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Groundwater Resources and Quality in the Lai Catchment: A Geophysical, Hydrochemical, and Geological integration in twin cities of Pakistan

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Abstract

The population residing in the Lai River Basin has been subjected to water management issues since long. The area is facing a surge in population due to migration of people from different cities into the twin cities of Rawalpindi and Islamabad. The present study integrated geophysical, geological and hydrochemical datasets to identify the subsurface aquifer system, delineate the source of contamination and identify the nature and type of contamination. The geophysical data comprised of 17 Audio Magneto Telluric (AMT) profiles coupled with 30 borehole data sets and 60 water samples. The geophysical data identified numerous shallow and deep aquifer system along with paleo channels. The lithologies were classified into high, low and intermediate resistivity zones. It was observed that higher resistivity zones were associated with surficial clay and silt deposits whereas low values were attributed to presence of contaminants that were seeped into shallow paleochannels. The geological data revealed presence of sandy clay, gravel as shallow aquifer system whereas at greater depth confined aquifer was encountered comprising of gravel and sand. It was further observed that the slope has greater influence on localized stream deposition. Results of hydrochemical analysis revealed the dominance of Ca^{2+} and Na^{+}, whereas HCO_3- followed by SO_4^{2-}, respectively. Based on this chemical composition, the river system had its origin mainly in major carbonate weathering and minor silicate dissolution. The presence of higher concentrations of these ions is attributed to the discharge of untreated sewage, industrial effluents and domestic waste into the Lai River. During groundwater recharge these contaminants infiltrate into the aquifers and pose significant threat to human and environmental health risk. This process in more concentrated in densely populated regions of Rawalpindi which lies in middle or lower reaches of Lai River Basin (LRB) area. The present research critically analysis the subsurface water bearing bodies and threats that are faced by those due to Lai River.

Keywords: Aquifer, Geophysical, Geological, Hydrochemical, Lithological, Paleo-channels, Twin cities.

1. Introduction

Water is a fundamental resource for human survival and development. According to the United Nations, approximately 2.2 billion people worldwide lack access to safe drinking water, and nearly half of the global population lives in areas facing water scarcity (Pant, 2018). This critical issue is aggravated by factors such as climate change, population growth, and unsustainable water management practices (Nisar et al., 2024). The deterioration of surface water quality due to pollution and over-extraction has led to a shift towards groundwater as a primary source of water supply (Martínez-Santos, 2017). The subsurface aquifer system is complex deposition of permeable lithologies that store the groundwater. Understanding these depositions is crucial for communities that are dependent on groundwater for livelihood. As the demand for freshwater continues to rise, understanding the dynamics of aquifers becomes increasingly important for ensuring sustainable water resources (Khan et al., 2024). Pakistan ranks among the top ten countries affected by climate change is rushing towards water scarcity (Iqbal, 2020). The densely populated cities face the load of population migration from rural areas thus severely inflicting water resources. It is need of time to understand the aquifer dynamics and how water quality and quantity coupled with geological deposition works for sustainable water management (Alabi et al., 2022).

Geophysical, geological techniques and hydrochemical, have proven to be invaluable tools in exploring aquifer systems and assessing their dynamics (Nisar et al., 2024; Khan et al., 2024; Daud et al., 2024). Geophysical methods, such as electrical resistivity, Audio magneto telluric (AMT), Frequency Selection Method (FSM) in MT and seismic surveys, can provide information about the subsurface structure, including the location and extent of aquifers (Alaran, 2020). AMT being a passive geophysical method utilizes the naturally occurring electromagnetic fields that permeate the Earth's surface. These fields are generated by various sources on and below the surface of the earth. AMT instruments measure the variations in both the electric and magnetic fields at specific locations. These measurements are recorded over a range of frequencies, typically from a few hertz to several thousand hertz. This method is economical and has now been widely used for subsurface paleochannels detection and contaminant plume identification (Adagunodo et al., 2023; Farzamian et al., 2019; Lu et al., 2023). Hydrochemical analysis allows for the assessment of water quality, identifying potential contaminants, and determining the sources of groundwater recharge. Geological investigations help in understanding the geological framework and the processes that influence aquifer formation and behavior. By integrating these techniques, researchers can gain a comprehensive understanding of aquifer characteristics, including their hydraulic properties, recharge and discharge rates, and vulnerability to contamination.

The study area is Lai River Basin area that expands from Islamabad to Rawalpindi (Fig. 1). The head water region for Lai River lies north of Islamabad towards Margalla hills whereas it finally merges into River Soan near Soan Ada Rawalpindi. With increase in urbanization, the catchment has been extensively flooded with migrants from different cities across Pakistan resulting in urban sprawl that is severely impacting the quality and quantity of aquifer in the area. The present study aims to assess this impact and thus provide a clear picture about the aquifer dynamics of the Lai River Basin area by integrating geophysical, geological and hydrochemical data sets acquired in the area. The generated cross-sections using geological datasets coupled with AMT profiles will brief about aquifer distribution coupled with any contamination present in aquifer. The hydrochemical analysis after informing about water quality will also act as validation tool to geophysical and geological datasets. The present study will be helpful for town planners and water managers as it provides an insight into water distribution coupled with quality.

1.1 Study Area

The Islamabad-Rawalpindi metropolitan region is in the Rawalpindi and Islamabad District, between Lat 33°30′ and 33°50′ N. and long 72°45′ and 73°30′ E. Rawalpindi and Islamabad experience a continental climate characterized by hot, dry summers and cold, foggy winters. Average annual temperatures range from 10°C in January to 39°C in July. Most of the annual precipitation, averaging around 550-600 millimeters (22-24 inches) falls during the monsoon season from July to September. Winters are generally dry with occasional snowfall.

The topography of the metropolitan region of Islamabad Rawalpindi comprises of flat plains and towering mountains, with a total elevation difference exceeding 1,175 meters (m). There are three physiographic zones that commonly extend in an east-northeast direction. The northern section of the metropolitan area is situated in the hilly landscape of the Margalla Hills, which are part of the lesser Himalayas (Fig. 2). This region also encompasses the Hazara and Kala Chitta Ranges. The Margalla Hills, located near Islamabad, have an elevation of 1,600 m (Ahmed et al., 2023) (Fig. 1). They are composed of many ridges made up of limestones and shales from the Jurassic to Eocene periods (Fig. 2). These rocks have undergone intricate thrusting, folding, and overturning processes. The Rawalpindi Group's folded sandstones and shales form most of the southward-sloping piedmont bench located south of the Margalla Hills (Miocene age). The piedmont region contains several peaks and valleys that have been covered by alluvial deposits from the hills, despite its usually low topography, which is characterized by vast plains of wind-blown silt (Ali, 2011). The interbedded sandy silt and limestone gravel that cover buried sandstone ridges often have a thickness of more than 200 m in certain places (Ali, 2011). These deposits have been split and subsequently buried beneath a layer of eolian loess and reworked silt that has a thickness of more than 40 m in certain places. Since gravel is the main ground-water aquifer and because it forms most construction foundations, gravel and loess are particularly significant to environmental geology. Plains of dense, readily eroded loess are widely divided west of Rawalpindi (Sheikh et al., 2008). On the north limb of the syncline north of the Soan River, the beds dip sharply, whereas on the south limb, the beds dip more gently. Stretching 150 km south-west, the Potwar Plateau has the piedmont bench and Soan valley as its northern boundary (Sheikh et al., 2008).

The Soan and Korang Rivers are the principal streams that drain the region. Their main tributaries are the Ling River, which flows in north-west direction into the Soan; Gumrah Kas, which flows westward into the Kurang from the area between the Korang and the Soan; and Lai River, which flows southward into the Soan from the mountain tops and urban areas (Sheikh et al., 2008). The Korang and Soan rivers are impounded at Rawal and Simli Dams, respectively, to provide water to the metropolitan area. Ground water is principally sourced from Quaternary alluvial gravels through a network of municipal and private wells reaching depths of up to 200 m (Fig. 2). The Lai River delivers liquid garbage from Rawalpindi, which pollutes the Soan River below its confluence. Solid waste disposal poses a danger to the quality of groundwater sources.

