; World Bank, 2011; Hasan et al., 2018).

Keeping in view the aforesaid issues, the hydrogeological and hydrogeophysical investigations have become essential for the evaluation of latest groundwater reserves in order to exploit the fresh water aquifers properly, maintaining its quality and future sustainability as well. The present study is helpful to understand the current groundwater scenario and to manage the groundwater resources of the study area. The findings of this study will also be helpful to the optimising site selection to install water bores. Moreover, it will support the policy makers to manage a long-sighted plan to rescue the groundwater resources.

Lithology and other characteristics of subsurface strata define the groundwater movement and its occurrence. It is essential to evaluate hydraulic properties of an aquifer which further leads to understand the groundwater setup of an area. The quantitative information of aquifer in a given area can be inferred with the help of these parameters such as transmissivity, hydraulic conductivity and discharge rate of aquifer. Usually, the pumping test is used for determining the hydrogeological parameters of the unconfined and confined aquifers (Li & Qian, 2012; Li et al., 2013a; Li et al., 2013b; Butt, 2017; Amiri et al., 2022).

The activity of pumping test is very expensive, so, it is usually not feasible to conduct large amount of pumping tests for a given area. However, the geophysical technique is comparatively cheaper and non-invasive method which provides an alternative for the estimation of aquifer parameters especially at those locations where the data of pumping tests is insufficiently available. The electrical and hydraulic properties of subsurface material depend upon the heterogeneity, pore geometry and structure. So, both of these properties can be correlated with each other (Todd 1980; Fitts, 2002; Lesmes & Friedman, 2005; Fetter, 2014). Vertical electrical soundings (VES) technique of geophysical method were used integrally with pumping tests data and lithological logs of the study area to assess the properties of aquifer (Soupios et al., 2007; Perdomo et al., 2014; Ullah et al., 2020). The hydraulic parameters at some specific locations where the pumping tests were not executed, can be estimated with the help of some relations between hydraulic parameters and geophysical data derived by different authors. Consequently, hydraulic properties of the entire study area can be estimated. The purpose of this research work is to apply the cost-effective geophysical data allied with pumping test analysis to estimate the characteristics of water-bearing layers and potentials of the whole investigated area (Todd, 1980; Singh, 2005).

Geological setting

Bari Doab is the interfluvial system between Sutlej and Ravi Rivers which is a part of Indus Plain in Punjab Province of Pakistan. Indus Plain is almost flat land with gentle slope of about 1 m per 5 km towards south and southwest (Kazmi & Jan, 1997; Butt, 2017). The two broad and distinct units of Indus

Plain are referred as Central Alluvial Plain and Piedmont zone. The Central Alluvial Plain is also simply termed as Indus Plain and Bari Doab is a part of it (Kazmi & Jan, 1997; Bender & Raza, 1995).

The thick Quaternary alluvial succession is believed to be deposited episodically by recent and extinct river channels adjacent to the study area which are the main source of deposition of Bari Doab. Exploratory drilling works confirm that these are unconsolidated sediments of Pleistocene to Recent aged and these sediments rest on the sedimentary succession and igneous/metamorphic rocks of Precambrian age. The sedimentary succession goes thicken towards west and pinches out towards east of the study area (Ahmad, 1974; WAPDA, 1980; Butt, 2017). The drilling data of Bari Doab reveals that the alluvial succession is more than 300 m thick and mainly comprised of intermixed/interbedded layers of sand, gravel, silts, clays and some inclusions of *kan-kars*. Some borehole litho-logs representing the main lithological distribution in the study area are shown in Fig. 2 (Ahmad, 1974; WAPDA, 1980; Ahmad & Chaudhry, 1988).

The sandy deposits of alluvium are considered aquifer in which groundwater occurs under water table conditions. Within coarser sandy/gravelly segments, the fine materials of silts and clays are presumed to be deposit by episodically reworked loess (Kazmi & Jan, 1997; Muhammad et al., 2022a). However, these interbedded finer sediments (clays/silts) do not hold a large lateral extension rather these exist as intermixed form within coarser lithology of sand/gravel and/or in the form of lenses which discontinuously extent horizontally or pinch out after some lateral continuation. In other words, it is confirmed that the finer sediments locally present in the study area. Moreover, these finer sediments only exist in the form of thin layers and somehow mostly with some intercalation of comparatively coarse particles of sand. These are the reasons that the overall aquifer package is believed to be exist in unconfined condition throughout the Punjab Plain as well as in the study area (Akhter & Hasan, 2016; Hasan et al., 2017; Hasan et al., 2018; Hasan et al., 2020). These Quaternary alluviums are classified into Meander Belt deposits of ancient streams, River Terraces and Older/Younger Flood Plain deposits (Fig. 3). The study area geology (Fig. 3) is mainly composed of Flood Plain deposits of lower terrace and loess

deposits of upper terrace at surface (WAPDA, 1980; Ahmad & Chaudhry, 1988; Butt, 2017).

Hydrogeological setting

A number of test holes have been drilled in and around the study area up to >1000 feet depth to estimate the groundwater resources. The geology and drill-logs clearly indicate the water-bearing characteristics of the alluvium package. The litho-logs of drillholes confirm the existence of Quaternary alluvium and also provide an idea about the structure and texture of alluvium (WAPDA, 1980; I&P, 2005; Muhammad et al., 2022b). Some of the lithological logs are shown in Fig. 2.

The thick alluvial succession of Indus Plain including study area holds a gigantic unconfined aquifer system. Geological information and lithological logs also confirm the argument. However, the existence of intermixed fine materials such as silts and clays at different subsurface levels may compromise the quality of fresh groundwater. These finer sediments mostly exist as thin layers with intercalation of some sandy material and do not extent too much laterally as well. The water table varies 5–26 m and the thickness of the saturated alluvium is believed >300 m in the study area (Akhter & Hasan, 2016; Muhammad et al., 2022a).

Methodology and dataset

Pumping test analysis

The Pumping test analysis is used worldwide to calculate the hydraulic parameters of aquifer (Freeze & Cherry, 1979; Fetter, 2014). In present study, the pumping tests data of water wells was used to compute the hydraulic properties of aquifer in the study area. Pumping tests were conducted by Water and Power development Authority (WAPDA) at evenly distributed eight boreholes/wells (T/W-1 to T/W-8) in the study area. Locations of these boreholes are shown in Fig. 4. The results of pumping test analysis of these boreholes were used to calculate hydraulic properties of unconfined aquifer of the study area. To perform pumping tests in each borehole, single wells were used keeping discharge rate (Q) as constant. Before commencing the pumping tests, the static level of water was

