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Original Research

Groundwater Quality Assessment for Drinking Purpose in Faisalabad City Using GIS and Water Quality Index

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Abstract

Water is an essential natural resource, fundamental to human survival, food production, energy generation, industrial development, environmental protection, and sustainable growth for future generations. Ensuring safe drinking water requires continuous monitoring of groundwater quality, particularly in densely populated and water-stressed urban centers. This study addresses the research gap in multi-year groundwater quality assessment by integrating GIS-based spatial analysis with the Weighted Arithmetic Water Quality Index (WQI) method for the first time to assess the potability of groundwater in Faisalabad, the third largest city in Pakistan, and a major industrial hub. A total of 1,188 groundwater samples were analyzed between 2015-2020 for physicochemical parameters, and groundwater suitability was assessed using the Weighted Arithmetic Water Quality Index (WQI). Spatial variation was mapped with the Inverse Distance Weighted (IDW) technique in ArcGIS 10.8. Results showed that pH ranged from 6.8-8.2, chlorides 20-1885 mg/L, total dissolved solids (TDS) 138-3926 mg/L, sulfate 10-893 mg/L, sodium 10-1411 mg/L, bicarbonates 68-1400 mg/L, total hardness (as $CaCO_3$) 80-1250 mg/L, and electrical conductivity (EC) 278-7852 µS/cm. The calculated Water Quality Index (WQI) averaged 84%, indicating overall poor quality. Groundwater quality was highest in the Gatwala area due to recharge from the Rakh Branch Canal, whereas the poorest quality was observed along Maqbool and Satyana Roads, largely influenced by textile dyeing industries. The findings highlight that Faisalabad's groundwater requires pretreatment before domestic or agricultural use. Sustainable groundwater management can be achieved through continuous monitoring, improved waste disposal practices, and the adoption of advanced treatment technologies.

Keywords: drinking water, water quality index (WQI), ArcGIS, physicochemical, water quality standards, IDW

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Introduction

Water is essential to life and growth. It remains a limited resource, and its scarcity often leads to emergencies. These shortages hamper economic growth and people's ability to live good lives. This can be assessed at various levels, including international as well as Pakistan's national and local initiatives aimed at improving access to clean, high-quality drinking water for the general public. According to an estimate, 60% of people in underdeveloped countries do not have access to potable water. The degradation of groundwater resources is the main reason for health-related issues. About 2.3 billion people worldwide are vulnerable to illnesses caused by contaminated water [1].

Water pollution remains a critical global health risk, contributing significantly to the nearly 9 million premature deaths annually linked to pollution. Although deaths from unsafe drinking water have declined in recent years, rising contamination of surface and groundwater from industrial effluents, agricultural runoff, and urban waste continues to endanger public health. Water pollution, closely tied to climate change and biodiversity loss, now demands urgent global action and sustainable clean water strategies [2]. Owing to widespread extraction, groundwater quantity and quality are declining in many regions; intensive pumping from public and private wells, especially in growing urban centers, lowers water tables and can aggravate salinity and contaminant mobilization [3, 4]. As global population growth, food production, and urbanization accelerate, integrated water-resources management is essential to meet rising demand; worldwide freshwater use has been increasing by about 1% per year since the 1980s, agriculture still accounts for roughly 70% of withdrawals, and industrial/municipal demands are growing fastest [5, 6]. The availability of safe drinking water is fundamental for public health, sustainable development, and is internationally recognized as a basic human right under the United Nations Sustainable Development Goals (SDG 6) [7].

Demographic growth and intensified agriculture drive water consumption per person upward, while rising industrial and energy demands compound this stress. In fact, Asia has seen some of the largest groundwater depletion rates globally, especially in irrigated regions, undermining the sustainability of water resources [8]. Recent global assessments show rapid groundwater level declines (>0.5 m/year) in agricultural and arid zones over the twenty-first century, signaling an acceleration of water-stress trends [9]. Concurrently, about 2.1 billion people worldwide lack access to safely managed drinking water, affirming that water insecurity remains a serious human rights and development challenge [10].

Situated in South Asia, Pakistan remains heavily reliant on agriculture. However, rapid industrialization and urban expansion now contribute significant untreated industrial and municipal effluents to surface and groundwater bodies, degrading water quality and undermining its suitability for irrigation and agricultural use [11, 12].