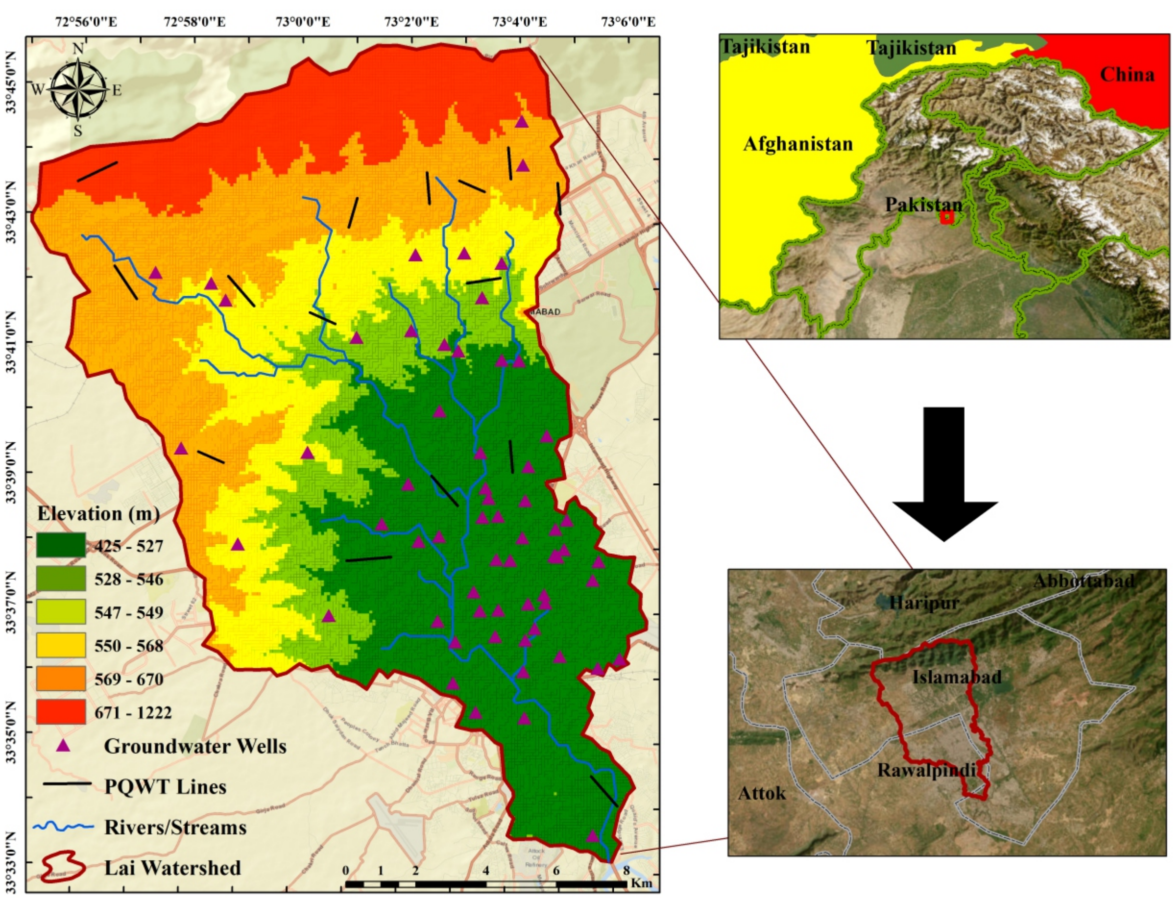

Fig. 1. Study area map showing elevation distribution along with sampling locations for PQWT, Groundwater wells for lithology and hydrochemical data.

2. Methodology

The study utilizes geophysical, geological and hydrochemical datasets, the acquisition methodology for each data set is as follows:

2.1 Geophysical data acquisition

GPS, measuring tapes, hammers, electrodes, connecting cables, host machines (PQWT-TC 500 and S 300) were employed for geophysical dataset. Borehole lithological log and water chemistry data were utilized to interpret the geophysical dataset (Fig. 3). Local geology information, reconnaissance survey and literature search were conducted prior to collecting geophysical data.

The actual conditions around the study area were also taken into consideration prior to selecting appropriate geophysical procedures used on the actual testing sites. Seventeen PQWT profiles were acquired having variable length from 5 m to 80 m horizontal distance. These groundwater detectors have the capability to image the subsurface up to 150~500 m depth. 1~5 m inter-data point interval was used between MN probes to acquire geophysical data. The borehole was scanned with a 1-m resolution, while the surrounding area was imaged at a coarser resolution of 2-5 m to assess the local geological conditions. This water detector equipment is highly sensitive and use EM field as source, which measures the potential difference between MN terminals on the testing site (Adagunodo et al., 2023). The natural field electromagnetic data obtained by the PQWT was processed. This detector has the capability to process the data through automatic built-in processing software. The software analyses analog-to-digital data to generate electrical potential difference curves at various frequencies and ultimately provide output map in the form of a 2D cross-section profile. A low convergence of these curves indicates a porous medium filled with fluid or a weathered rock formation, while a high divergence suggests a highly resistive, compacted, or hard rock terrain. The amplitude of the electromagnetic field decreases as it penetrates deeper below the surface, resulting in lower frequencies and decreased conductivity as well as greater penetration depth (Yulong et al., 2023). The penetration depth of natural electromagnetic survey is depended upon the subsurface material conductivity and the frequency of the electromagnetic field. The amplitude of the electromagnetic field decreases as it penetrates deeper below the surface. Only four of the seventeen (17) PQWT profiles that were collected were included in this paper.

2.2 Geological data

The lithological data of thirty (30) bores were acquired from different governmental and nongovernmental organizations. The sample of bore log data was converted into lithology map and then cross-sections were generated using GMS software (Bayat et al., 2020). Total eight (08) cross-sections were generated out of which four cross-sections were north south trending whereas three cross-sections were east west trending. The cross-sections were integrated to generate a fence diagram.

2.3 Hydrochemical data acquisition

A total of sixty groundwater samples were collected for this study in 2023 during pre-monsoon time from various locations near the Lai River. Before collecting the freshwater samples from each well, the bottles were rinsed three times using the same groundwater. The depth of each well was noted. The samples were placed in 50 ml pre-washed ultra-clean high-density polyethylene bottles after being filtered through 0.45 µm millipore nitrocellulose filter sheets to remove suspended particles. The samples were kept at 4 °C for up to 30 days following sample collection, or until the laboratory analyses were completed. Using a multi-parameter measuring instrument (HI-98129, HANNA, Romania), the pH, electrical conductivity (EC), and total dissolved solids (TDS) were determined on the spot. Furthermore, the laboratory analyses were carried out on the 2.3water samples at Bahria University Islamabad. The concentrations of the major anions (Cl^-, NO_3^-, and SO_4^{2-}) and cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were measured using ion chromatography (ICS-2500, Thermo Fisher Scientific, Waltham, MA, USA, LOD = 0.01 mgL−1) and inductively coupled plasma optical emission spectrometry (ICP-OES, Optima 5300 DV, PerkinElmer, Waltham, MA, USA, limit of detection (LOD) = 0.01 mgL−1). The titration method was used to determine the alkalinity as HCO3-. The national standard solutions acquired from the German Certified Reference Material Centre were used to prepare the external standards for the major cations and anions.

