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Integrated Assessment of Groundwater Quality, Agriculture Suitability and Health Risk Assessment in the Upper Indus Basin, District Gujranwala, Pakistan

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Abstract

Public health protection, sustainable agricultural practices, and environmental degradation mitigation, all depend on the quality of groundwater. Groundwater quality remains a critical concern in the densely populated cities of Pakistan. Integrated assessment of groundwater quality in an area provides a comprehensive understanding to support effective resource management and policy-making. The focus of this study is to evaluate the ionic concentration of groundwater and subsequent consequences based on twenty-eight groundwater samples acquired from different water schemes in the Gujranwala District, Punjab, Upper Indus Basin, Pakistan. This study analyzes the type of ions, the effect of contamination on agriculture and groundwater contamination-based health risks. Results show that the concentration of major ions in nearly all the groundwater samples lies within World Health Organization (WHO) limits except for arsenic (As). In about 64% of the total samples, the arsenic concentration exceeds the limit recommended by WHO which is 10 µg/L. The chemical composition of groundwater is influenced by rock weathering according to the Gibbs plot. Magnesium, bicarbonate, and sodium ions contribute to the groundwater's total dissolved solids as indicated by a Piper plot. Most of the water samples are suitable for irrigation purposes, except magnesium hazard values of about 57% substantially impact soil alkalinity. Hazard quotient (HQ) and carcinogenic risk (CR) assessments were also used in the study. The HQ values in the study area lie in the range of 0.012 to 4.97, with an average value of 1.21, and about 57% of samples exceed the toxic risk index values. The CR value range is 5.41667×10^{-6} to 0.001, indicating a serious health threat to the residents in the area. Prolonged use of arsenic-contaminated water will cause severe health issues for the area's residents. Appropriate remedial and preventive actions should be undertaken to mitigate arsenic pollution in the area.

1. INTRODUCTION

Water is the most vital natural resource for the existence of life and the sustainability of ecosystems (MACDONALD et al., 2016). Water quality is controlled by the concentration of dissolved elements and ions, constituting an integral part of its chemical composition (ADETOYINBO et al., 2010; SINGH et al., 2008). Groundwater is an important source of available freshwater across the globe. However, groundwater quality deteriorates due to many anthropogenic and geogenic factors contributing to freshwater contamination (TALIB et al., 2019). The contaminants in groundwater are leading cause for waterborne health issues worldwide (HASHMI, 2000; LI et al., 2021). According to the UN Environment Programme, about 80% of the World's wastewater, containing toxic chemicals and human waste, is discharged into the ecosystem without any treatment (LIN et al., 2022). The yearly UN World Water Development Report, states that around 1.7 billion people worldwide use contaminated drinking water (UN-WATER, 2021). Among the common contaminants in groundwater include arsenic (As), nitrate, iron, and manganese (AHMED et al., 2019; ZHANG et al., 2020). Every physical state was declared as a severe risk to human health by the United States Environmental Protection Agency (SARKAR & RUPALI, 2007; US-EPA, 2005). The consumption of groundwater contaminated with As for a prolonged period can have dire consequences, resulting in bladder cancer, hyperkeratosis, coronary heart disease, bronchiectasis and arsenicosis (MAZUMDER, 2008; SHAJI et al., 2021). Groundwater contaminated with As has been confirmed in about more than 105 countries of Southeast Asia, including Pakistan (SMEDLEY, 2008). In Pakistan, the percentage of groundwater with significant As contamination reaches about 9%. Around 25% to 36% of residents of the Sindh and Punjab provinces of Pakistan are consuming water polluted with As (ZUBAIR et al., 2018). Punjab holds the most significant groundwater reservoirs in Pakistan. The sediments in the Indus plain are alluvial and deltaic, and their thickness varies in different parts of the plain. The groundwater aquifers in the Indus plain mostly lie in the Quaternary sedimentary deposits. Elevated As concentrations were reported in the aquifers within the sedimentary deposits of this area (SMEDLEY, 2008; ALI et al., 2019b).

Of the 40 million people living in the 27 districts of Pakistan, about 13 million are exposed to drinking water contaminated with As (ALI et al., 2019b). Moreover, it is reported that 656 villages and 6,173,680 people are facing serious risk of As poisoning (ALI et al., 2019a, b). In the Jhelum and Chakwal regions of Punjab province, coal mining and anthropogenic activities are the main sources of As contamination (ULLAH et al., 2023). In the Tharparkar desert of Sindh province, the reductive dissolution of As and fluoride ion induced by the arid environment and complex geology led to contamination of 100–2580 µg/L in the groundwater sources (BRAHMAN et al., 2013). According to (RABBANI et al., 2017) in the Thari mirwah, Kot digi, Sobo Dero, and Kingri regions, the alluvial deposits of the Indus is the main factor that affects the groundwater quality. To evaluate the suitability of groundwater quality, various hydro-chemical methods have been applied worldwide. Many integrated approaches help delineate the causes and effects of deteriorating water quality (ASHRAF et al., 2018). Consequently, identifying the concentration of ion-causing contamination and its source is the key aspect to comprehending the pattern of groundwater contamination and the associated health risk impact of any region (SAPPA et al., 2014).

The evolution of surface water chemistry has been summarized by GIBBS (1970) based on the analysis of samples collected from rainfall, lakes, rivers, and oceans of different regions. The Gibbs diagram was originally developed to study surface water chemistry and the main governing processes of water chemistry, including evaporation, precipitation, and water-rock interactions (MARANDI & SHAND, 2018). The Gibbs plot, however, may overlook the groundwater controlling mechanism, i.e., the geochemical processes and environmental factors which lead to the concentration of certain minerals and ions (ALLEY et al., 1998; MARANDI & SHAND, 2018). To deal with this problem, hydrochemistry is further analyzed using the Piper plot (MERINO et al., 2021; PEETERS, 2014). According to PIPER (1944), the triangular diagram evaluates the relationship between aquifer rock types and water composition (KUMAR, 2013).