Pakistan is a predominantly agricultural economy, and to meet irrigation deficits it abstracts ~60-80 BCM of groundwater annually, with national assessments indicating ~62 BCM and basin-scale estimates attributing ~82 BCM yr^{-1} of irrigation water to groundwater [13]. Groundwater quality in many Pakistani cities – such as Lahore, Faisalabad, Rawalpindi, Peshawar, and Karachi – has degraded due to untreated industrial and urban waste discharges, combined with heavy use of agrochemicals (fertilizers and pesticides) in surrounding agricultural zones [14]. Much of Pakistan lies within arid to semi-arid climatic zones, characterized by low annual rainfall and limited natural groundwater recharge, making the country heavily dependent on over-exploited aquifers for water supply [15]. Due to inefficiencies and poor management, over 60% of Pakistan's freshwater – especially in irrigation systems – is lost before it reaches end users. Meanwhile, only ~20% of the country's population currently has access to truly safe drinking water, making water quality a critical governance issue [16]. The Pakistan Council of Research in Water Resources (PCRWR) initiated research to investigate the quality of the water in 23 big cities across all of Pakistan's provinces from 2002 to 2006. Afterwards, the study was extended to include a total of 25 cities in 2015, and it is estimated that between 84% and 89% of water sources do not meet the minimum requirements set for human use by the EPA [17]. One of Pakistan's most pressing groundwater health risks is the co-occurrence of microbial contamination, imbalances in major anions/cations, and toxic heavy metals, repeatedly reported across multiple urban and agro-industrial settings [18, 19]. Waterborne diseases in Pakistan contribute substantially to the health burden: many studies suggest that ~33-40% of illnesses and deaths are related to contaminated water and sanitation issues. The impacts include hospital admissions for cholera, typhoid, hepatitis, diarrhea, and other waterborne infections, particularly in areas relying on polluted groundwater sources [20, 21].

This sustained industrial expansion in and around Faisalabad has led to the discharge of large volumes of untreated effluents rich in organic matter, nutrients, dyes, and heavy metals such as chromium, cadmium, and lead. These pollutants infiltrate both surface water and aquifers, causing deterioration of water quality, bioaccumulation risks in crops irrigated with wastewater, and long-term health hazards for local communities [22]. The groundwater quality of Chokera, Faisalabad (Pakistan) was assessed using the Water Quality Index (WQI) approach to evaluate both temporal and spatial variations in groundwater status. A total of sixty groundwater samples were analyzed for their physicochemical characteristics, and WQI was calculated following the methodology proposed by Tiwari and Mishra. The WQI values ranged between

73 and 270, indicating that the majority of samples fell within the poor to very poor quality category. The findings suggest that the groundwater in Chokera requires treatment prior to consumption and necessitates protective measures against further contamination [23].

Materials and Methods

This study was conducted in Faisalabad, northeastern Punjab, Pakistan (31.4504°N, 73.1350°E; Fig. 1). The climate is hot desert (Köppen–Geiger BWh), with typical temperatures of 18-33°C and mean annual rainfall around 370 mm. Winters (December-February) are cooler, while the southwest monsoon peaks in July-August. Because precipitation is limited, natural groundwater recharge is low. Dominant crops include wheat, rice, cotton, sugarcane, and maize.

During 2015-2020, groundwater was sampled at 99 fixed borehole locations across Faisalabad twice annually (pre- and post-monsoon; depths 50-120 m), yielding 198 samples per year and 1,188 samples in total. Samples were collected in precleaned 2-L high-density polyethylene (HDPE) bottles, triple-rinsed with sample water, and handled under clean conditions. Collection, preservation, and transport followed Standard Methods. Immediately after collection, samples were stored at ~4°C and transported in chilled coolers to the Water and Sanitation Agency (WASA) Research Laboratory, Faisalabad, for physicochemical analysis. QA/QC measures were applied throughout to minimize contamination.