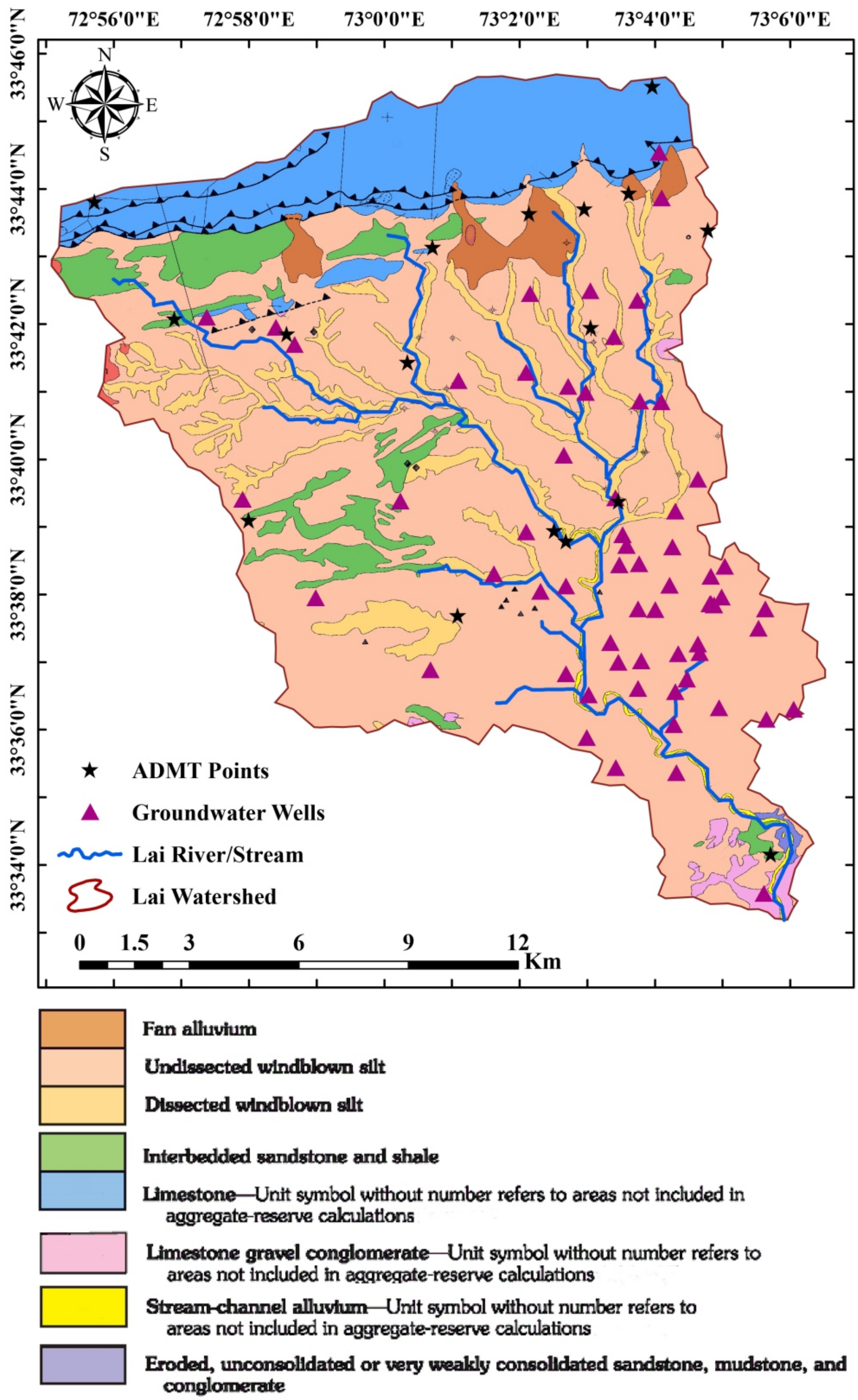

Fig. 2. Showing the geological distribution of different rock types in study area (map retraced from following source: https://gsp.gov.pk/wp-content/uploads/2024/02/Geological-Map-of-Islamabad-min.pdf)

Fig. 3. Water sample and geophysical data acquisition.

3. Results and Discussion

3.1 Geophysical

The PQWT profiles were analyzed to determine the location of paleochannels, aquifer depth, and lithological characterization. Figure 4a shows the location of the PQWT profile 8 which is extended 22 m (m) east-west across the study area with 11 data points spaced 2 m apart. A convergence of electrical potential difference curves was observed between 10 and 14 m (points 5 to 7) indicating presence of saturated lithologies. Red zones indicate high resistance (> 0.71 mV), yellow and green zones indicate intermediate resistance (0.36-0.71 mV), and blue zones indicate low resistance (0.0-0.36 mV). The profile was acquired perpendicular to the visible paleo channel, the high resistance red zone is interpreted as sandstone with interbedded shale formation and blue is interpreted as paleochannel comprising of gravel and sand.

The intermediate resistance values are interpreted as fragments of conglomerates, siltstone and claystone. The high resistance values (> 0.71 mV) are interpreted as sandstone with interbedded shale (Muree Formation) suggesting subsurface with limited groundwater. Conversely, the blue zone indicates paleo channel attributed to the potential interaction point between surface and subsurface water, allowing for easier infiltration of surface water into deeper layers (Kresse et al., 2011). The derived results of borehole log data and water chemistry indicate presence of potential contamination in this paleochannel. The groundwater water resource from shallow aquifer system in the proximity of Lai River are discouraged as there is high probability that the harmful contaminants directly enter into aquifer system under the influence of gravitational force (Nisar et al., 2024). The PQWT profile 13 was acquired near the Nala Lie catchment, this profile covers a length of 14 m and 7 data points were acquired with an interval of 2 m, the orientation of this profile was northeast to southwest (Fig. 4b). Yellow, green, and blue zones indicate moderate resistance (0.25-0.71 mV), low resistance (0.0-0.25 mV), while red zones imply high resistance (> 0.71 mV). It is anticipated that the upper 10 m cross-section is a surficial deposit made up of clayey material (Alabi et al., 2022). The red zone of high resistance is understood to represent a sandstone formation, whereas the blue zone represents aquifer systems that are present at varying depths. Two convergences of electrical potential difference are observed at a distance 4 and 10 m laterally. These convergences are interpreted as two confined aquifers system present at depth of 120 m and 240 m. The top high resistive zones imply that there is a less chance of pollutants percolating vertically under the influence of gravity. In general, the pollutants travel through the geological formation in both vertical and lateral direction until it encounters the nearest aquifer system (Niaz et al., 2017; Nisar et al., 2018; Kingston et al., 2022). Therefore, surface geological conditions are essential to the contamination's infiltration. Furthermore, the vertical fractures and near surface paleochannel serve dual purpose, it helps in recharging the aquifer but also facilitates the direct infiltration of contaminants into the aquifer system (Nisar et al., 2018; Nisar et al., 2021).

The PQWT profile 5 is oriented in the north-south direction (Fig. 4c). This profile covers 10 m horizontal distance with each electrode spaced 1m apart. This profile can be divided into three zones. Yellow, green, and blue indicating moderate resistance (0.11-0.27 mV), low resistance (0.0-0.11 mV), while red zones imply high resistance (> 0.27 mV). The low resistance zone can be further divided into (0.0-0.02 mV) and (0.02-0.11 mV). Figure 4c depicts high conductivity on (points 1-5), indicating probable contaminated zone, that has reduced the overall conductivity of the layer down to a depth of 30m. The first five points are predominantly saturated with contaminants. The convergence points on the profile map indicate areas with the lowest resistivity, suggesting a medium with high water content (porous formation) (Awan, 2019; Vinoth Kingston et al., 2022; Adagunodo et al., 2023; Lu et al., 2023). Yellow and green zone is interpreted as conglomerate and fragments of sandstone, siltstone and claystone. The high resistive values indicate the sandstone with shale formation (Murree Formation). The surface geological conditions and electrical potential difference values suggest that leachate infiltration is occurring in the topsoil attributed to dumpsites that lie in the vicinity of Lai River (Sheikh, 2008).

Profile 10 (Fig. 4d) was acquired in the foothills of Margalla hills, covering length of 42 m with 21 data points, spaced 2 m apart, oriented east-west. The profile revealed electrical potential difference curve convergences at points 12 and 17, interpreted as vertical faults associated with the local tectonics. These blind faults are extending from 15 to 135 m. It appears from the electrical potential difference measurements that groundwater is not present in these faults. However, they could potentially enhance groundwater recharge in the downstream area (Awan et al., 2019; Khan et al., 2024). The shallow layer at the surface is likely overburden material consisting of sandy silt, clay, soil, and weathered rock fragment. The thickest overburden material was found in the western part of the profile (Fig. 4d), extending to a depth of 17 m. The overburden thickness gradually decreases towards the eastern end of the profile.

3.2 Borehole datasets

Figure 5 depicts the cross-sections oriented in east-west direction in the Lai catchment. These cross-sections are generated by combining data of different boreholes in the area (Nisar et al., 2021). The lithologies present in the cross-sections depict episodic deposition with clay as the topmost layer towards the north and centre of the basin, further moving downstream the clay is replaced by silt as top layer. The deposition of these finer lithologies is associated with Lai flooding causing episodic deposition of clay and silt as topmost layer. The second dominant layer spread throughout the area is clayey sand that indicated the decrease in stream velocity followed by a flooding event resulting in deposition of coarser lithology mixed with finer lithology (Nisar et al., 2024). The third major lithology throughout the area is sand followed by sand gravel beds this deposition is associated with decrease in stream velocity resulting in deposition of courser sediments. Interestingly patches of gravel appear at shallow depths that can be termed as paleo channels often deposited by the river. These paleo channels often serve as aquitard and at some places, additionally these channels act as carriers of surficial contaminants to the local shallow aquifer system (Nisar et al., 2018). Figure 6 depicts the cross-sections oriented in north-south direction.