Water quality for agricultural processes depends upon the concentration of the minerals dissolved in the water uptake by plants from soil (WILCOX, 1958). An appropriate balance of each ion and mineral is necessary for better crop yields. To circumvent the accumulation of salt around the plant roots and soil deprivation, an appropriate balance of salt is necessary (LETEY et al., 2011; SKAGGS et al., 2012). Prolonged usage of poor-quality water will not only affect crop production but also cause alkalinity and salinity in the region (SHAKIR et al., 2002). The electrical conductivity method provides the crucial assessment of salinity hazard impacting the quality of water used in irrigation (ABBAS et al., 2015). Consequently, the ratio of sodium (Na) with respect to magnesium (Mg) and calcium (Ca) in water, also known as sodium-adsorption-ratio (SAR) is sensitive to the permeability of the soil and provides information on the effect of infiltration rate on agriculture (TADESSE et al., 2009). Na is among the most important cations an excess of which can lead to a reduced crop yield (NARSIMHA, 2012). Kelly's ratio and Na percentage also govern the impact of excessive Na in water used for agricultural purposes (SUDHAKAR & NARSIMHA, 2013).

Similarly, a surplus of Mg ion in the soil is responsible for alkalinity, which reduces crop production and is assessed through Mg hazard analysis. Therefore, the health risk assess-

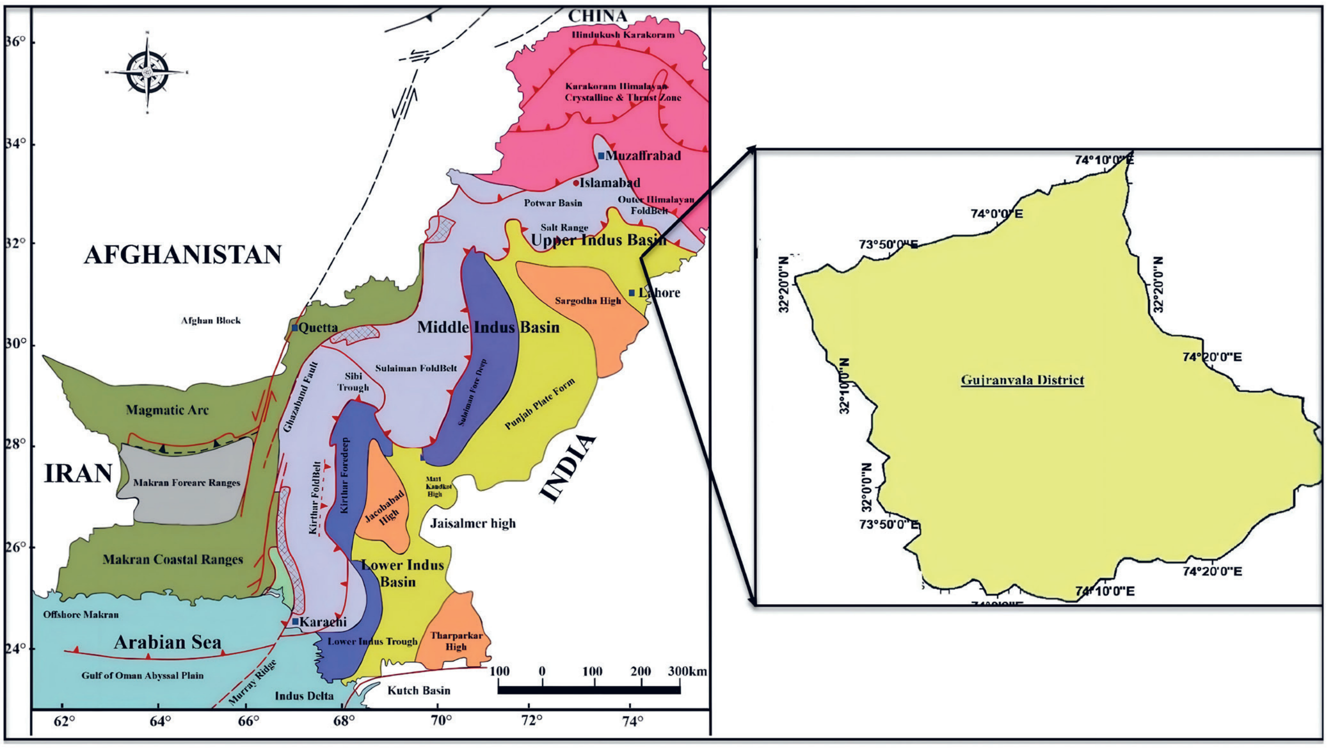

Figure 1. The map of Pakistan with the location and detailed section of the Gujranwala district.

ment associated with the presence of certain contaminants in the water is vital (CELEBI et al., 2014). To assess the threat caused by various elements immersed in water, the U.S. Environmental Protection Agency (US-EPA) proposes the Hazard Quotient (HQ) analysis (EID et al., 2024).

This study investigates several physico-chemical parameters to detect the presence of ions or elements affecting the groundwater quality of the Gujranwala District using statistical analysis and graphical techniques. These coordinated techniques enable the identification of the variables influencing the hydrochemistry of groundwater and produce more meaningful results for effectively managing water resources. The findings from this study can give us fundamental knowledge on the quality of the groundwater in the study area and may help with implementing sensible water quality management strategies.

2. STUDY AREA

The Gujranwala district is located in the plains of Punjab, Upper Indus Basin, Pakistan. The geographic coordinates of Gujranwala are 32°9'58.8636''N, 74°11'45.2400''E with an area of 3,622 km² an average elevation of 231 m (758 ft) and hosting a population of 6,011,066 (2017 census). Gujranwala is the 5th largest city in Pakistan. Adjacent regions of the Gujranwala district are the Gujrat, Sialkot, Mandi Bahauddin, Hafizabad and Sheikhupura districts. It sits at the upper part of Rachna Doab, which is the piece of land between two Rivers: the Chenab and Ravi, running from the northeast to the southwest. Rachna Doab is part of the Indo Gangetic plain, filled with alluvium. The population density of the Gujranwala district is about 932 per sq. km. The main water source is groundwater which can be drawn by installing tube wells. The average water depth is almost 16.76 metres, and the depth of tube wells varies from 137–198 metres (GREENMAN et al., 1967).