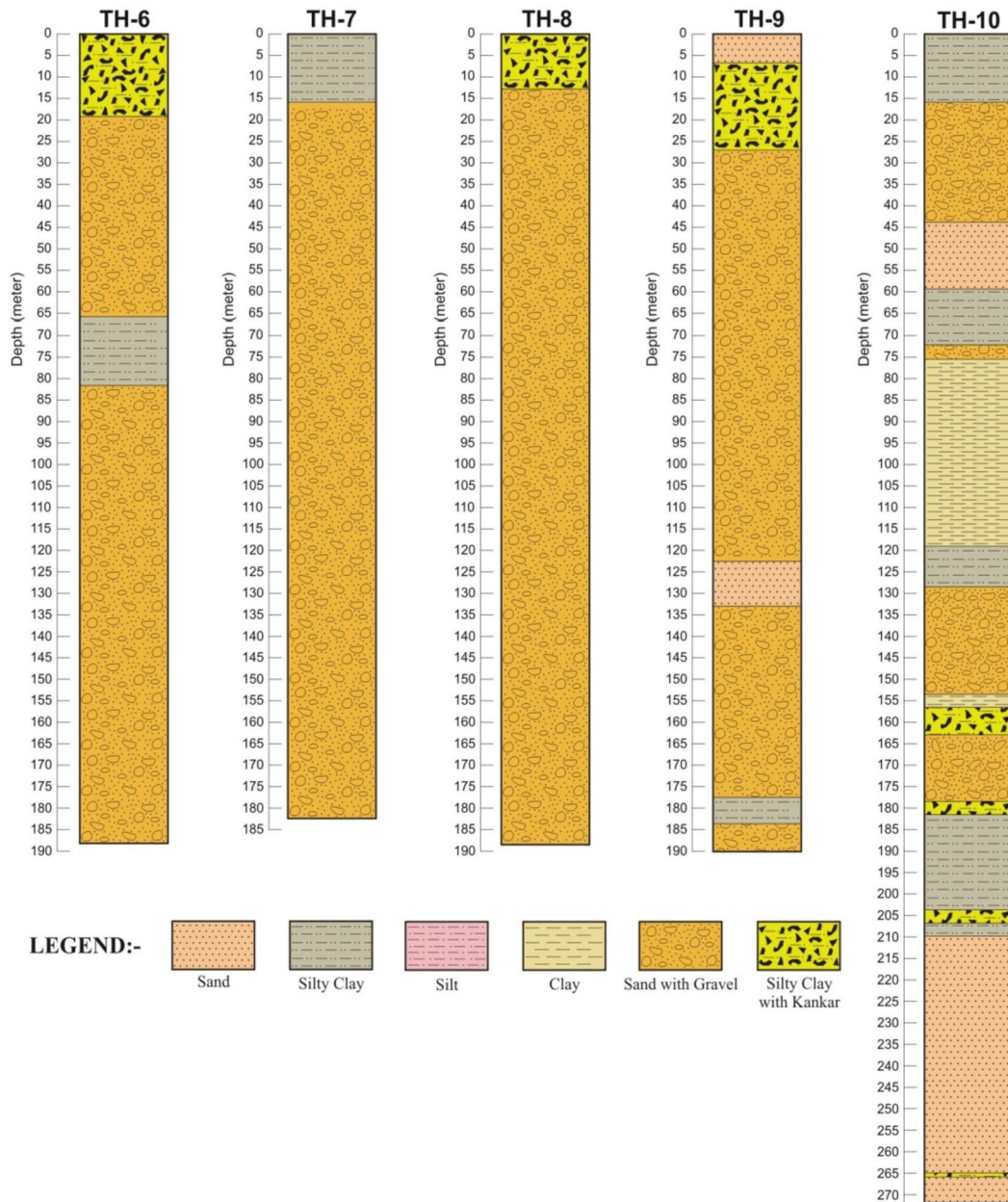


Fig. 2 Borehole litho-logs of the study area (source: hydrogeological data of Bari Doab, WAPDA, 1980)

measured. Moreover, the drawdown was measured in pumping wells and nearby observation wells after intervals of time during pumping-out phase. The VES data, lithological drill-logs and geological information of the study area altogether confirm that the unconfined saturated alluvium is mainly comprised of inter-mixed sand-gravel as coarse sediments and clays and silts as fine sediments. In present study, the hydraulic

parameters such as specific yield (S_y) and transmissivity (T) of unconfined aquifer system were calculated with the help of hi-tech software AQTESOLV using Theis (1935) solution. Hydraulic conductivity was further computed by Eq. (1).

$$T = Kb \tag{1}$$

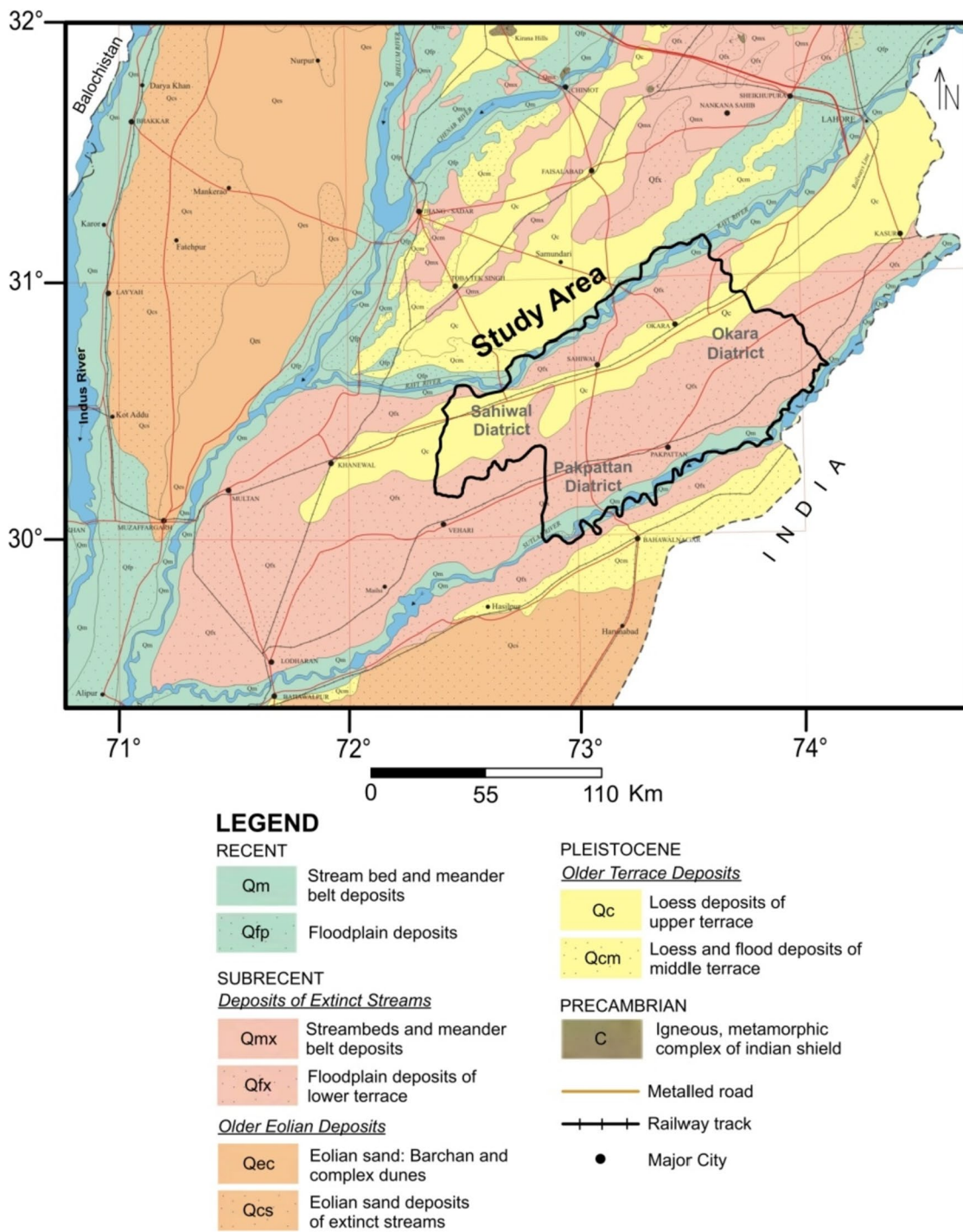


Fig. 3 Regional and study area geology (Afridi et al., 2011)

whereas b value is the average thickness of aquifer and is measure in m. It is actually the averaged thickness of saturated layers calculated by processed VES

data of specific wells locations. T is transmissivity and K is hydraulic conductivity, measured in m^2/day and m/day respectively.