Parameters with major influence on groundwater quality – EC, TDS, pH, carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), total hardness (TH), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), sulfate (SO_4^{2-}), and chloride (Cl^-) – were measured in the Water Quality Laboratory. EC, pH, and TDS were determined using a calibrated multiparameter meter (TOA-WQA-20A) following standard calibration with appropriate buffers/standards. Sulfate was analyzed by UV-Vis spectrophotometry using the turbidimetric barium chloride method (APHA 4500-SO_4^{2-} E). Sodium was quantified by flame photometry (APHA 3500-Na). Calcium and magnesium were obtained by EDTA titrimetry with TH computed as $CaCO_3$ (APHA 2340 C), while alkalinity (HCO_3^-/CO_3^{2-}) was measured by acid titration (APHA 2320 B) and chloride by argentometric titration (APHA 4500-Cl^- B). All procedures, including sample preservation, instrument calibration, and QA/QC checks (blanks and duplicates), followed Standard Methods [24].

Water Quality Index (WQI)

The Water Quality Index (WQI) is one of the most commonly used tools to describe water quality. Aggregation methods are utilized to reduce enormous water quality data into a single value or index. Models of the Water Quality Index typically consist

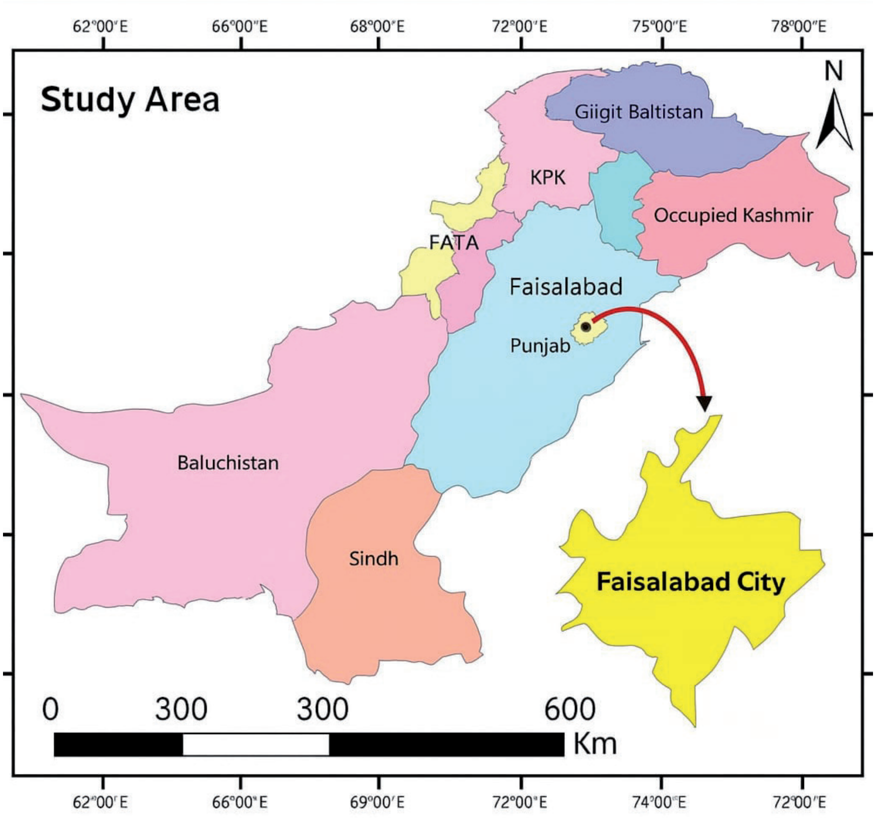

Fig. 1. Map showing the study area of Faisalabad.

of the following four steps in sequential order: (1) determining the relevant factors of water quality, (2) developing sub-indices for every available parameter, (3) calculating parameter weighting values, and (4) formulating the WQI by adding up the component indices. Multiple studies have used WQI models in diverse situations to estimate the water quality of different bodies of water, including rivers, lakes, reservoirs, and estuaries. According to the weighted arithmetic WQI classification, water quality is rated as excellent (WQI 0-25), good (26-50), poor (51-75), very poor (76-100), and unsuitable for drinking when WQI>100.