The climate conditions of the district are moderate, with temperatures reaching up to 40 ºC in summer while the temperature can drop down to 5 ºC during the coldest part of the winter (JANJUA et al., 2021).

3. GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

The study area lies in the upper Indus Basin, Pakistan. Gujranwala lies in the upper part of Rachna Doab, which consists of alluvial deposits of Tertiary age overlapping an older rock formation. Lithological units in the upper part of Rachna doab consist of silt, medium to fine-grain sand and clay, which the Indus River and its tributaries deposit. Recurring floods and meandering of river channels, along with the rate of change of flow across the land surface, have caused recent deposition. The soil texture chiefly ranges from medium to coarse grain with permeable aquifers (GREENMAN et al., 1967). The sediments in the Indus plain are alluvial and deltaic, and their thickness varies in different parts of the plain. The groundwater aquifers in the Indus plain mostly lie in the Quaternary sedimentary deposits (SMEDLEY, 2008; ALI et al., 2019b).

The historical river dynamics during the Shekhupura aggradation stage, when the river originally flowed near Sialkot through Gujranwala to Shahkot, generating broad floodplains between Hafizabad and Sheikhupura, have formed the hydrogeology of the Gujranwala area. It is possible to identify at least three channels from this phase that demonstrate a steady westward migration. The sand, silt, and clay deposits of the floodplain are similar to the contemporary Chenab River deposits and indicate high groundwater potential because of well-developed alluvial aquifers. A river as extensive as the current Chenab is indicated by huge meander scars, indicating significant water flow and sediment transport under current climate conditions. These historical processes have produced alluvial aquifers with improved groundwater recharge and storage which are important for the management of the area's water resources (KAZMI & JAN, 1997).

The high-yield aquifers are mostly deep, unconfined, and relatively homogeneous in the study area, while anisotropy is due to the presence of clay which causes lower vertical permeability than horizontal in the strata. The impermeable basement rocks provide the lower boundary of the groundwater reservoir. The specific yield of a sandy aquifer is 0.15 m, the clay layer is 0.06 m, and the hydraulic conductivities mean values range from 1.5E-5 m/s and 1.2E-3 m/s in the vertical and horizontal directions, respectively, in the inter-fluvial region of the Rachna Doab (GREENMAN et al., 1967).

4. DATA SET AND METHODOLOGY

4.1. Groundwater sampling

Qualitative assessment of the groundwater in the district provides insight into determining the contamination caused by hazardous elements in the water. Twenty-eight groundwater samples were taken from eighteen functional government schemes and three non-functional schemes to estimate the quality of groundwater supply schemes in the Gujranwala district. Functional government schemes are referred to as sources of water supply from boreholes to the surrounding community, while nonfunctional are not currently providing any water services. A total of twenty-one water schemes as shown in Figure 2, were observed from which some were resampled therefore acquiring a total of twenty-eight groundwater samples. From the twenty-one schemes, three of them, namely, Nizaam Abad, Rasool Nagar, and Wandah were nonfunctional while the rest were functional.

Collecting the groundwater samples from each location was handled carefully to ensure the reliability of the data for water quality assessment. To collect water samples, bottles were properly decontaminated and cleaned. Nitric acid was used to rinse the 1.5-litre sample bottles i.e., polythene bottles. Samples were collected into two bottles. Some important parameters, including electrical conductivity (EC), total dissolved solids (TDS) and pH were determined by a portable TDS meter in the field as soon as the samples were collected while the detailed analysis for water quality was carried out in the Pakistan Water Resources Research Council (PCRWR) laboratory. Collected samples were handled carefully and transported to prevent surficial reactions that could cause sample contamination.

4.2. Methodology

The physico-chemical properties of groundwater samples, collected from Gujranwala district are examined through a