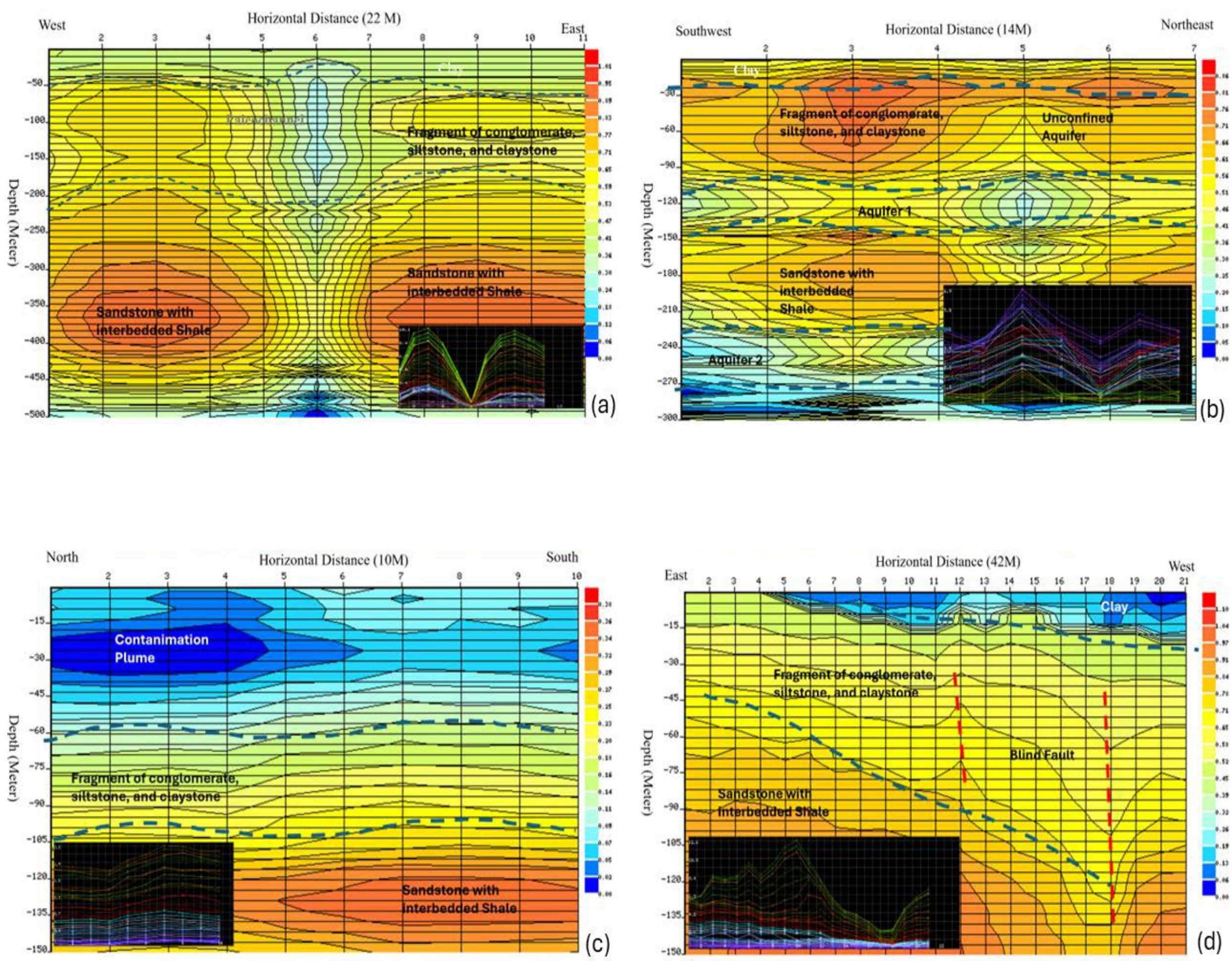

Fig. 4. Showing AMT profiles acquired at different locations

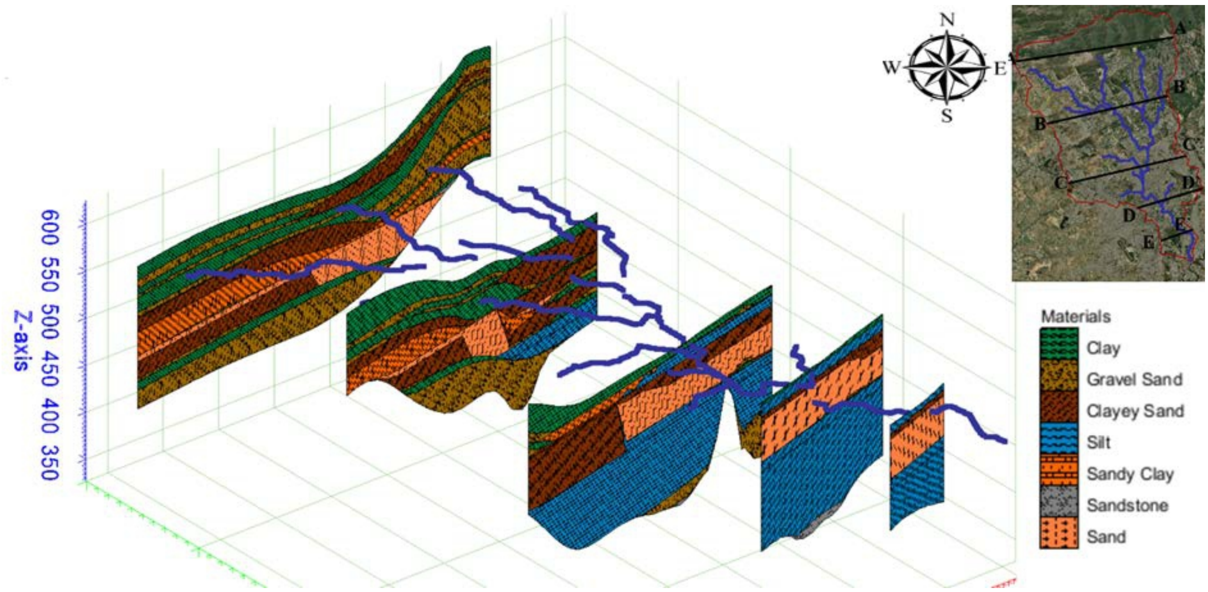

Fig. 5. Showing the cross-sections that were East-west trending.

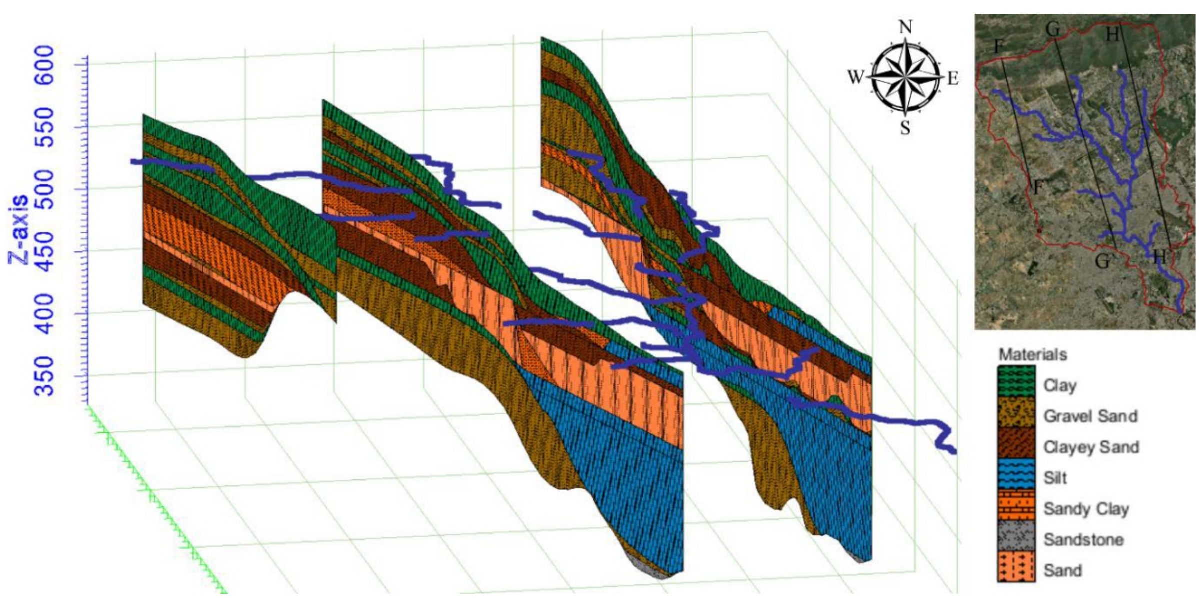

Fig. 6. Showing the cross-sections that were east-west trending.