Following the World Health Organization (WHO) guidelines [25], the Water Quality Index (WQI) was computed using the weighted arithmetic method. This approach was originally proposed in 1965 [26] and later modified in 1972 [27]. The general form of the weighted arithmetic WQI is expressed as follows:

$$WQI = \sum_{i=1}^{n} W_i\, Q_i / \sum_{i=1}^{n} W_i$$

where:
Qi = quality value of the concerned water quality parameter,
n = number of variables and parameters,
Wi = unit weight for the concerned parameter.

The unit weight (Wi) of different water quality parameters is determined based on an inverse relationship with their respective recommended standards.

$$W_i = K / S_n$$

where:
K = proportionality constant,
Wi = unit weight for the concerned parameter,
Sn = standard value for concerned parameters.

$$K = 1 / \sum (\frac{1}{S_n})$$

As per Brown et al. (1972), the quality rating or sub-index (Qi) is determined using the following Equation:

$$Q_i = 100[\frac{V_\circ - V_i}{S_n - V_i}]$$

where:
Sn = standard permissible value of the concerned parameter,
Vo = observed value of the concerned parameter at a given sampling site,
Vi = ideal value of the concerned parameter in pure water.

Results

Groundwater hydrology provides essential information on water quality, which is critical for assessing its suitability for drinking and irrigation purposes. To evaluate drinking water quality, the standards set by the Pakistan Standards and Quality Control Authority [28] and the World Health Organization [25] were used.

Drinking Water Quality

Water quality covers the chemical, biological, and physical characteristics of water. Variations in groundwater composition largely reflect aquifer geology and residence time, as water-rock interactions control solute acquisition and evolution [29]. Accordingly, most groundwater studies routinely measure TDS, EC, pH, major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^-, Cl^-, SO_4^{2-}), and total hardness (TH) to evaluate suitability for use [30].

pH

The pH scale is one of the most widely used indicators for assessing soil and water quality. Ranging from 1 to 14, it reflects the degree of acidity or alkalinity in water. A value of 7.0 represents neutrality, values below 7.0 indicate acidity, and values above 7.0 denote alkalinity. According to the standards of the World Health Organization (WHO) and the Pakistan Standards and Quality Control Authority (PSQCA), drinking water should have a pH within the range of 6.5-8.5 [25, 27]. In the present study area, the pH of groundwater samples varied between 6.8 and 8.2, with a mean value of 7.5 and a range of 1.4. As illustrated in Fig. 2, most of the samples fall within the permissible range defined by WHO guidelines, indicating that the majority of the water in this region meets acceptable pH standards for drinking purposes.

Electrical Conductivity (EC)

Electrical conductivity (EC) represents the ability of water to conduct an electric current and serves as an important indicator of salinity and of overall water quality. It directly reflects the concentration of dissolved salts and mineral content, which are critical for determining the suitability of water for drinking purposes. In the present study area, EC values ranged from 278 to 7852 µS/cm, with an average of 2838 µS/cm and a range of 7574 µS/cm. According to the standards set by the World Health Organization (WHO) and the Pakistan Standards and Quality Control Authority (PSQCA), the permissible limit for drinking water is 1500 µS/cm [25, 27]. As illustrated in Fig. 3, approximately 61% of the analyzed groundwater samples exceeded this threshold, while only 39% remained within safe limits. These findings highlight that groundwater quality in much of the study area is unsuitable for drinking due to elevated salinity levels.

Total Dissolved Solids (TDS)

Total dissolved solids (TDS) comprise dissolved inorganic salts with traces of organics in water. In groundwater, the dominant ions typically include the cations Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and the anions HCO_3^{-}, Cl^{-}, SO_4^{2-}, and NO_3^{-}, reflecting water-rock interactions and residence time [31]. Elevated TDS is closely linked with salinity, taste/palatability issues, scaling/corrosion, and hardness, and thus serves as a practical indicator of drinking-water suitability [32]. Accordingly, most