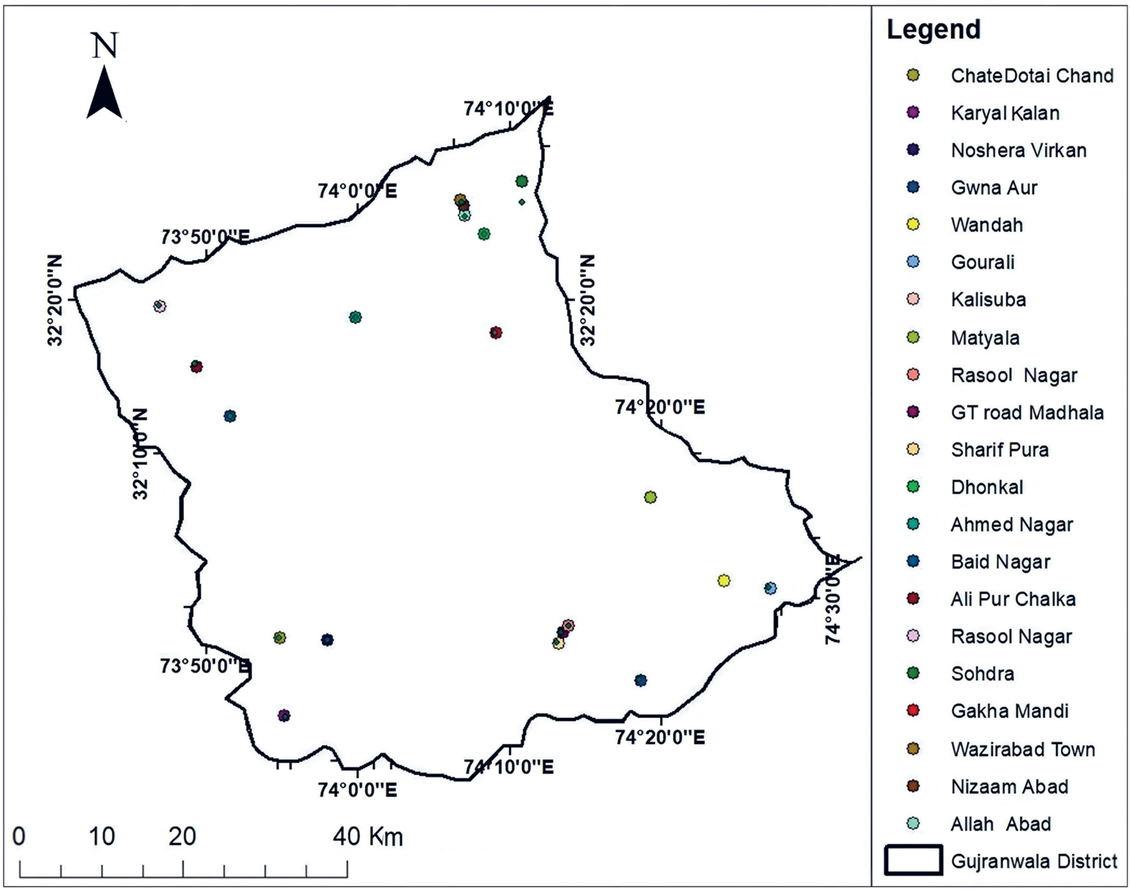

Figure 2. Location map of groundwater samples collected from water schemes in the Gujranwala district.

statistical summary that represents the concentrations of ions dissolved in groundwater, their comparison with maximum allowed limit proposed by the WHO and other hydrogeological parameters including hardness, pH, turbidity, electrical conductivity (EC), bicarbonates (HCO_3^-), chloride (Cl^-), carbonates (CO_3^{2-}), sulfate (SO_4^{2-}), magnesium-ion (Mg^{2+}), calcium-ion (Ca^{2+}), potassium-ion (K^+), sodium-ion (Na^+), nitrate (NO_3^-), fluoride (F^-), iron (Fe), phosphate (PO_4^{3-}) and arsenic (As).

The Gibbs diagram is inferred by analyzing the scatter plots for cations and anions, displayed by the (Na+K)/(Ca+Na+K) ratio, which are plotted against total dissolved solids (salinity) for cations (Fig. 3a) and Cl/(Cl+HCO_3^-) ratios are plotted against total dissolved solids (salinity) for anions (Fig. 3b) respectively (MARANDI & SHAND, 2018).

The Piper diagram represents the major anions and cations percentages plotted on a separate triangle in a milli-equivalent unit, the overall character of water is determined by points projected into the central diamond field (SAJIL KUMAR P.J., 2012).

For assessment of groundwater quality used for irrigation purposes SAR analysis, salinity index, Kelly's ratio, Magnesium-Hazard ratio (MH) and Na percentage (Na%) were carried out.

The soil permeability varies with SAR, which is the measure of the relative concentration of Na, Ca and Mg and is quantitatively calculated by the formula given in equation (1) (MARGHADE et al., 2011):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (1)$$

Based on electrical conductivity values, qualitative analysis for determining the salt content in the water samples, and salinity hazard analysis was carried out (ABBAS et al., 2015; CARDON et al., 2003; BAUDER et al., 2011).

Kelly's ratio and the Na percentage also govern the impact of excessive Na in water used for agriculture. KR and Na% are quantitatively calculated using equations (2) and (3), respectively (SUDHAKAR & NARSIMHA, 2013).

$$\mathrm{KR} = \frac{Na^+}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}} \quad (2)$$

$$Na\% = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \quad (3)$$

MH is also known as the magnesium hazard or magnesium adsorption ratio. The presence of a higher Mg content affects the soil quality, making it more alkaline, and affects crop yield (SUDHAKAR & NARSIMHA, 2013). The formula for MH is given in equation (4) as:

$$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (4)$$

The concentration of all the parameters used in the above equations (1), (2), (3), and (4) are in meq/L units. Health risk analysis was carried out to estimate the health implications of prolonged consumption of As-contaminated water with reference to average daily dose (*ADD*), the HQ, and carcinogenic risks (CR). *ADD* can be assessed using US-EPA derived model. The average daily dose of As intake through water was calculated using equation (5) (REHMAN et al., 2020; SHAHID et al., 2018; TABASSUM et al., 2019; US-EPA, 2001).

$$ADD = \frac{C * IR * ED * EF}{BW * AT} \quad (5)$$

Here, As concentration (in mg/L) is denoted by *C*, *IR* stands for water consumption rate (Approximate 2 L/day), exposure duration is denoted by *ED* (Approximately 67 years according to the literature), exposure frequency (365 days/year) is denoted by *EF*, *BW* symbolizes average body weight (72 kg) and average life cycle (24,455 days) is represented by *AT* (REHMAN et al., 2020; SHAHID et al., 2018; TABASSUM et al., 2019).

HQ was calculated in order to estimate the non-cancerous health concerns triggered by the consumption of As polluted groundwater using equation (6) (RASOOL et al., 2017; IRIS, 2011; US-EPA, 2001; TABASSUM et al., 2019):

$$HQ = \frac{ADD}{RfD} \quad (6)$$

The As oral reference dose is denoted by *RfD* and taken as 0.0003 mg/kg/day. Samples with HQ values < 1 mg/kg/day are considered safe, while samples > 1 mg/kg/day pose serious health concerns.

Carcinogenic threats related to As in groundwater are well documented and pose serious health risks for humans. Cancer risk was estimated by equation (7) (US-EPA, 2001):

$$CR = ADD*CSF \quad (7)$$

Here *CR* represents the cancer risk, and the slope factor is denoted by *CSF*.

5. RESULTS AND DISCUSSION

5.1. Statistical Analysis

The distribution of different hydro-chemical parameters examined in the Gujranwala district compared to the WHO recommended limits in groundwater samples are listed in Table 1.