This figure gives a comprehensive picture of clay beds that are uniformly distributed thought the north and central parts of the Lai River Basin but as we move towards the southern part of the area the reduction in stream velocity results in deposition of the silt. The other two lithologies are also justified by the east-west cross-section with coarser deposition associated with high stream velocity coupled with higher elevation, as the Lai River moves towards center and further south of the area the decrease in slope (Fig. 1) results in finer sediment deposition.

Figure 7 represents the combination of both east-west, north-south trending cross-sections in the form of fence diagram. The figure overall depicts the dominance of surficial clay towards the north and central part of the study area followed by the mixture of clay and sand with further deposition of sand beds attributed to the episodes of high and low stream velocities.

The fence diagram furthermore sheds light on the local aquifer system of the area, the sandy clay at shallow level serves as an unconfined aquifer system with limited permeability ought to supply less quantity of water. As the depth increases a confined aquifer system situated in mixture of gravel and sand often covered with silt and clay is found. Towards the north and centre mixture of clay and sand serves as a low yielding unconfined aquifer system, furthermore with increase in depth the sand beds intermixed with gravel serve as confined aquifer system. In addition to these several aquitards are found in the area, these gravels beds embed in clays serve as path of contaminants from stream to shallow aquifer system. Similar results are observed in geophysical and geochemical data sets (Dil et al., 2008; Diop et al., 2015; Niaz et al., 2017; Singh et al., 2015a).

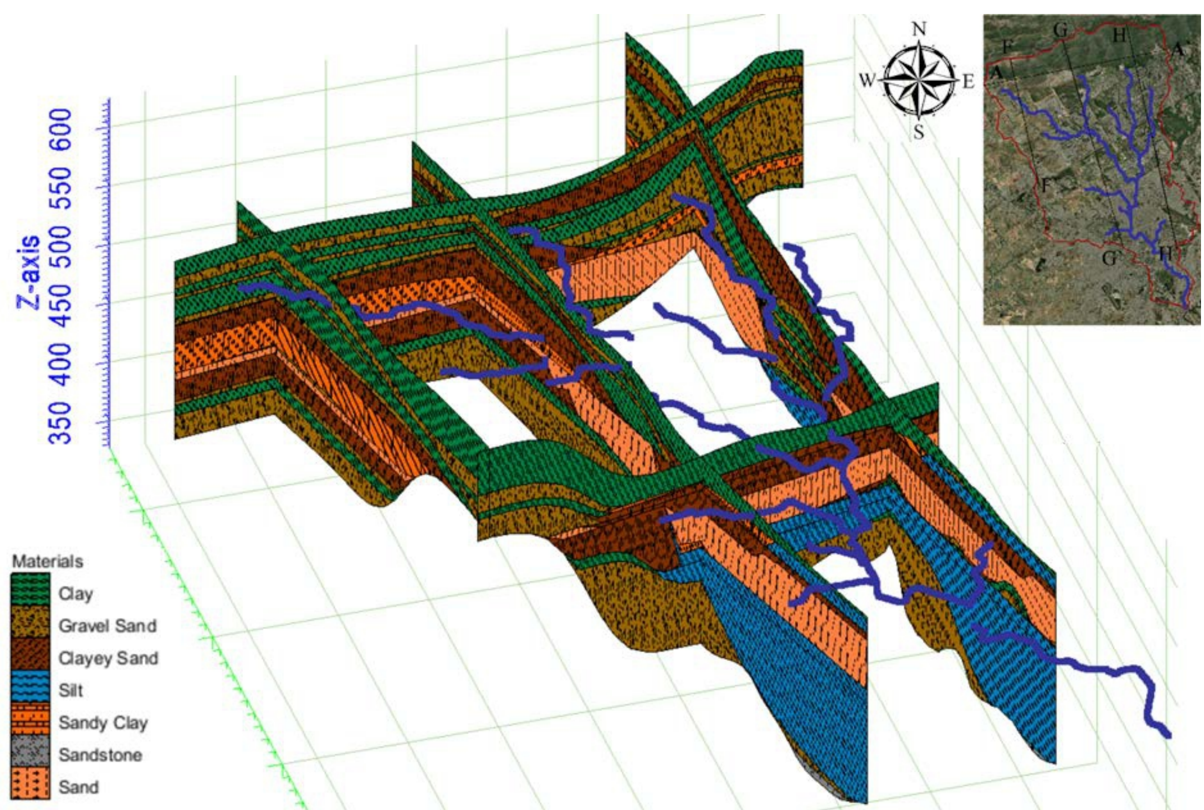

Fig. 7. Fence Diagram depicting the deposition of lithologies in the Lai River Basin area.

3.3 Hydrochemical Analysis

Table 1. summarizes the hydrochemical features of Lai River Basin area (LRB). The water was weakly alkaline in the LRB, which showed an average pH of 7.25 ± 0.24 (Table 1). The waters of the Himalayan River Basins and associated localized streams are known to be mildly alkaline (Qaiser et al., 2023; Verplanck et al., 2008). The EC and TDS measurements indicate low to moderate level of contaminations mainly due to human activities, alongside high mineralization activities within this study area suggesting poorly managed environment. To analyze water quality, identified bicarbonate (HCO_3^-), Cl^- and SO_4^{2-} are the most prominent discriminators representing natural environment of aquatic ecosystems where human activities may leave an imprint announced through different indicators. High (80mg/L) calcium (Ca^{2+}) and sulphate (SO_4^{2-}) 38.03 mg/L concentrations reflect carbonates dissolution is likely to be mainly mediated by organic breakdown processes in the LRB (Diop et al., 2015; Egbi et al., 2019; Mapoma et al., 2017; Zheng and Liu, 2009).

It became apparent that, for cations and anions, respectively, $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ and $Ca^{2+} > Mg^{2+} > N^{a+} > K^+$ constituted the overall dominancy order of major ions in the LRB. With a share of 56.84%, Ca^{2+} was the most abundant cation, followed by Na^+ (22.23%). The combined contribution of these two major cations amounts to 79.07% of the total cationic budget. The remaining combined cationic budget is made up of Mg^{2+} and K^+ at 20.93%, with Mg^{2+} making up a significantly larger portion than K^+. In contrast to carbonate weathering, silicate weathering is notably more prevalent in the middle and lower region of LRB. Given that most of the aquifers in this area are unconfined, this could be caused by the high dissolution of west water from the Lai River in the groundwater during recharge. Nevertheless, HCO_3^- accounted for 76.58% of the total anionic budget in the river basin, making it the dominant anion. SO_4^{2-} (13.89%), Cl^- (6.80%), and NO_3^- (2.73%) came next.

Most the ion's "mean" concentrations were quite identical to those found in the groundwater of Lahore, Pakistan (Jalees et al., 2021; Kresse et al., 2012; Singh et al., 2015b), and the Brahmaputra River Basin in India (Library et al., 2012; Mahanta et al., 2015). It was found that most hydrochemical variables had low concentrations in the LRB when comparing the current study to the WHO permissible limit. This suggests that the groundwater in Lai had moderate levels of anthropogenic contamination (Table 1). The hydro-geochemistry of the LRB is regulated by an ionic dissolution mechanism that is triggered by anthropogenic activity, as indicated by the relatively higher concentrations of Ca^{2+}, Na^+, Mg^{2+}, SO_4^{2-}, and HCO_3^- compared to mean values in other river basins in Pakistan. These concentrations indicate that the carbonate and silicate dissolution dominates in the presence of dominant anions. The sedimentary geology and mature soil rich in organic matter in the Lai River Basin area create a semi-arid environment where silicate weathering is not predominant (Gaillardet et al., 1999; Jordán et al., 2004; Si et al., 2009).