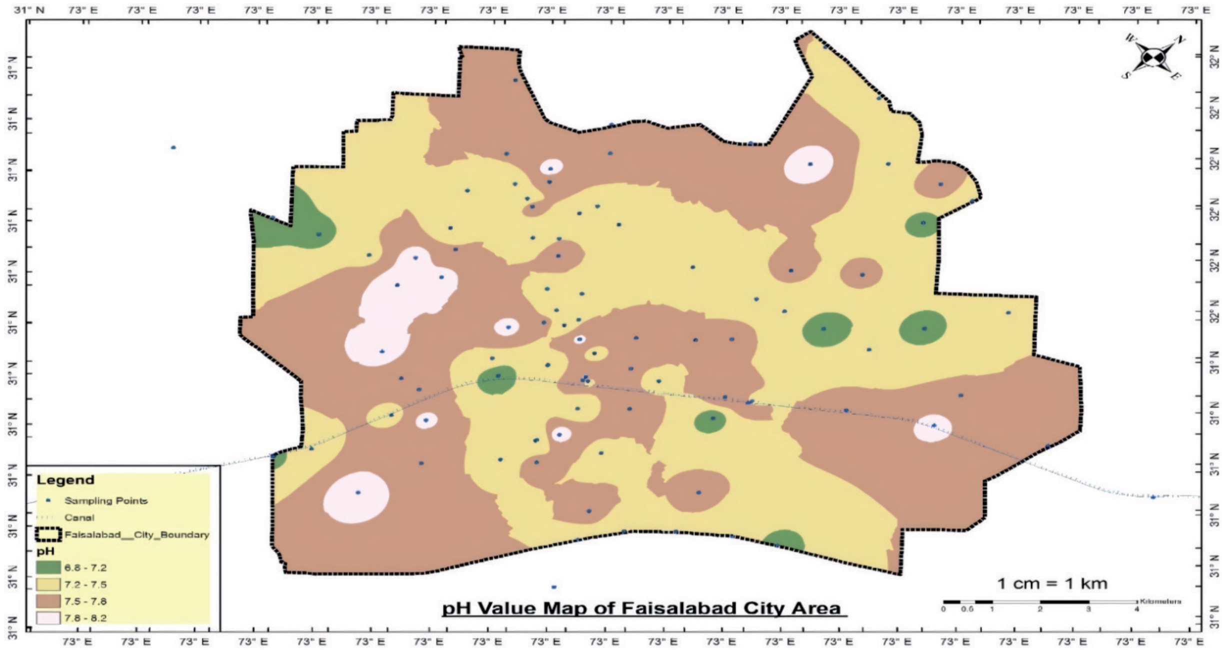

Fig. 2. Spatial variation of pH in the study area of Faisalabad city.