The groundwater samples from the Gujranwala district are mostly slightly alkaline with pH values ranging from 7.00 to 8.06 with an average of 7.6 and all the collected samples lie within the maximum threshold limit (Table 1). Values of electrical conductivity range from 499–1140 µS/cm with an average value of 672.9 µS/cm (Table 1), indicating that the values in all the groundwater samples are within the maximum allowed limit. Furthermore, fluoride, sulfate, hardness, bicarbonate, potassium, magnesium, pH, chloride, and sodium in all 28 samples are within the standard limit described by WHO (Table 1). In three samples, the concentration of iron is high (Table 1). The As concentration ranged from 0.13 to 53.75 µg/L with an average of 13.14 µg/L (Table 1). However, the maximum allowed limit suggested by WHO is 10 µg/L, so the As contamination in the region is quite alarming around 64% of all samples (Table 1).

Table 1. Summary of important parameters in the groundwater samples and comparison with WHO standards.

Observed Parameters	Units	Minimum value	Maximum value	Average	Maximum concentration limit (WHO, 2011; WHO, 2017)	% age within a limit	% age exceeds the limit
EC	µS/cm	499	1140	672.9	1500	100	_
pH	–	7	8.06	7.6	6.5–8.5	100	_
TDS	mg/L	182	848	392.3	1000	100	_
HCO_3^-	mg/L	135	390	298.8	350	100	_
CO_3^{2-}	mg/L	nil	nil	nil	200	100	–
Cl^-	mg/L	2	142	16	250	100	_
SO_4^{2-}	mg/L	2	179	29.9	400	100	_
Ca^{2+}	mg/L	20	64	43.6	300	100	_
Mg^{2+}	mg/L	13	58	30.4	150	100	_
Hardness	mg/L	140	310	232.9	500	100	_
Na^+	mg/L	14	180	51.5	200	100	_
K^+	mg/L	2.2	11.7	5.17	10	100	_
NO_3^-	mg/L	0.1	1	0.49	45	100	–
PO_4^{3-}	mg/L	0.002	0.1	0.04	0.3	100	_
F^-	mg/L	0.11	0.64	0.30	1.5	100	_
Fe	mg/L	0.03	0.41	0.14	3	89	11
As	µg/L	0.13	53.75	13.14	10	36	64

5.2. Formation Mechanism of Groundwater Chemistry

Two subplots were generated representing cations and anions controlling factors, as (Na+K)/(Na+K+Ca) were plotted as a function of total dissolved solids (TDS) and $Cl/(Cl+HCO_3^-)$ as a function of TDS, respectively as shown in Figure 3.

The data points on the Gibbs diagrams for cations and anions suggest that the groundwater chemistry is controlled principally by the predominant rock type.

A Piper plot was developed in the study area from the geochemical data from the analyzed groundwater samples (Fig. 4). The Piper plot shows most of the cations are present in the C zone, a few samples lie in the zone of no dominance and two samples lie in the Na type representing that the groundwater sample in the Gujranwala area is mainly of the "Mg type" cation chemical composition. While anion samples frequently lie in the E zone, that is the "Bicarbonate Type" except for two samples in the no dominance zone. Nearly all the samples are

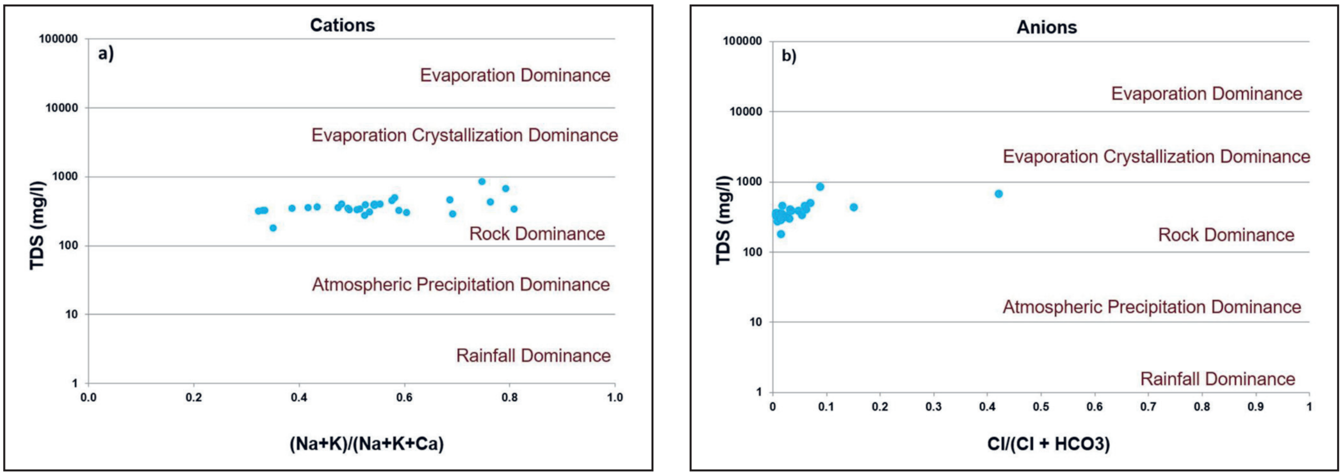

Figure 3. a) The Cation-based Gibbs plot indicating the controlling factors of the groundwater chemistry of the samples; **b)** The Anion-based Gibbs plot indicating the controlling factors of the groundwater chemistry of the samples.