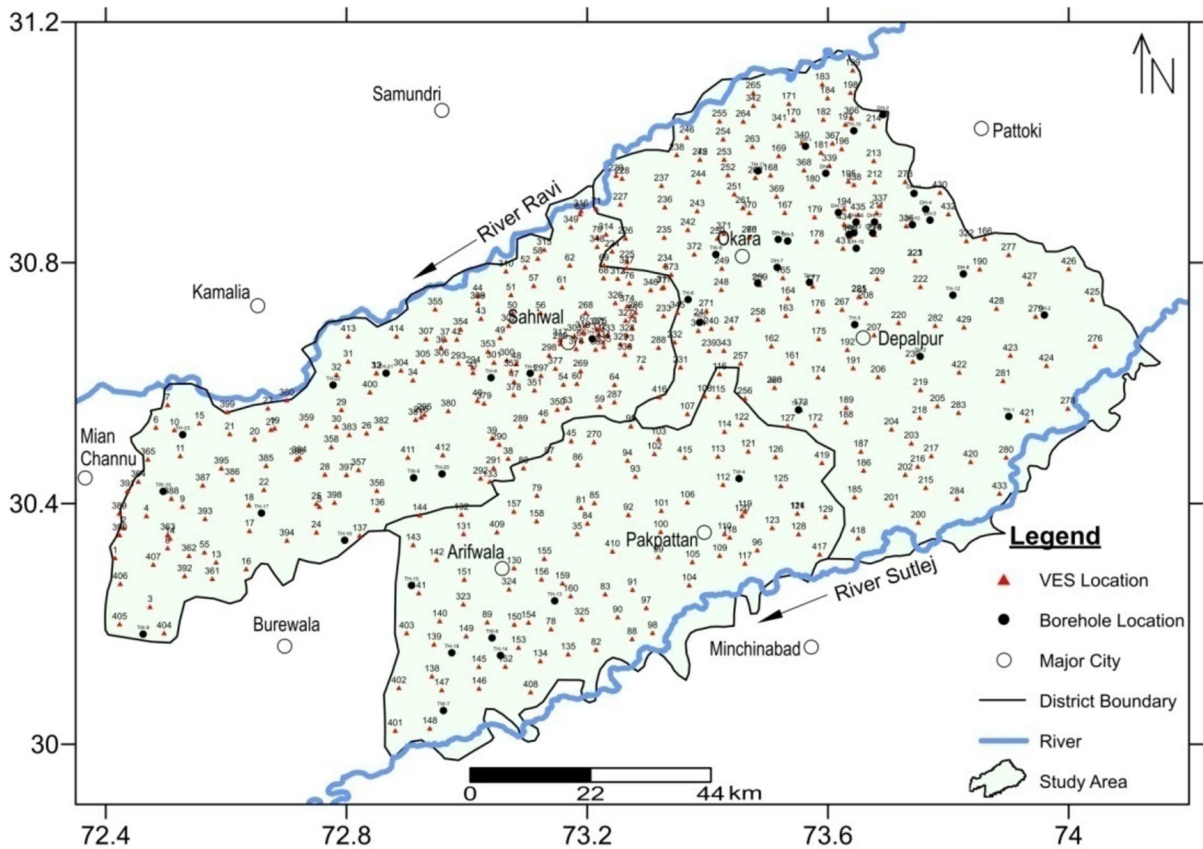


Fig. 4 Base map of the study area showing boreholes and VES locations

Geophysical investigations

The electrical resistivity survey (ERS) of geophysical investigations is utilised to describe the electrical properties of subsurface saturated layers which lead further to compute the hydrologic properties of aquifer (Chandra et al., 2008; Muhammad & Khalid, 2017; Farid et al., 2017; Muhammad, 2021; Muhammad et al., 2022b). During the last decade, ERS data was acquired in the study area by PCRWR, Diviners & Bitman International, Terra Technology, Geo-Dynamics and Geoscience Associates. However, more than 30% ERS data was acquired by the authors in 2020–2021 to cover un-acquired patches and to increase the data density in the study area. A total of 435 VES probes at sparsely distributed stations covering the study area were utilised for the present research work (Fig. 4). The high-tech resistivity instrument ABEM Tarameter was deployed to measure the subsurface

electrical resistivities during the field survey with VES technique using schlumberger electrodes configuration. Maximum 300 m depth was achieved during the data acquisition of each probe. The field resistivity is termed as apparent resistivity and is calculated by using Eq. (2).

$$\rho_a = (V/I) (K) \tag{2}$$

whereas

$$K = [(AB/2)^2 - (MN/2)^2](\pi)/MN \tag{3}$$

whereas ρ_a is the apparent resistivity measured in Ω -m, I is induced current through current electrodes measured in amp and V is potential difference measured in volts. K is the geometrical factor calculated specifically for schlumberger electrodes configuration. AB and MN represent spacing between current and potential electrodes respectively and measured in meters.

VES data and evaluation of aquifer parameters

The VES data is able to provide electric properties of aquifer of an area. Nevertheless, its accuracy is limited because of site-specific parameters such as grain/pore size, tortuosity, fluid saturation and salinity. This relates to hydrologic properties on the basis of some relationships produced by many workers for different areas of different lithologies. However, one empirical relation for a specific area should not be used for another area if both areas have utterly different depositional settings (Niwas et al. 2006; Khalili et al., 2009; Fatoba et al., 2014). The relationships between drilling and VES data exist for evaluation of hydrologic parameters at specific areas where drilling data is not sufficient. Nevertheless, these relationships are dependent upon coefficient of lithology or tortuosity (α), formation factor (F) and porosity (ϕ) (Huntley, 1986; Mazac et al., 1988; Lima & Niwas, 2000; Khalid et al., 2018). To calculate the aquifer hydraulic parameters, some analytical relationships have also been developed by using the results of pumping test analysis and VES data (Urish, 1981; Mazac et al., 1988; Borner et al., 1996; Rubin & Hubbard, 2005).

Determination of formation and groundwater electrical resistivity

The hydrological parameters such as groundwater electrical resistivity (R_w) and formation/aquifer's electrical resistivity (R_f) lead to estimate porosity and formation factor of saturated subsurface layers (Salem, 1999; Ellis & Singer, 2007; Perdomo et al., 2014; Muhammad, 2021). The values of R_f were taken from VES processed models. The groundwater electrical conductivity (EC) of evenly distributed water samples of the study area was computed during field by using portable instruments. The EC values were led to R_w with the help of Eq. (4). The values of R_f and R_w represent averaged resistivity values.

$$R_w = 10000/EC \quad (4)$$

Determination of formation factor

Formation factor (F) is a vital hydrologic parameter depends upon grain size, pore spaces and geometry,

fluid content in pore spaces, clayey content, degree of cementation, lithology etc. (Tiab & Donaldson, 2004; Muhammad, 2021). Formation factor decreases with decrease in cementing factor and increase in porosity and clay content. Pure and coarse sand gives higher value of formation factor whilst decrement is observed with the inclusion of finer contents even the other physical parameters were same (Helander & Myung, 1983; Perdomo et al., 2014). The electrical and hydraulic properties of aquifer are related to each other as both are dependent upon heterogeneity and pore-geometry. Archie (1942) described that the formation resistivity of saturated layers is related to the formation factor. Usually, geophysical logging is used to measure the formation factor and formation resistivity; however, Eq. (5) is used to measure these parameters due to the unavailability of geophysical logging data of the study area.

$$F = R_f/R_w \quad (5)$$

Usually, the formation factor differs from lithology to lithology and has not unique value. Its value is about 2 for dirty sand (sand with finer content) and it ranges of 3 for fine to medium sand. For large sediments like boulders/gravel its value may exceed from 7 also (Vinegar & Waxman, 1984; Bloemendaal & Sadiq, 1985; Worthington, 1993).

Determination of porosity

The general Archie relationship (Eq. 6) was used to measure porosity in which formation factor combines with cementation factor, pore shape/spaces and porosity.

$$F = \alpha\phi^{-m} \quad (6)$$

whereas F , α , ϕ and m are the formation factor, coefficient of lithology, porosity and cementing factor respectively. The α depends upon site-specific lithology and is kept as '1' in many cases. A number of factors depend upon the value of m such as tortuosity, overburden, grain and pores size/shape, anisotropy etc. (Tiab & Donaldson, 2004; Khalili et al., 2009; Todd & Mays, 2013; Muhammad, 2021). For the study area, both the values of α and m were kept as fix.

The calculation of m and α independently for each location in a given area is the best procedural way;

however, it is not feasible practically due to the lack of drilling data at each required location. To overcome this limitation, some workers evaluated these values experimentally for different lithologies (Todd & Mays, 2013; Muhammad, 2021). The drillhole data of the study area is also not sufficient; thus, both of these values were adopted from reported literature ($m= 1.33$ and $\alpha= 1$) keeping the lithology of the study area under consideration.