3.4 Spatial variations of hydrochemistry

To accurately illustrate the spatial variations of the LRB's hydrochemical attributes, the 60 groundwater well parameters and their locations are listed in Figure 8. In general, the south-east and south-west portions of the basin had comparatively higher TDS and EC levels. The WHO permissible limit (Figure 8 A and B) is nearly two times higher than the EC and TDS values recorded in some of the sampling points (GW-21: EC=1474 μS/cm and TDS=884 mg/L), suggesting the possibility of anthropogenic interference, particularly in the central urban areas of the Lai River Basin area. The pH levels in the LRB were also found to exhibit spatial disparities. As an illustration of the groundwater alkaline character of the underlying basin geology, the highest pH was found in the vicinity of the head tributaries of LRB, such as GW-10, GW-12, GW-13, GW-19, GW-21, and GW-26 (values between pH=7.87 – 7.60). Comparably, the Ca2+ and Na+ spatial patterns showed that the core urban areas of the river basin—the area between IJP Road and Noor Khan Air Base—have relatively high values. The majority of the 18 samples for Ca^{2+}, which have high values ranging from 89 to 128 mg/L, are located in the old Rawalpindi, where the Lai River has turned into a dump for all types of waste (sewage, industrial, and domestic) (Figure 8C). Similarly, a few samples from different sectors of Islamabad (E-11, F-11, I-10 etc.) showed higher concentrations of Na+ at the same location where Ca2+ is high. F-7. G-6, G-11, G-10, and G-5) exhibit low Na+ concentrations. This validates our analysis, which suggested that the high Na+ dissolution could be caused by organic decomposition mixing through Lai recharge in the groundwater. Along with a few layers of silicate-dominant lithology, the dominance of Ca2+ and Na+ ions throughout the basin defined the carbonate-dominant lithology, which is further corroborated by literature from the Himalayan River Basins, particularly in the Indo-Pakistan region (Nisar et al., 2024; Qureshi et al., 2010).

Table 1: The hydrochemical compositions of groundwater samples in Pakistan's Lai River Basin (LRB) are summarized statistically, and their results are compared with those of other groundwater hydrochemistry and the WHO guideline values.

Groundwater (GW)	Parameter	pH	EC	TDS	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Reference
Lai Groundwater	Mean	7.25	741.68	414.16	80.10	25.02	2.15	28.97	20.73	5.82	38.03	257.16	This study
	SD	0.24	211.55	130.14	17.86	11.93	2.28	26.37	16.39	8.94	37.31	91.13	
	Min	6.85	342.00	193.00	40.00	6.00	0.55	2.51	1.40	0.50	8.19	24.00	
	Max	7.87	1474.00	884.00	128.00	61.00	10.25	140.00	74.00	39.44	170.00	455.00	
Khanewal GW, Pakistan		7.79	783.00	507.28	52	20.78	6.42	90.87	46.78	0.3	117.5	243	Iqbal et al., 2023
Lahore GW, Pakistan		7.50	417.54	497.15	51.2	14.4	7.79	84.6	58.49	4.32	45.72	185.4	Jalees et al., 2021
Indus River Basin		7.91	1603.85	1154.11	90.34	50.59	12.15	168.74	132.65	44.63	285.48	370.53	Qaiser et al., 2023
Inner Magnolia		7.9	1040	717.21	21.3	25.5	1.5	151	86.9	0.05	14.2	409	Smedley et al., 2005
Tibet		7.55	215.42	225.54	55.25	18.69	3.09	34.93	47.67	-	54.68	169.67	Yuan et al., 2015
Brahmaputra River Basin India		6.88	369.6	412.11	70.91	20.64	4.6	10.8	7.12	0.25	3.07	301.84	Mahanta et al., 2015
WHO limit		6.5–8.5	-	500	100	50	100	200	250	50	250	600	(Dil et al., 2008), WHO (2014)

All units in mg/L, except EC: µS/cm and pH, SD standard deviation, Min : minimum, Max: maximum.

Conversely, among the 60 wells in the basin, HCO_{3-} was the most prevalent anion, indicating that the lithology is dominated by carbonates (Fan et al., 2014). The most concentrated levels of HCO_3^-, SO_4^{2-}, and NO_3^- were found in the densely populated areas of Rawalpindi, near IJP road, G-10, G-11, H-8, and F-6, in that order. The apparent indicator of anthropogenic contaminations, NO_{3-}., was found to be higher in the groundwater in the G-7, G-8, G-9, I-8, I-9, and I-10 regions of Rawalpindi. The densely populated area lies between IJP road and Noor Khan Air Base. For the whole Lai watershed, the concentration of major anions is as follows: $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$. In general, the erratic pattern of major ions in the LRB suggested the presence of anthropogenic signatures in the groundwater, particularly in the middle and downstream sections, which may be influenced by the high levels of anthropogenic activity associated with this area. When compared to HCO_3^- and SO_4^{2-}, the groundwater samples from some of the sampling sites, such as I-10, Peerwadhai, Ghala Mandi, Raja Bazar, and Glass Factory, consistently displayed high concentrations of dissolved solutes (Figure 8 G, H and I).

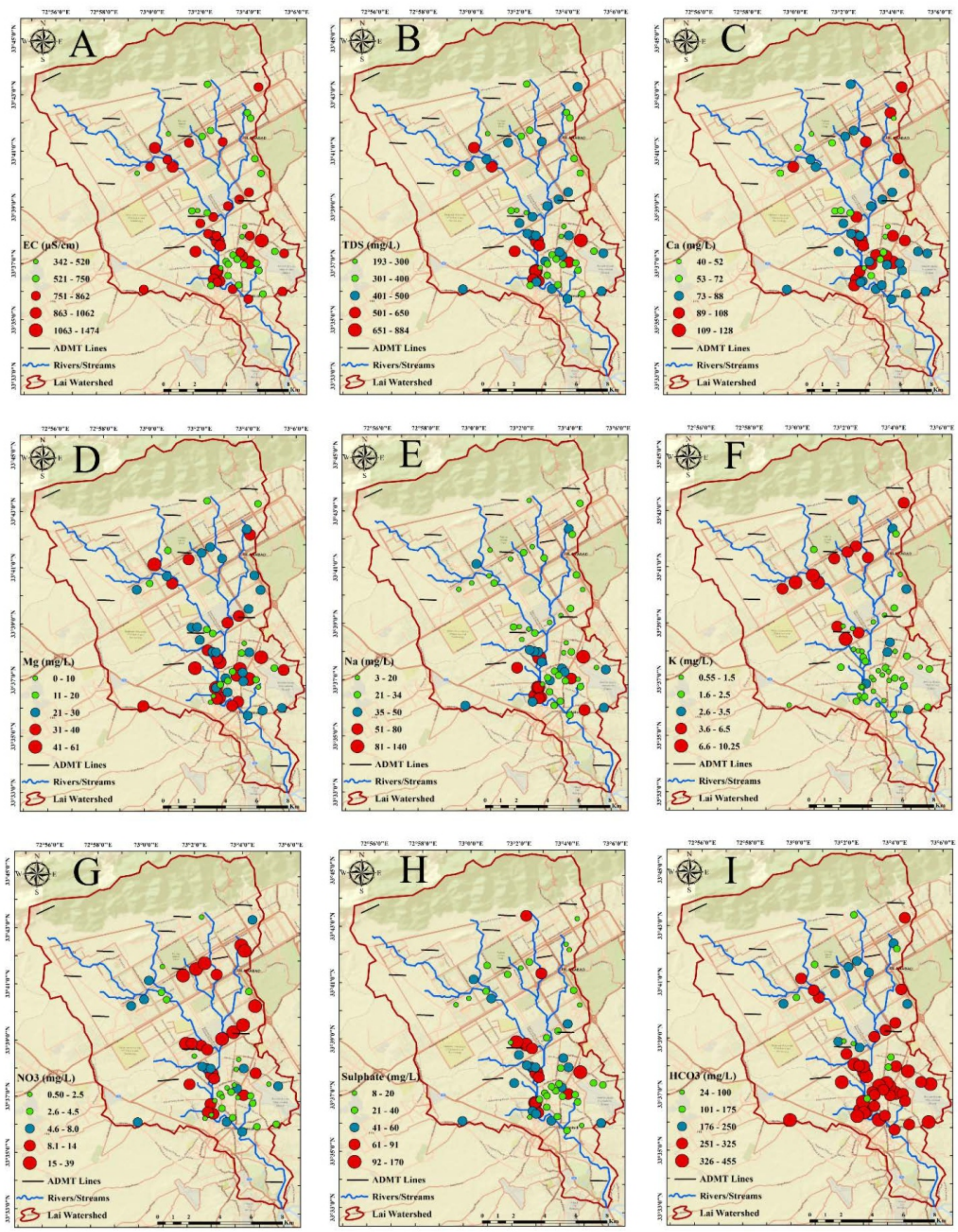

Fig. 8. Spatial distribution of EC, TDS and all major cation and anions along the Lai River Basin area. Only EC is measured in µS/cm remaining all parameters are in mg/L.