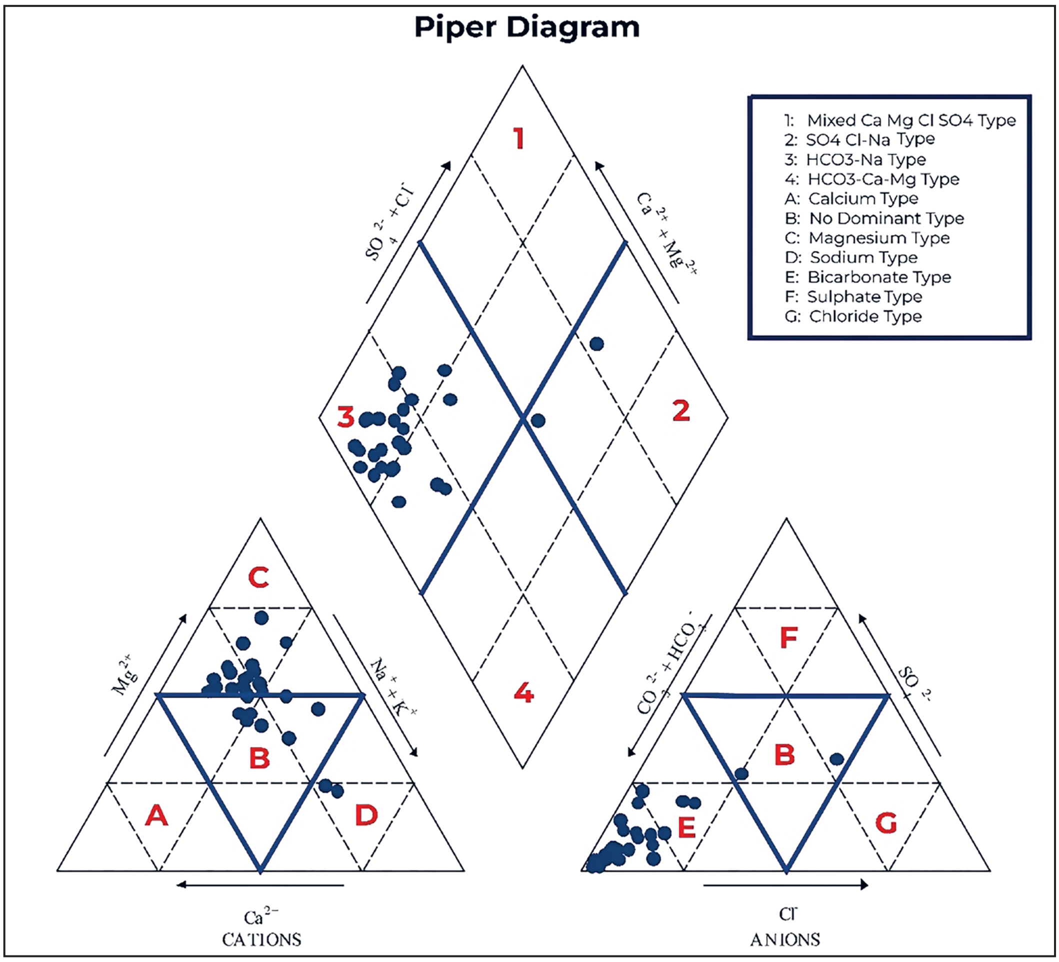

Figure 4. The type of ions present in the acquired groundwater samples indicated by the Piper plot.

present in zone 3, and two samples are plotted in zone 2. So, in the study area HCO_3^- & Na^+ are abundant ions.

The geology and mineral composition of the Punjab Plain have a significant impact on the groundwater in the area. The Punjab Plain, part of the larger Indo-Gangetic Plain, sits atop a complex alluvial structure deposited during the mid-Tertiary period in a tectonic trough. This diverse alluvial complex, largely composed of fine- to medium-grained sands, silts, and clays, reflects the dynamic processes of the Indus River and its tributaries. Notably, the presence of calcium carbonate concretions within the fine-grained sediments points to extensive secondary mineralization activities. The interaction between water and the mineral components of the sediment in this area influences the geochemical processes that dictate the composition of the groundwater. The presence of Mg cations in the groundwater is attributed to the dissolution of dolomite and magnesite rocks, while the prevalence of bicarbonate anions is a result of the dissolution of calcite and the reaction of carbon dioxide with water. The groundwater in this region is likely to be slightly alkaline due to presence of dissolved carbonate minerals and contributes to its bicarbonate-rich composition. The characteristics of groundwater are significantly influenced by hydrogeological factors. In the Punjab Plain, the alluvial deposits give rise to an exceptionally permeable aquifer system, resulting in unconfined groundwater. The flow and residence time of groundwater is affected by the permeability and heterogeneity of the alluvium, which is determined by the scattered distribution of fine-grained materials and local clay bodies.

In summary, the distinct mineralogical composition, hydro-geochemical processes, and geological heritage of the Punjab Plain collectively influence the groundwater composition within the region. The chemical constituents of groundwater are determined by its interaction with heterogeneous alluvial sediments and the hydrogeological attributes of the aquifer.

Table 2. Outcomes of the agriculture analysis carried out for the acquired groundwater samples.

Electrical Conductivity			
Water Quality	Range	No. of samples	% age of Samples
Excellent	0–250	–	–
Good	271–750	22	79%
Permissible	751–2250	6	21%
High	2251–6000	–	–
Very high	6001–10000	–	–
Extremely high	10001–20000	–	–
SAR			
Quality	Range	No. of samples	% age of Samples
Excellent	<10	28	100%
Good	10–18	–	–
Doubtful	19–26	–	–
Na Percentage			
Quality	Range	No. of samples	% age of Samples
Excellent	<20	5	18%
Good	20–40	18	65%
Permissible	40–60	3	10%
Doubtful	40–60	2	7%
Unsuitable	>80	–	–
Kelly Ratio			
Quality	Range	No. of samples	% age of Samples
Suitable	<1	25	89%
Marginally suitable	1–2	3	11%
Unsuitable	>2	–	–
Mg Ratio			
Quality	Range	No. of samples	% age of Samples
Suitable	<50	12	43
Harmful	>50	16	57

5.3. Agriculture potential of the study area

The quality of groundwater used for irrigation has an important impact on the yield of crops. Depending on the aquifer's exposure to the type of contaminant materials, groundwater may become polluted with domestic, agricultural, or industrial waste due to using fertilizers, pesticides, and other harmful chemical products.

Classification of the groundwater based on electrical conductance values shows that 78% of the water samples (22 out of 28) lie in this range of 271–750 μS/cm, which is considered as good quality water for irrigation (NARANY et al., 2014), while the other 21% of water samples falls in the permissible range. Data of EC of the study area represent the range from 499 to 1140 μS/cm.