Results and discussion

VES data

The field data of VES represents the apparent resistivity (ρ_a) values. The partial curve matching practice with auxiliary point technique was utilised for the processing of each VES field curve of the study area. However, for final interpretation, the interactive software IPI2WIN was used to generate subsurface VES processed models with true resistivities and thicknesses/depths of geoelectric layers at subsurface with minimum RMS error (<1.5 %). Half of the current electrode distances ($AB/2$) were plotted at X-axis

whilst the apparent resistivity values were plotted at Y-axis as input parameters on bi-log graphs in the software. Some of the software-based processed VES models are shown in Fig. 5.

By analysing Fig. 5, the tiny black circles are the representation of apparent resistivities which were acquired during the geophysical field data collection. The black lines joining the black circles indicate the graph of apparent resistivity values. The black line is superimposed by red line which represents the processed data. The red line is in best fitting with black line with least RMS error. Furthermore, the final outcome of processing is the blue line with sharp edges. Its vertical and horizontal parts are the representative of true resistivity and thickness of particular geoelectric subsurface layer respectively. Following the aforementioned procedure, the true resistivities and depths/thicknesses of individual geoelectric layers for each VES probe were evaluated. Each modelled layer is limited to minimal lithological layers. A total of 3–6 subsurface geoelectric layers were interpreted in the entire study area. The bottom layer thickness cannot be estimated because of the limitations of maximum investigated depth. To make a final interpretation, the processed VES data was analysed

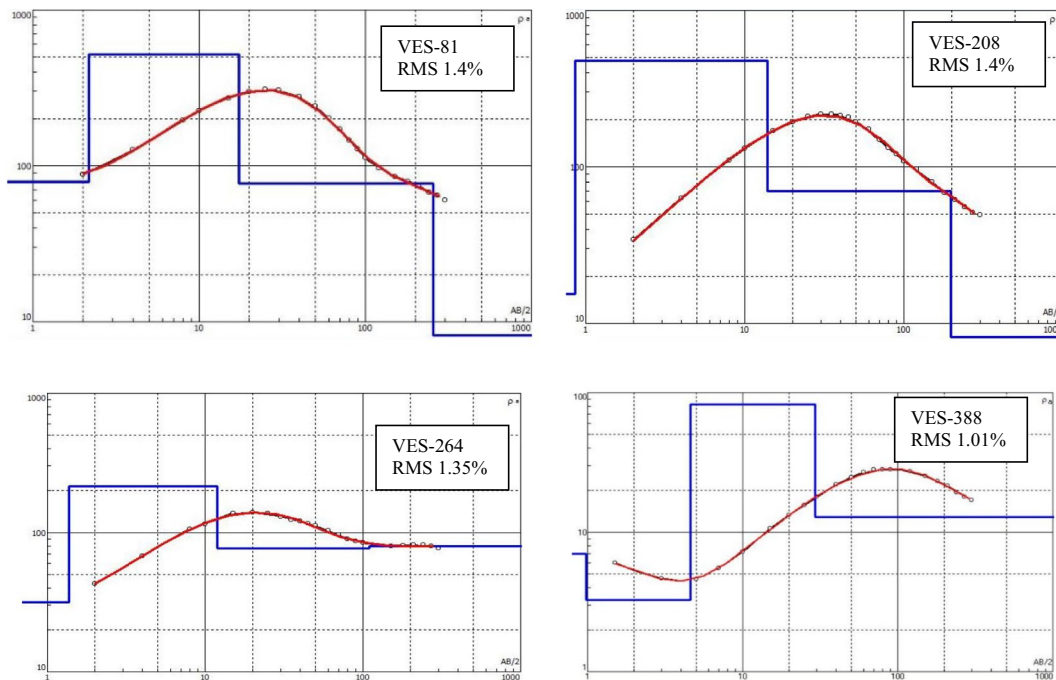


Fig. 5 Processed graphs of VES-81, VES-208, VES-264 and VES-388

concurrently with the field information of reconnaissance visits, litho-logs of the study area, surface and subsurface geology, water table information and previous literatures. Eventually, a correlation of true resistivity values with their interpreted lithological description was developed especially by examining the processed VES data with the litho-logs of boreholes (Table 1).

The electrical resistivity range is interpreted as 0.014–777 Ω -m in the study area whilst the water table varies from 5 to 26 m. Interpreted resistivity values are classified as two zones i.e., below and above the water table (Table 1). The primary goal of VES survey was to evaluate the thickness and true resistivity of each saturated layer at each VES probe which further led to estimate the aquifer parameters.

Measurement of hydraulic parameters using pumping test analysis

The pumping test analysis was performed for 08 numbers of sparsely distributed wells denoted as T/W-1 to T/W-8. The computer programme AQTESOLVE Pro (ver. 4.02) was used for the computation of hydraulic properties of aquifer in these wells/boreholes and presented in Table 2.

Table 2 clearly deciphers that the study area holds very good discharge rate with sufficient hydraulic conductivity and transmissivity. In detail, Table 2 describes that the boreholes T/W-6, 8 show comparatively low discharge rate due to the low hydraulic conductivity and transmissivity. Litho-logs of these boreholes show the sand and gravel with intermixed

Table 1 Cut-off true resistivity values with interpreted lithological description

Resistivity zone	Resistivity range (Ω -m)	Interpreted lithological description
> 230	Very high	Above water table:- Interbedded dry sediments predominantly composed of sand and sand-gravel with kankar inclusions at different subsurface levels. Below water table:- Interbedded saturated sediments predominantly composed of sand-gravel with kankar inclusions at different subsurface levels.
> 100–230	High	Predominantly interdeded layers of sand and sand-gravel, saturated under water table conditions.
> 40–100	Medium	Intermixed sediments predominantly composed of sand with minor gravel, saturated under water table conditions.
20–40	Low	Dry strata predominantly composed of silty clay above the water table. Intermixed saturated layers of sand with fine sediments of silts/clays below water table.
< 20	Very low	Predominantly silty clay above water table. Predominantly intermixed sand and sand-gravel layers saturated with groundwater of saline/brackish quality below the water table.

Table 2 Computed hydraulic parameters using pumping test analysis

Well ID.	Q (m^3/hr)	T (m^2/day)	K (m/day)	S_y	b (m)	Lithology
T/W-1	255	4357	30	0.00430	289	Predominantly sand-gravel.
T/W-2	204	4874	35	0.0733	284	
T/W-3	306	5154	56	0.0164	292	
T/W-4	280	6011	47	1.179	286	
T/W-5	280	4401	31	0.00181	282	
T/W-7	255	7384	29	0.3313	280	Intermixed strata predominantly composed of sand-gravel with fine clays/silts.
T/W-6	150	3802	27	0.0591	279	
T/W-8	183	1947	8	0.00891	281	

layers of finer clays and silts. Such fine contents try not to raise the resistivity values. These fine contents also try to increase drawdown and restrict discharge rate, transmissivity and hydraulic conductivity (Table 2). Higher values of discharge rate represent low drawdown. Boreholes T/W-1, 2, 4, 5 and 7 represent comparatively high hydraulic conductivity and high transmissivity (Table 2). These higher values correspond to sand-gravel lithology in dominance in respective boreholes which allow the transmission of water with high rate. Borehole T/W-3 holds highest discharge rate amongst all which again corresponds to high transmissivity and hydraulic conductivity (Table 2) depicting sand-gravel lithology in dominance. VES processed data/results and lithology of all boreholes also confirms the values of Q , T and K (Table 2) for all boreholes.