3.5 Characterization of hydrochemical facies

The Piper diagram (Figure 9) explains the ionic composition of the groundwater of the LRB during the sampling period. Ca–HCO_3 makes up 99% of the water samples in the LRB, only one sample with high percentage of SO_4^{2} lies in Ca-Cl type dominancy. This sample lies in Islamabad industrial zone (I-10) with very high concentration of SO_4^{2-} in comparison with Cl^- and HCO_3^-, this might be due to industrial waste dumping as there are many Led Acid Battery factories located in that region specifically. Furthermore, the Piper diagram made it evident that the carbonate-dominant lithology in the basin was caused by the alkaline earth metals (Ca^{2+}+ Mg^{2+}) surpassing the alkali metals (Na^+ + K^+) and the weak acids (HCO_3^-) surpassing the strong acids (SO_4^{2-} + Cl^-). The primary factors used to differentiate the spatial variability of hydrochemical facies are underlying lithology and anthropogenic interferences. The outcomes align with earlier research carried out in the Asian region's medium-sized river basins (Abdulsalam et al., 2022; Gautam et al., 2015; Pacheco Castro et al., 2017a, b; Pant, 2013; Pant et al., 2020, 2019; Qaisar et al., 2018; Singh et al., 2005; Ullah et al., 2009).

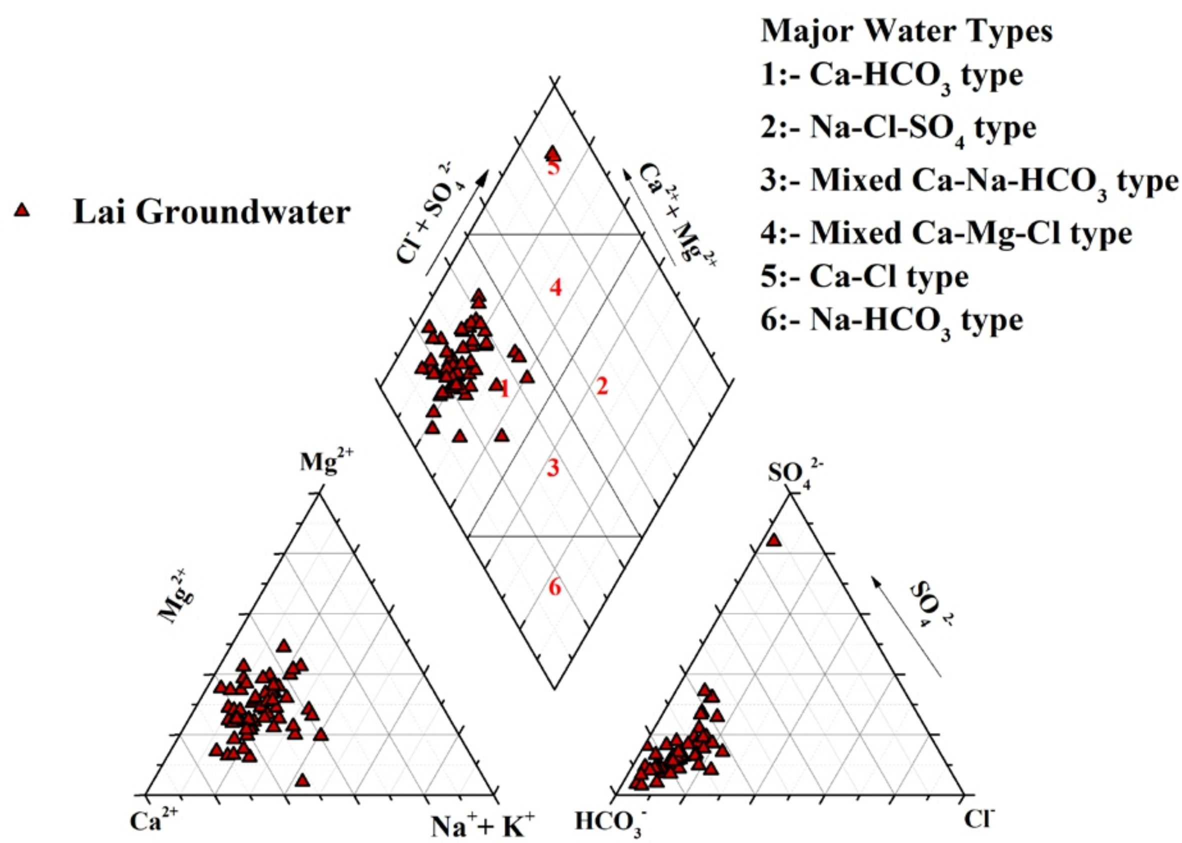

Fig. 9. Piper diagram characterizing the hydrochemical facies in the water samples of the Lai River Basin area (SRB), Pakistan.

3.5.1 Gibbs plot

The majority of the water samples in the current investigation had medium TDS values and low ratios of Cl^- versus (Cl^- + HCO_3^-) and Na^+ versus (Na^+ + Ca^{2+}) (Figure 10 A). As a result, the sampling locations on the left side of the central zone suggest that major ions in the LRB are primarily produced by rock weathering. Since few samples are approaching the Evo-crystallization zone, a result of the high concentration of Na^+ (Figure 10 B) also reflects the relatively higher TDS concentration of LRB in the densely populated region of Rawalpindi, as was previously discussed (Pant et al., 2020, 2019).

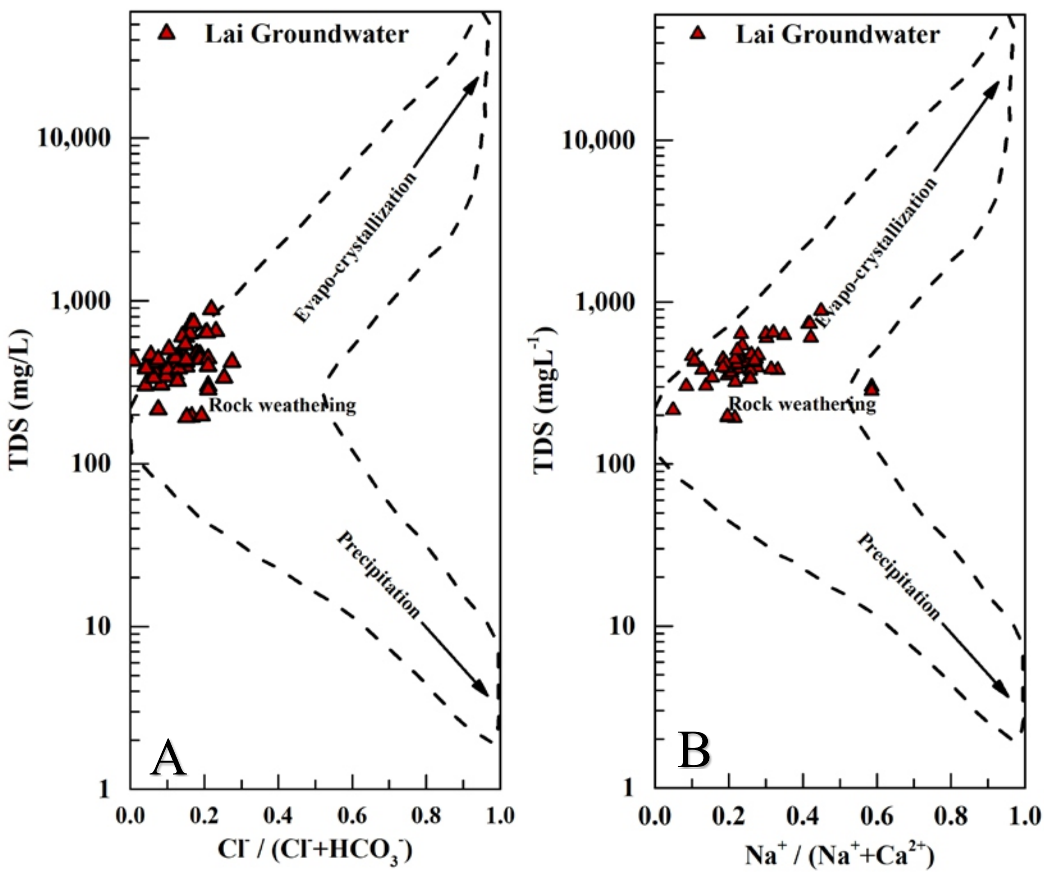

Fig. 10. Gibbs plots (A and B) characterizing the controlling mechanisms of hydrochemistry in the Lai River Basin area (LRB), Pakistan.