The relative concentration of Na content in groundwater was assessed through the SAR analysis and it depicts that all the values of SAR lie in the excellent water quality range used for irrigation as from Table 2 we can infer that all the groundwater samples are lying in the range <10. Na percentage values of the region indicate that around 7% of samples fall in the range of doubtful water quality, 10% of samples lie in the permissible range and 65% of samples are considered as good quality water.

Kelly's ratio is basically used to assess groundwater quality used for irrigation purposes. By analyzing Kelly's ratio values from Table 2, it is clear that 25 out of 28 samples (89% of samples) are considered as suitable for irrigation purposes and the remaining 3 samples lie in the marginally suitable range.

In natural water, Mg and Ca are in a state of equilibrium if either one of these cations has high values it can increase the pH of the soil and reduce the infiltration capacity of the soil, which has a really bad impact on crop yield. As the Mg percentage was found to be high in the collected samples, the MH ratio was evaluated in this study. Based on the MH ratio, it is concluded that 12 out of 28 lie in the suitable range while the remaining 57% of samples have MH ratio values greater than 50, so they are considered harmful, affecting the soil.

5.4. Spatial distribution of As concentration map of the Gujranwala area

Arsenic concentrations calculated in groundwater of the Gujranwala area range from 0.13 to 53.75 μg/L with an average

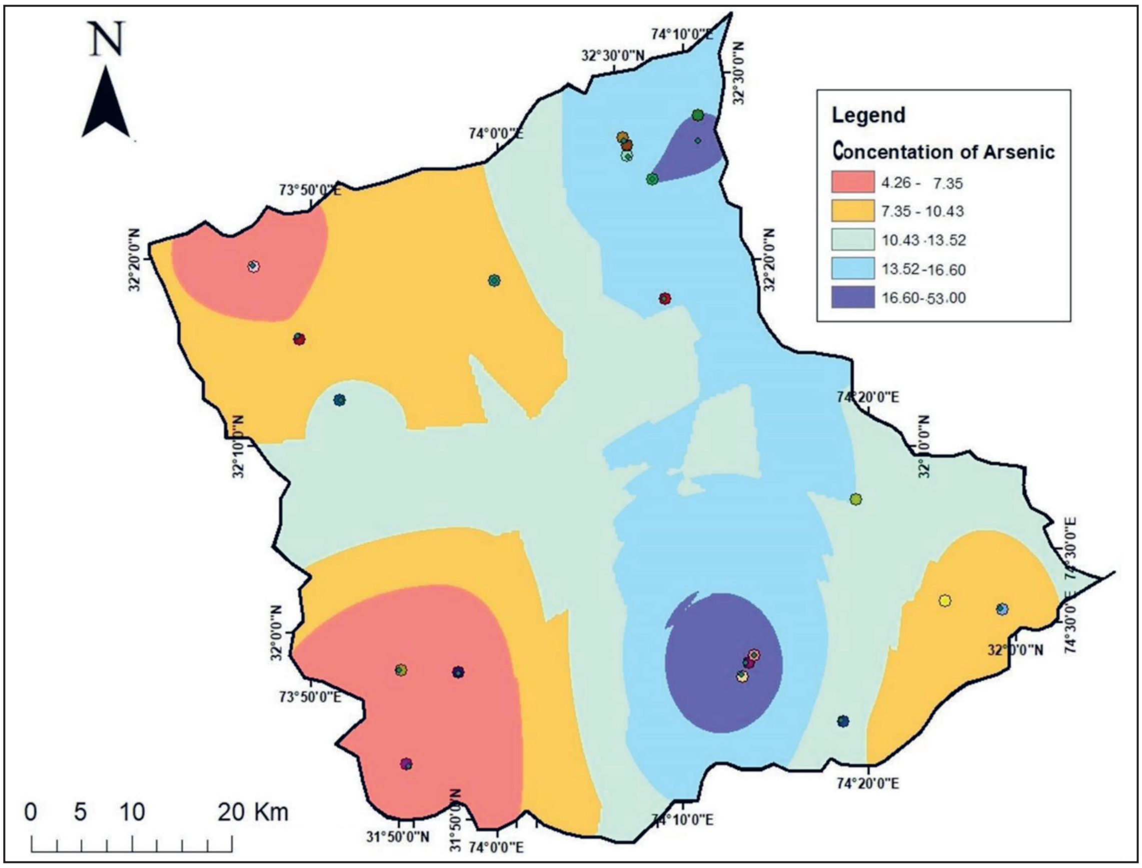

Figure 5. A map depicting the concentration of arsenic indicates that the shades of blue and purple colour depict a contaminated area. The orange colour indicates a moderate concentration of As while the pink indicates a low As value.