Estimation of hydrological parameters using VES data

The aquifer hydrological parameters (K , ϕ , F , T) depend upon a numbers of factors such as depositional setup and lithology of an aquifer body (Worthington, 1993; Tiab & Donaldson, 2004). However, transmissivity and hydraulic conductivity have been estimated already (Table 2). Equation (5) and Eq. (6) are used to compute the formation factor and porosity respectively. The formation resistivity (R_f) and groundwater resistivity (R_w) are input data for Eq. (5). R_f represents averaged electrical resistivity of saturated layers which were taken out from processed models of VES located at respective wells. R_w was calculated for respective wells by using Eq. (4). Thus, the hydrological parameters at all boreholes locations were estimated and presented in Table 3.

Two boreholes (T/W-6, 8) exhibit relatively low formation factor and high porosity (Table 3). The reason of high value of porosity in these boreholes is the presence of finer contents of clay/silt intermixed with sand and gravel lithology. The finer contents try to restrict the formation factor from exceeding. Relatively low Q , T and K values of hydraulic parameters (Table 2) were encountered in these boreholes. Both the results of hydraulic and hydrologic parameters are in accordance with each other (Tables 2 and 3).

Boreholes T/W-1, 2, 4, 5 and 7 exhibit comparatively high formation factor with low porosity (Table 3) which represents coarser sediments of sand-gravel in dominance along with very minor or negligible intermixing of finer ones such as clay/silt. The predominance of coarser lithology tries to raise Q , T and K values of hydraulic parameters (Table 2) in these boreholes. Hydraulic and hydrologic parameters are again in accordance with each other (Tables 2 and 3). Amongst all boreholes, only T/W-3 exhibits lowest porosity (Table 3) representing the lithology predominantly composed of sand-gravel. High values of hydraulic parameters and hydrological parameters in this borehole are again in the support of each other (Tables 2 and 3).

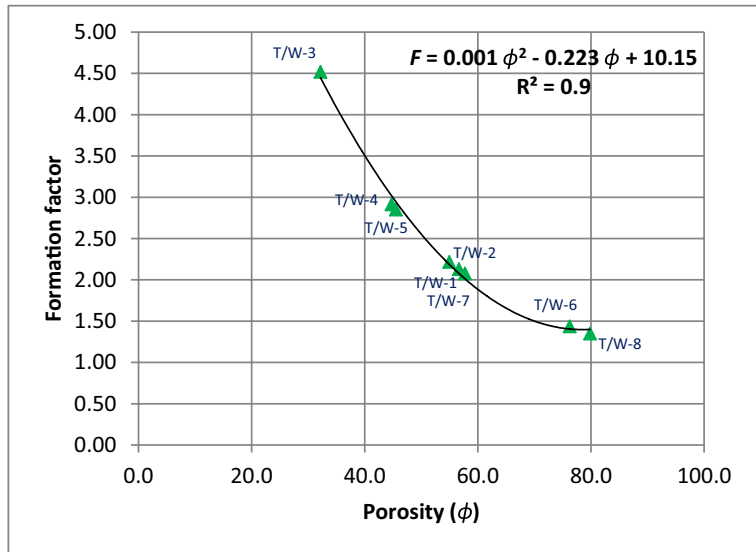
Relationship between formation factor and porosity

Groundwater resistivity (R_w), formation resistivity (R_f) and formation factor (F) further help to compute porosity. The formation factor varies with hydraulic conductivity and transmissivity as well and depends upon the grain size and formation resistivity. To observe the correlation of formation factor with porosity a cross-plot was established and presented in Fig. 6. In all boreholes of the study area, the porosity

Table 3 Estimated hydrological parameters

Well no.	R_f (Ω .m)	R_w (Ω .m)	ϕ	F	Lithology
T/W-1	29	14	57	2	Predominantly sand-gravel.
T/W-2	36	16	55	2	
T/W-3	44	10	32	4.5	
T/W-4	43	15	45	3	
T/W-5	32.5	11	45.5	3	
T/W-7	25	12	58	2	
T/W-8	11	8.4	80	1.3	
T/W-6	17	12	76	1.4	

Fig. 6 Regression curve of formation factor with porosity at well locations



ranges from maximum 80 % to minimum 32 % and shows an inverse relationship with formation factor (Table 3). The increase in porosity depicts the intercalation of fine sediments (clays/silts) within coarse sand-gravel sediments. Two boreholes T/W-6, 8 revealed highest porosity and lowest formation factor as mentioned in Table 3. Rest of the boreholes exhibited a relative increase in formation factor with decrease in porosity which depicts the coarsening of sediments i.e. sand-gravel (Table 3). Figure 6 describes a regression curve of second-order polynomial indicating a strong correlation between porosity

and formation factor with a regression coefficient $R^2=0.9$. The results of formation factor, groundwater resistivity, porosity and formation resistivity confirm the Worthington (1993) approach.

Relationship of formation factor with transmissivity and hydraulic conductivity

The cross-plots were developed showing the behaviour of formation factor with transmissivity (Fig. 7) and hydraulic conductivity (Fig. 8). By considering Figs. 7 and 8, it can be clearly decipher that the

Fig. 7 Regression curve of formation factor with transmissivity at well locations

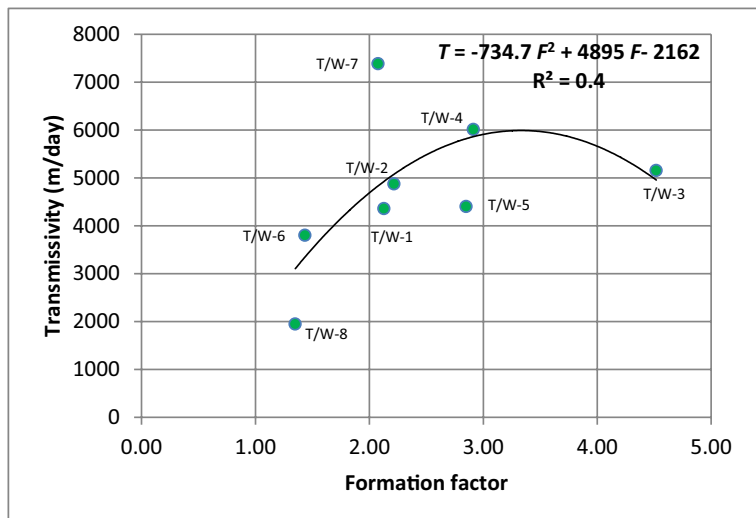
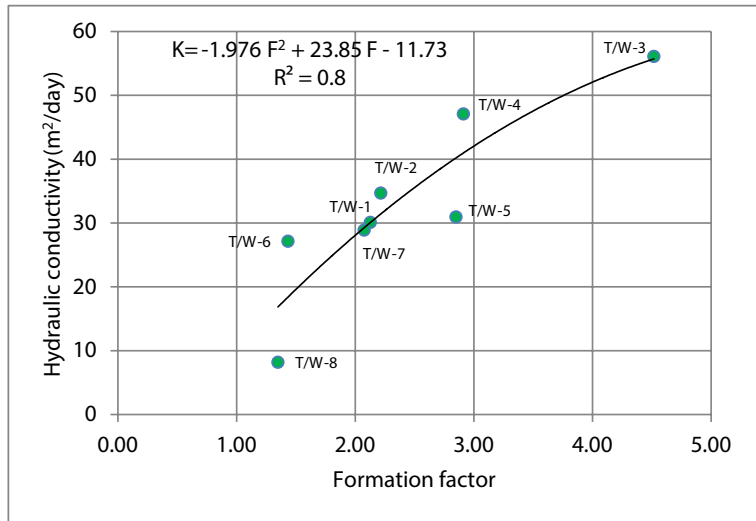


Fig. 8 Regression curve of formation factor with hydraulic conductivity at well locations



transmissivity and hydraulic conductivity increase with increase in formation factor. The regression curve of second-order polynomial indicates that the formation factor exists as a good correlation (regression coefficient $R^2=0.4$) with transmissivity (Fig. 7) and as a strong correlation (regression coefficient $R^2=0.8$) with hydraulic conductivity (Fig. 8). Two boreholes T/W-6, 8 respond with low transmissivity and low hydraulic conductivity which correspond to the lithology composed of intermixing of clay/silt as fine sediments within coarser ones of sand-gravel (Figs. 7, 8). All of other boreholes exhibit higher formation factors which represent higher values of transmissivity and hydraulic conductivity (Figs. 7, 8) representing the coarse alluvial package of sand-gravel.