All samples had a relatively constant Cl− concentration, except for those located in the middle and lower regions of the LRB. Based on ionic variations and controlling factors in the LRB, these results demonstrated the importance of rock-water interaction in the presence of anthropogenic factors. Major contribution of these contaminants are generated from domestic and sewage wastewater dumping. This may also be due to the old construction in densely populated regions of LRB, where swage waste management system of Rawalpindi city might be leaking organic waste in the groundwater system directly during recharge.

Consistent with the previously mentioned results, earlier studies emphasize the importance of carbonate weathering in identifying the hydrochemical composition of the Islamabad, Pakistan (Ahmed et al., 2020; Alam et al., 2022; Iqbal et al., 2023; Shabbir and Ahmad, 2015).

3.5.2 Mixing diagrams

The LRB groundwater is primarily influenced by carbonate rock weathering, with moderate to slight silicate weathering influence in the LRB, as demonstrated by the Na^+ normalized ratios of Ca^{2+} versus HCO_3^-

(Figure 11A) and Ca^{2+} versus Mg^{2+} (Figure 11B). The results also revealed that some samples slight shift from the carbonate to silicate domain indicates a greater influence from rock-water interactions with the high rate of recharge, particularly in the vicinity of the Lai River. In Pakistan, Nepal and India similar trend has been observed in many Urban River Basins such as Ravi River through Lahore Pakistan, Kabul River through Nowshera, and Swat River through Mardan city, Kali Gandaki River through Bharatpur, Seti River through Damauli, Rapti River through Ghorakpur, Ganga Plain India. These basin shows the characteristics of semi-arid region where anthropogenic influence start impacting minorly and start altering the dominancy pattern from carbonate dissolution dominancy to silicate dissolution dominancy (Adagunodo et al., 2023; Ali et al., 2012; Ejaz et al., 2011; Farzamian et al., 2019; Khan et al., 2015; Lu et al., 2023; Pant et al., 2020, 2018a, 2018b; Raza et al., 2023; Singh et al., 2015b).

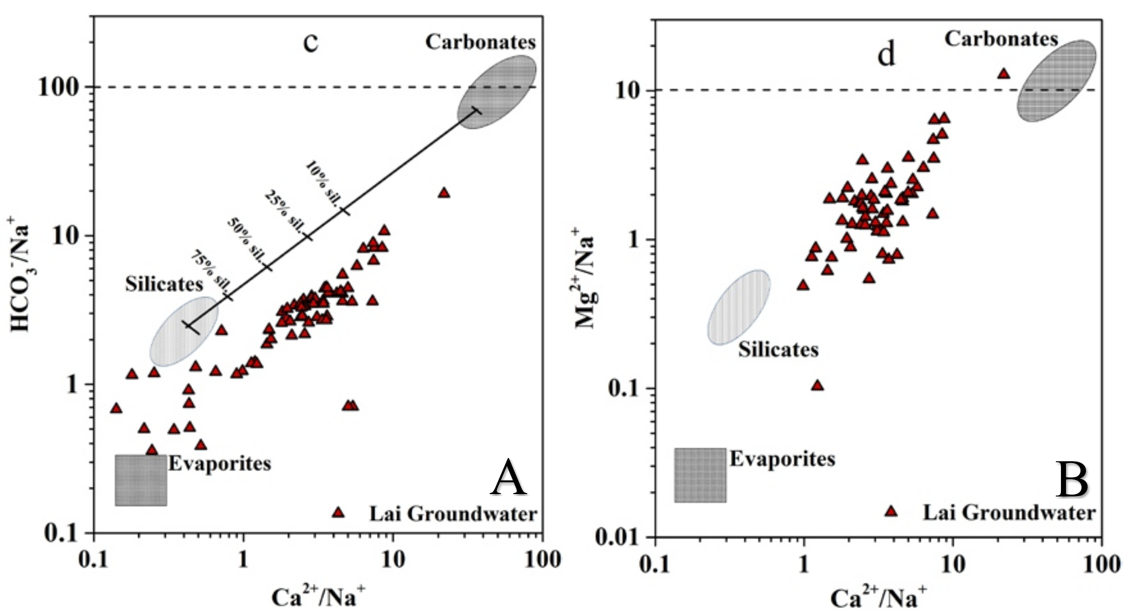

Fig. 11. Mixing diagrams using Na-normalized molar ratios (A and B) in the water samples of the Lai River Basin area (LRB), Pakistan.

The hydrochemistry of the LRB is primarily controlled by carbonate-dominant underlying lithology, as indicated by the clustering of samples in the near carbonate domain. This is further supported by a high ratio of Ca^{2+}/Na^{+}, HCO_3^{-}/Na^{+}, and Mg^{2+}/Na^{+}. Consequently, the findings demonstrated that carbonate weathering dominates the hydrochemistry of the LRB, with minor silicate weathering signatures found throughout the basin.

4. Conclusions

The study analyzed the integration between geophysical, geological and hydrochemical datasets to address the water management issues in Lai River Basin (LRB), Rawalpindi, Punjab, Pakistan. The geological data revealed the dominating lithologies as clay, sandy clay, gravel and sandstone at varying depths. The deposition of these lithologies is attributed to stream velocity variations, it was further observed that slope plays a dominant role in deposition along with climatic conditions. The recharge units include Margalla hills and Soan River.

Towards the north and centre clay dominates as a surficial deposit but towards south silt dominates as the slope decreases the avulsion area of river also decreases. Stream episodes are observed with north having high stream velocity then south. The geophysical datasets reveal three zones of resistivity namely low, intermediate and high. The high resistivities were attributed to local sandstone beds, intermediate with sand, gravel and saturated clay whereas low resistivity was attributed to presence of contamination. The contamination is observed mostly in the profiles that are acquired in the vicinity of Lai, the sandy clay coupled with paleo channels formed by stream avulsion serve as carriers of contaminants from stream into the local shallow aquifer system.

The geophysical and geological datasets revealed three types of aquifer systems, the first system is a shallow unconfined aquifer that comprises of sandy clay, this aquifer is mostly shallow, less permeable therefore can yield less quantity of water. Additionally, this aquifer system is at threat of surficial contamination due to is partial transmissive nature. The second aquifer system is confined aquifer that lies at greater depth comprising of sand and gravel beds, this aquifer system is least affected by the surficial contamination as this system is overlain by clay and silt beds. The third aquifer system lies in paleo channels that are formed because of stream deposition; this aquifer provides the shallow water for the residents, but these paleo channels also carry the surficial contamination to local aquifer systems.

Overall, the water quality of LRB is good, but few samples from middle and lower reaches of LRB shows high concentration of EC and TDS. The hydrochemical analysis indicates a significant dominance of Ca^{2+} and Na^{+} along with HCO_3^- and SO_4^{2-} in the water. Gibbs plot suggested rock weathering with slight influence of evapo-crystalization which is due to high concentration of Na^{+}. The groundwater geochemical signature thus implies that the major control is dominated by carbonate weathering along with moderate silicate dissolution process. The chemical signature suggests high levels of water contamination, probably reflecting widespread human activity. These ions are present in high concentration and can be related to the disposal of untreated sewage, industrial effluents and domestic waste into the river. These contaminants enter the Lai River, and during groundwater recharge, they further deteriorate the water quality, posing significant human and environmental health risks. Piper diagrams categorizes groundwater of LRB is of Ca–HCO_3 type which support our finding of carbonated weathering dominated river basin. This type of water is mostly considered as hard water and cause serious human health problems such as digestion issues, high blood pressure, and dermal abrasion. According to mixing diagram influence of evaporates and silicate dissolution is more dominant in those regions where we have observed high TDS. This happened when water alkalinity drops down to acidic environment where influence of anions is more than cation. This contamination is particularly acute in the densely populated areas of Rawalpindi, located in the middle to lower reaches of the Lai catchment. The combined effect of population density and poor waste management systems leads to high levels water contamination. The groundwater in these regions is especially altered by anthropogenic influence, deserving intervention and management plans to modulate their effects on the hydro-ecosystem. Lai River Basin desperately need batter waste management system and groundwater management system. For this we city municipal department and NGO's collect seasonal data for more detail study and pinpoint the major recharge zones of groundwater in Lair River Basin and make water quality, water management policies for sustainable development.

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Authors' Contribution

Muhammad Farooq proposed the main concept and was involved in geophysical write up along with field data acquisition. Faizan ur Rehman Qaisar was involved in data analysis writing the hydrochemical section along with generation of maps. Umair Bin Nisar was involved in writing the introduction, borehole interpretation, result and discussion along with preparation of the initial draft.

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