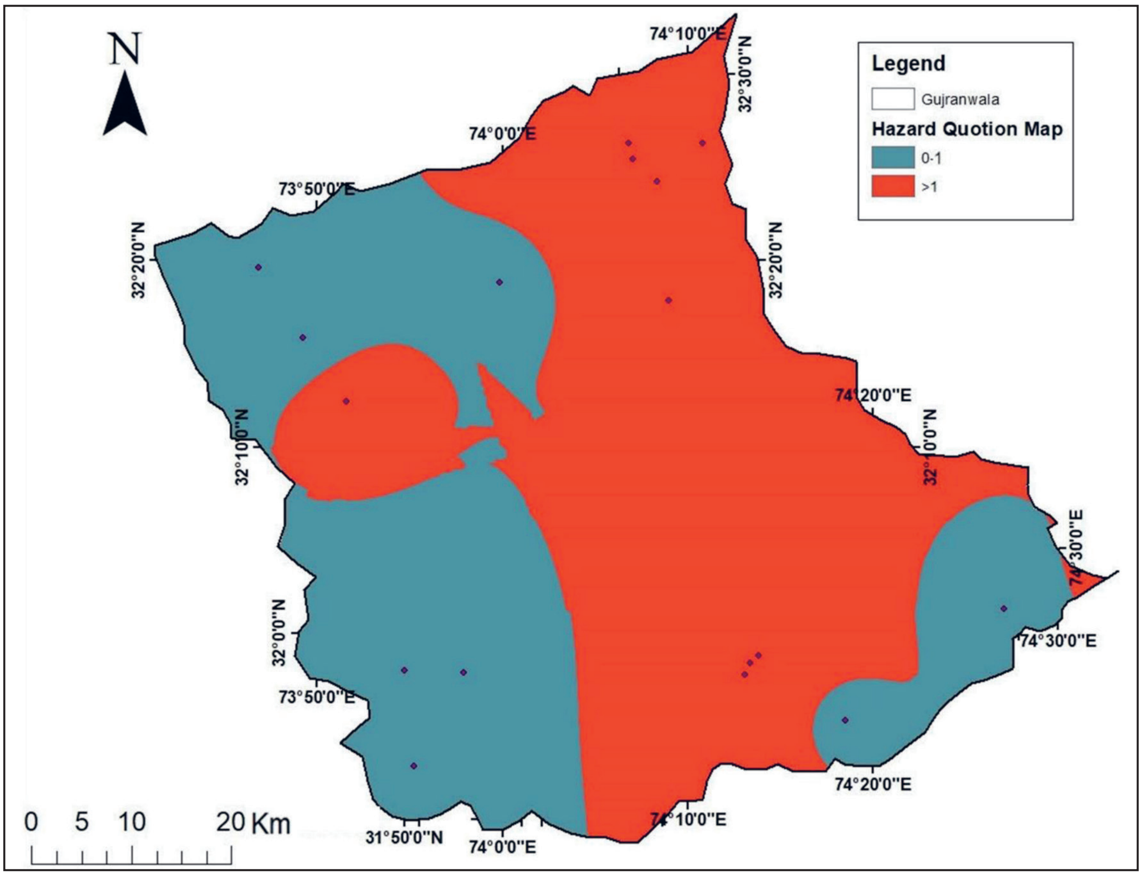

Figure 6. The HQ map with potential health risks indicated by red color.

of 13.14 µg/L. Almost 36% of samples lie within the safe limits described by the WHO, while 64% of samples are considered to exceed the safe limit. The spatial distribution of As concentration in the study area is shown in Figure 5. Among the 28 water samples, 18 have As values higher than the maximum allowed limit described by the WHO.

5.5. Health Risk Assessment

The current research study results show that the average daily dose ranges from 3.61E-6 to 1.49E-3 mg/kg/day with an average of about 3.73E-4 mg/kg/day. The HQ values of samples collected from the study area range from 0.012 to 4.97, with 1.21 as the average value. Almost 43% of the collected samples have HQ values within the threshold limit (i.e., "1") while the rest of the 57% of samples exceed the toxic risk index. So, based on the overall results of "HQ" it is suggested that there is a substantial risk of As poisoning in the study area. The carcinogenic risk due to As contamination ranges from 1.11E-3 to 5.41E-6. Based on the above health analysis, we can conclude that the inhabitants of Gujranwala are subjected to a substantial health risk from As contamination in the collected groundwater samples.

Table 3. The results of ADD (mg/kg/day), HQ and cancer risk assessment for groundwater samples.

As	ADD	HQ	CR
20.42	5.67E-4	1.890	8.51E-4
11.46	3.18E-4	1.061	4.78E-4
6.529	1.81E-4	0.604	2.72E-4
15.28	4.24E-4	1.414	6.37E-4
13.14	3.65E-4	1.216	5.48E-4
12.45	3.46E-4	1.152	5.19E-4
18.63	5.18E-4	1.725	7.76E-4
17.58	4.88E-4	1.627	7.33E-4
18.76	5.21E-4	1.737	7.82E-4
18.25	5.07E-4	1.689	7.6E-4
10.55	2.93E-4	0.976	4.4E-4
11.28	3.13E-4	1.044	4.7E-4
4.702	1.31E-4	0.435	1.96E-4
2.722	7.56E-5	0.252	1.13E-4
18.32	5.09E-4	1.696	7.63E-4
8.162	2.27E-4	0.755	3.4E-4
21.98	6.11E-4	2.035	9.16E-4
26.64	7.4E-4	2.466	1.11E-3
18.31	5.09E-4	1.695	7.63E-4
53.75	1.493E-3	4.976	2.24E-3
10.13	2.81E-4	0.937	4.22E-4
13.84	3.84E-4	1.281	5.77E-4
2.83	7.86E-5	0.262	1.18E-4
5.41	1.5 E-4	0.500	2.25E-4
2.31	6.42E-5	0.213	9.63E-5
2.67	7.42E-5	0.247	1.11E-4
0.13	3.61E-6	0.012	5.42E-6
1.69	4.69E-5	0.156	7.04E-5

CONCLUSION

A study of 28 groundwater samples from Gujranwala district revealed that 64% of them have exceeded WHO arsenic levels. Sodium, magnesium, and bicarbonate are the dominant ions. While 79% of the samples are irrigable, 57% are too rich in magnesium, which is a threat to soil health. Health testing shows high risk, where 57% are above the toxic risk index. The hydrogeological characteristics of the Punjab Plain are significantly influenced by its geological formation, comprising a Quaternary alluvial complex deposited within a tectonic depression. This geological setting gives rise to a diverse aquifer composed of predominantly fine- to medium-grained sand, silt, and clay. The composition of groundwater is largely influenced by geochemical processes, particularly the weathering of rocks. When carbonate minerals including dolomite and calcite dissolve, the predominant ions in the groundwater are magnesium (Mg), bicarbonate (HCO_3), and sodium (Na). Hydrogeological conditions, notably the high permeability of the uppermost alluvial deposits, facilitate the movement of groundwater and engender substantial interaction between water and rock, resulting in the enrichment of groundwater with dissolved minerals. In conclusion, the composition of groundwater in the Gujranwala district is influenced by a intricate interplay of mineral content, geochemical processes, and geological structures. The quality and chemical composition of the groundwater are shaped by its interaction with alluvial sediments and the hydrogeological characteristics of the aquifer. This has significant implications for its suitability for drinking and irrigation purposes.

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