Estimation of hydraulic parameters of aquifer using Dar-Zarrouk parameters

Pumping test is considered a primary tool to measure hydraulic parameters; however, it is a time taking, expensive and invasive procedure. Therefore, it has been observing a deficiency of pumping test data in different kinds of projects (Niwas & Singhal, 1981; Shevnin et al., 2006; Chandra et al., 2008; Hasan et al., 2017). To overcome this problem, the experts established geophysical technique as an alternate procedure for the estimation of hydraulic properties of an aquifer system as it is the best in terms of time and cost efficiency. Instead of pumping test, the geophysical technique is relatively quick, less expansive

and non invasive technique which can be used for the estimation of hydraulic parameters like transmissivity and hydraulic conductivity especially at those points where the pumping tests were not conducted.

The main Dar-Zarrouk (D-Z) parameters include longitudinal conductance, transverse resistance and longitudinal resistivity eventually lead to evaluate the hydraulic parameters at those locations where the well data was not available (Shevnin et al., 2006; Todd & Mays, 2013; Youssef, 2020; Hasan et al., 2020). The calculations of D-Z parameters were made by the following Eqs. 7, 8, 9.

$$S_c = h/\rho \tag{7}$$

$$T_r = \rho h \tag{8}$$

$$\rho_L = h/S_c \tag{9}$$

The ρ_L , T_r and S_c are expressed as longitudinal resistivity, transverse unit resistance and longitudinal unit conductance respectively and measured in Ω -m, Ω -m² and mho respectively. The symbols h and ρ represent averaged thickness and averaged electrical resistivity of subsurface saturated layers respectively and are expressed in meters and Ω -m respectively. Both of these parameters were extracted for each VES probe of the study area by using processed VES models. The D-Z parameters (S_c , T_r , ρ_L) were computed with the help of Eqs. (7, 8, 9) and specific ranges of these parameters were obtained depend upon the

hydro-geological, hydro-geophysical and boreholes data of the study area. Figures 9, 10 and 11 represent the distribution of D-Z parameters within the study area.

By analysing Figs. 9, 10 and 11, the longitudinal conductance inversely related to longitudinal resistivity and transverse resistance; however, the transverse resistance is directly related to longitudinal resistivity. In Fig. 9, the lower values of longitudinal conductance appear as higher values of transverse resistance and longitudinal resistivity in Fig. 10 and Fig. 11 respectively. Furthermore, in Fig. 10, the zones of lower values of transverse resistance appear similarly

as the zones of lower values of longitudinal resistivity in Fig. 11 and vice versa. In Fig. 9, the violet colour represents relatively low longitudinal conductance which correspond to coarser lithology of sand-gravel with minor or negligible intermixing of clay/silt as finer ones. The violet colour of low longitudinal conductance appears as high transverse resistance in Fig. 10 and indicates again coarseness of sediments in dominance. The colour shades except violet colour represent relatively higher longitudinal conductance (Fig. 9) that appear as low transverse resistance in Fig. 10 and low longitudinal resistivity in Fig. 11. These values reflect the saturated sand-gravel with

Fig. 9 Distribution of longitudinal conductance in the study area

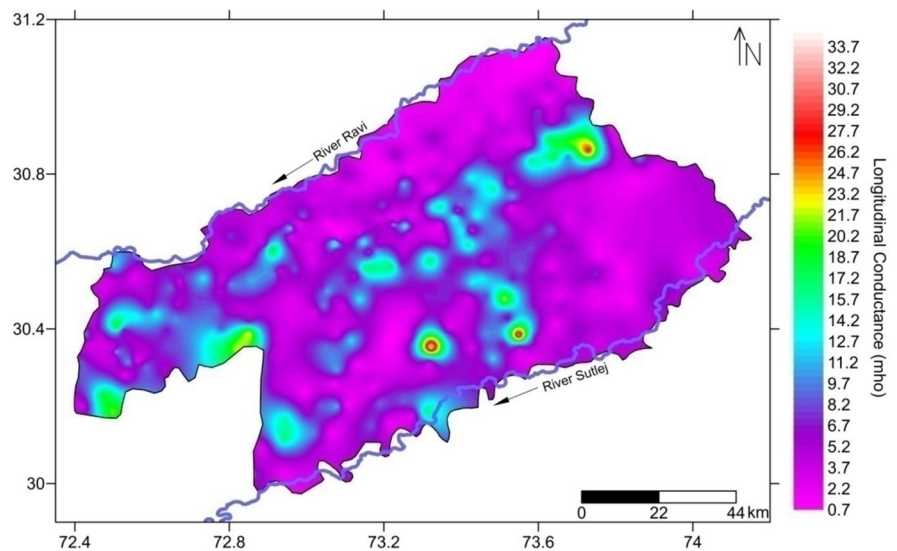


Fig. 10 Distribution of transverse resistance in the study area

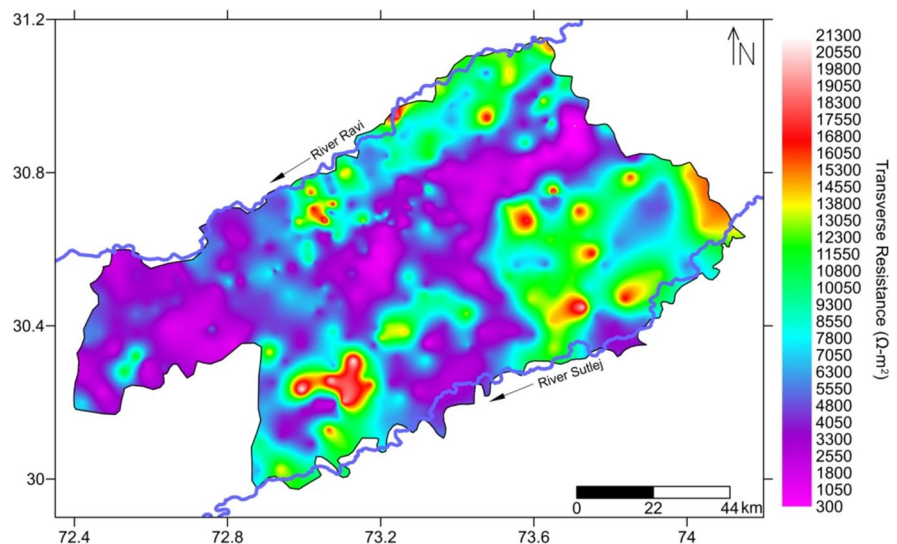
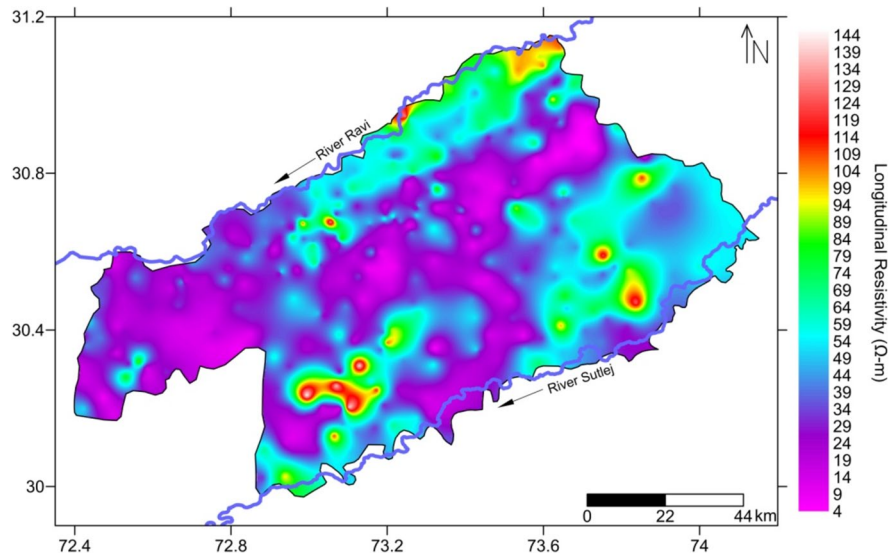


Fig. 11 Distribution of longitudinal resistivity in the study area



intermixing of fine sediments such as clay/silt. The rising values of longitudinal conductance shown in Fig. 9 relate to the fineness of sediments that may eventually lead to the salinity in aquifer.

To estimate hydraulic parameters for the whole study area, the empirical relationships between hydraulic and electrical parameters (D-Z parameters) were developed by using regression analysis. The D-Z parameters are indeed referred as electrical parameters which have been estimated already (Table 3), and hydraulic parameters such as hydraulic conductivity and transmissivity which have also been measured by using pumping

test analysis (Table 2). A relationship was developed between pumped transmissivity and transverse resistance (T_r) shown in Fig. 12, whilst the other relationship was developed between pumped hydraulic conductivity and longitudinal resistivity (ρ_L) shown in Fig. 13. Both of the established empirical relations are given in Eqs. 10, 11.

$$T_{DZ} = T_r(1.03) + 232.5 \tag{10}$$

$$K_{DZ} = \rho_L(1.11) - 0.33 \tag{11}$$

Fig. 12 Relationship of transverse resistance (electrical parameter) with pumped transmissivity (hydraulic parameter)

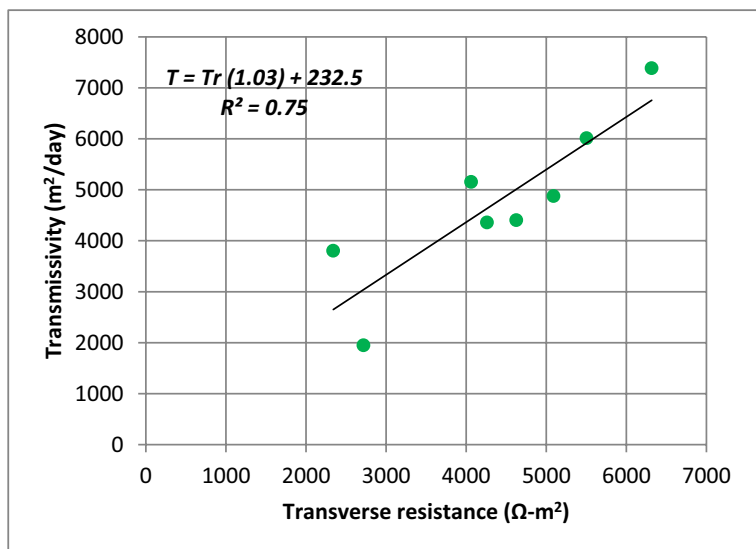
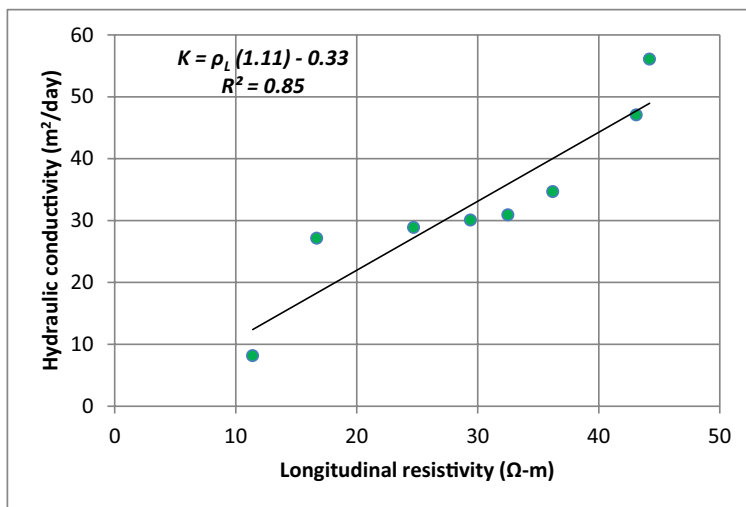


Fig. 13 Relationship of longitudinal resistivity (electrical parameter) with pumped hydraulic conductivity (hydraulic parameter)



whereas T_{DZ} represents transmissivity and K_{DZ} represents hydraulic conductivity measured in m^2/day and in m/day respectively and estimated by using D-Z parameters.

By understanding Figs. 12 and 13, a strong correlation can be observed between pumped transmissivity with transverse resistance and between pumped hydraulic conductivity with longitudinal resistivity having a regression coefficient 0.75 and 0.85 respectively. The hydraulic parameters such as T_{DZ} and K_{DZ} were evaluated for whole of the study area through D-Z parameters for each VES point by using Eq. (10, 11). Figures 14 and 15 represent

the distribution of hydraulic parameters (T_{DZ} , K_{DZ}) estimated through D-Z parameters.

Comparatively lowest potential of aquifer in the study area was evaluated as $T_{DZ} < 4000 m^2/day$ and $K_{DZ} \leq 27 m/day$, represented in Fig. 14 and Fig. 15, respectively, and shown with greyish colour. These lowest values are interpreted as coarse sediments of sand-gravel with other fine clays/silts. Relatively high aquifer potential in the study area was evaluated as $T_{DZ} > 4000 m^2/day$ and $K_{DZ} > 27$, represented in Fig. 14 and Fig. 15, respectively, and shown with rest of the greyish colour. These higher values represent the lithology of coarse content i.e. sand-gravel with minor or negligible silts/clays as fine content. It can

Fig. 14 2D map of estimated transmissivity using D-Z parameters

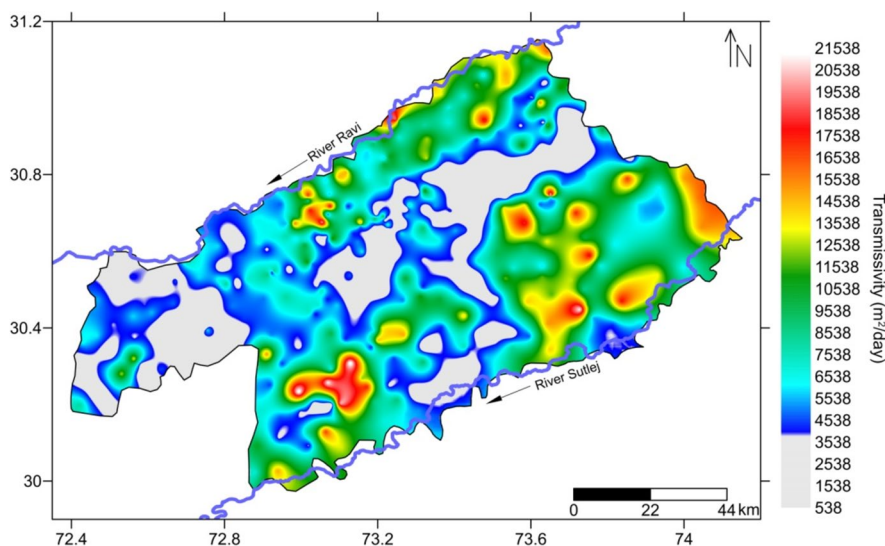
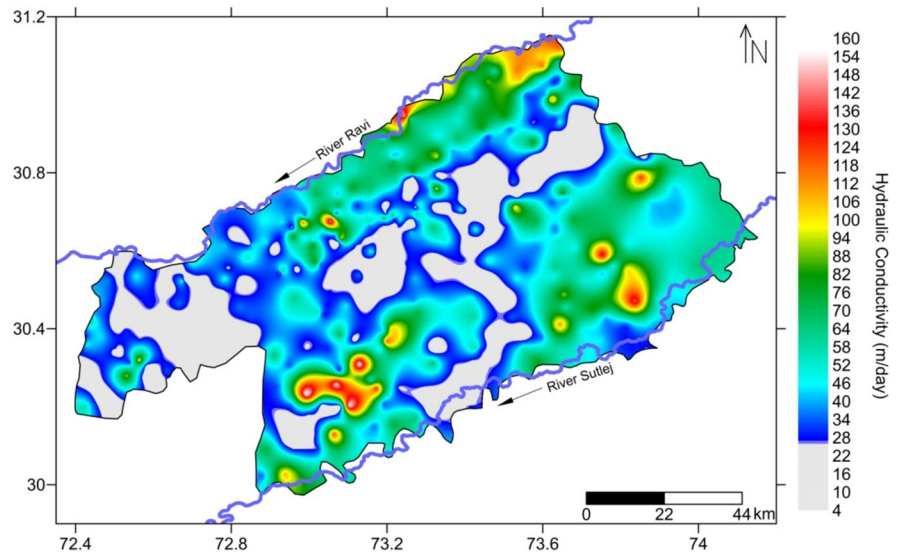


Fig. 15 2D map of estimated hydraulic conductivity using D-Z parameters



also be observed that high potential zones of aquifer (shown with rest of greyish colour) vastly cover the study area except some pockets (shown with greyish colour) of relatively low aquifer potential (Figs. 14 and 15).

A comparison between hydraulic parameters such as transmissivity and hydraulic conductivity computed through pumping tests and estimated through D-Z parameters is shown in Figs. 16 and 17. For the ease of understanding, the hydraulic parameters computed through pumping test analysis are termed as measured hydraulic parameters whilst estimated through D-Z parameters are termed as estimated hydraulic parameters (Figs. 16 and 17). These figures clearly indicate good matching of measured hydraulic

parameters with estimated hydraulic parameters. Conclusively, it is obvious that the estimated and measured hydraulic parameters are well fitting with each other. The blue dots represent the measured hydraulic parameters whilst the green dots represent estimated hydraulic parameters and both coloured dots are located closely with each other for each well showing very good comparison (Figs. 16 and 17).

Conclusions

An integral approach of pumping test analysis, results of VES and D-Z parameters were utilised to evaluate the aquifer parameters of Okara, Sahiwal and

Fig. 16 Comparison between measured and estimated transmissivity

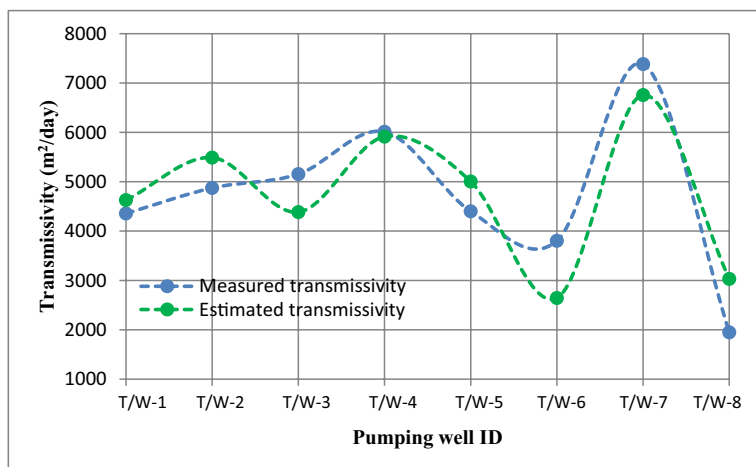
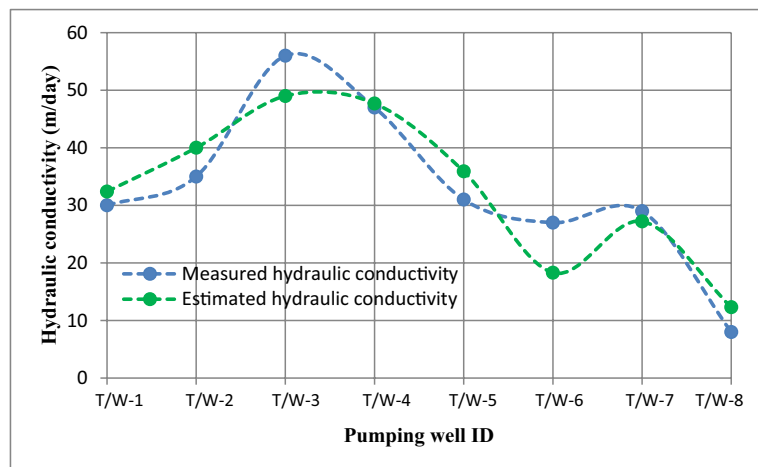


Fig. 17 Comparison between measured and estimated hydraulic conductivity



Pakpattan districts representing the central part of Bari Doab in Punjab province. The purpose of the study was to determine the aquifer characteristics and yield potential in the study area. This study will be beneficial to manage the groundwater resources and its sustainable supply for the future perspective. The results of geophysical investigations allied with boreholes lithological logs clearly decipher that the subsurface strata is of alluvium in nature and primarily comprised of intermixed lithology i.e. sand, gravel, silts, clays and some kankar inclusions. Electrical resistivity of the study area is interpreted as very high ($>230 \Omega\text{-m}$), high ($>100\text{--}230 \Omega\text{-m}$), medium ($>40\text{--}100 \Omega\text{-m}$), low ($20\text{--}40 \Omega\text{-m}$) and very low ($<20 \Omega\text{-m}$).

The hydraulic and hydrologic parameters of aquifer in the study area show some variability depends upon the deposition style and hydrogeological conditions. Out of eight wells, two wells T/W-6, 8 indicate comparatively high porosity with lower values of hydraulic conductivity, transmissivity and formation factor. The interpreted lithology is sand-gravel with intermixing of clays/silts as fine sediments. Remaining six wells represent relatively low porosity and higher values of hydraulic conductivity, transmissivity and formation factor. Lithology of such combination of values is interpreted as predominantly intermixed coarse sediments of sand-gravel with negligible/minor fine content of clays/silts. Regression curve appeared as good correlation of formation factor with transmissivity and strong correlation of formation factor with hydraulic conductivity. The

D-Z parameters were further used for the estimation of hydraulic parameters (hydraulic conductivity and transmissivity) to whole of the study area. The strong correlations were appeared between D-Z parameters and pumped hydraulic parameters through regression curves. The empirical relations of these regression curves further led to the estimation of hydraulic parameters (hydraulic conductivity and transmissivity) to the entire study area. A large part of the study area represents the zones of comparatively higher aquifer potential ($T_{DZ} >4000 \text{ m}^2/\text{day}$ and $K_{DZ} >27 \text{ m/day}$). Lithology of these zones is interpreted as mainly coarser sediments of sand-gravel with minor/negligible clays/silts as fine sediments. Rest of the study area holds the aquifer zones of relatively low potential ($T_{DZ} <4000 \text{ m}^2/\text{day}$ and K_{DZ} by $\leq 27 \text{ m/day}$). Lithology of these zones is interpreted as sand-gravel with fine contents of clays/silts which may cause some retardation in aquifer yield within these zones.

Acknowledgements The authors will be grateful for the technical suggestions and valuable comments from editors and anonymous reviewers to improve the manuscript. WAPDA, PCRWR, Terra Technology, Diviners and Bitman, Geo-Dynamics and Geoscience Associates are also highly acknowledged for providing dataset used in the research work. The present study is related to Ph.D. research work of author Shahbaz Muhammad.

Author contributions The main author Shahbaz Muhammad is a PhD student and wrote the text of manuscript along with analysis and developing of models/figures. The other two authors Pervez Khalid and Muhammad Irfan Ehsan are his supervisors. They reviewed and supervised whole of the research work.

Data availability The data used in this manuscript is available on demand.

Declarations

All authors have read, understood and have complied as applicable with the statement on 'Ethical responsibilities of Authors' as found in the Instructions for Authors.

Ethics approval and consent to participate This article does not contain any studies with animals and human subjects. The authors confirm that all the research meets ethical guidelines and adheres to the legal requirements of the study region. Moreover, this manuscript has not been published previously in any form (partially or in full) and is not under consideration for publication elsewhere.

Consent for publication The authors declare that this manuscript does not contain any individual person's data and material in any form.

Conflict of interest The authors declare no competing interests.

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