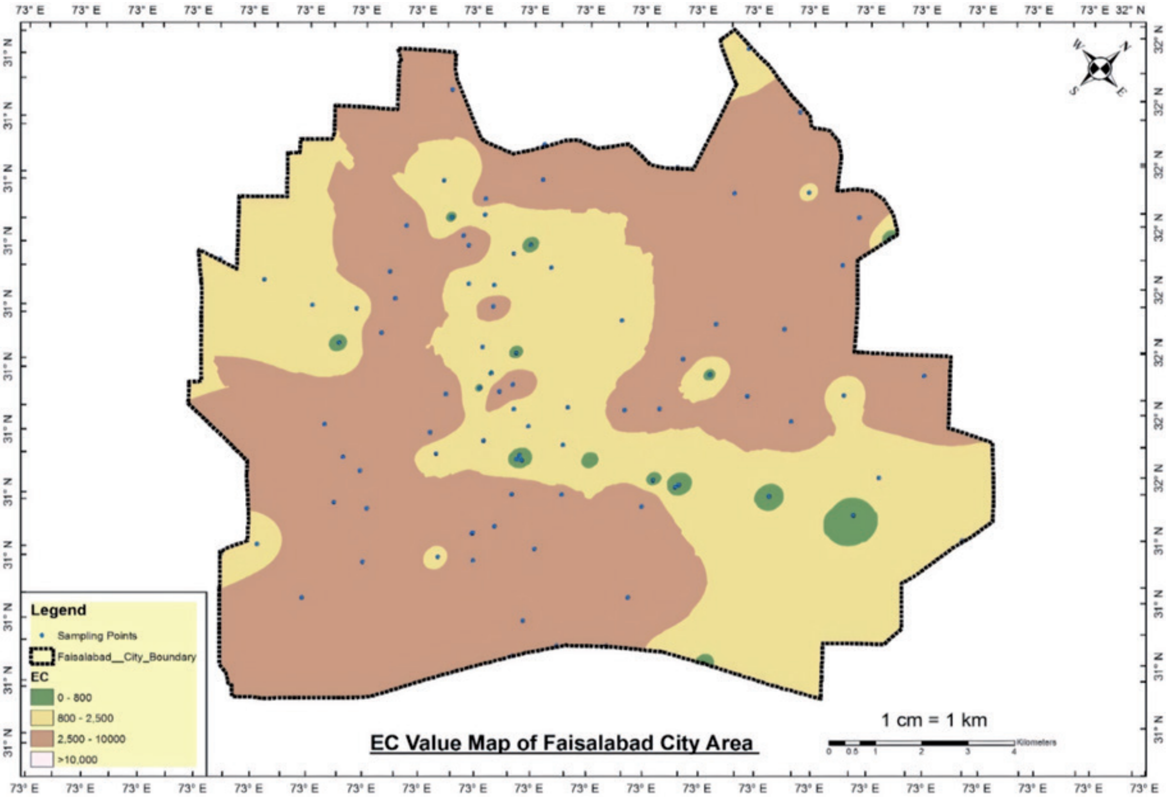

Fig. 3. Spatial variation of EC in the study area of Faisalabad city.

groundwater assessments routinely quantify TDS, EC, pH, major cations/anions, and total hardness (TH) to evaluate use constraints [33]. WHO and PSQCA recommend a maximum TDS concentration of 1000 mg/L in potable water. In the study area, the TDS value ranges from 138 to 3926 mg/L with a mean value of 1440 mg/L and a range of 3788 mg/L. Fig. 4 shows the spatial variation of TDS in different parts of the city.

Total Hardness (TH)

Total hardness (TH) arises from the combined concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}). TH was computed as mg L^{-1} as $CaCO_3$ using the standard relation

$$TH\ (mg\ L^{-1}\ as\ CaCO_3) = (Ca^{2+} + Mg^{2+}) \times 50$$

where Ca^{2+} and Mg^{2+} are in meq L^{-1} [33].

In the study area, TH ranged from 80 to 1250 mg L^{-1}, with the maximum at sampling point 83 and the minimum at sampling point 33. For drinking water acceptability, the reference value is 500 mg L^{-1} as $CaCO_3$ under WHO guidelines and PSQCA national standards [25, 27]. As shown in Fig. 5, large portions of the area exceed this limit, indicating widespread hardness and the need for appropriate treatment prior to consumption.

Chloride (Cl^-)

Chloride (Cl^-) occurs naturally in groundwater at low-moderate levels from mineral dissolution, while elevated concentrations often reflect salinization processes (e.g., wastewater/industrial effluents, irrigation return flows, or seawater intrusion) [34]. In drinking water, chloride mainly affects palatability rather than causing direct health effects; accordingly, the WHO assigns a taste-based guideline value of 250 mg L^{-1}, and Pakistan's national standards generally adopt the same benchmark [25, 35]. In the present study area, chloride ranged from 20 to 1885 mg L^{-1} (Fig. 6); thus, a substantial share of samples exceeded 250 mg L^{-1}, indicating localized salinity loading. Elevated chloride also increases water corrosivity, which can destabilize pipe scales and mobilize metals into distribution water.

Sulfate (SO_4^{-2})

Sulfate (SO_4^{2-}) in groundwater primarily originates from dissolution of evaporitic minerals (e.g., gypsum/anhydrite) and oxidation of sulfides and may also be introduced via industrial and municipal effluents. Although not usually linked to systemic toxicity, elevated sulfate impairs organoleptic quality and can exert an osmotic (laxative) effect, especially when present as sodium or magnesium salts [36]. WHO does not set a health-based guideline value for sulfate; taste impairment is generally minimal below 250 mg/L [25]. In our study area, SO_4^{2-} ranged from 10-893 mg/L (mean: 346 mg/L), with a substantial fraction exceeding 250 mg/L (Fig. 7), indicating zones affected by evaporite dissolution and anthropogenic inputs and suggesting a risk of gastrointestinal discomfort in unaccustomed consumers at higher concentrations. For the national context, Pakistan's notified drinking-water standards (NDWQS/PSQCA) are widely applied operationally and align with WHO on acceptability ranges; many local studies treat ~250 mg/L as the practical threshold for potable supply [27].

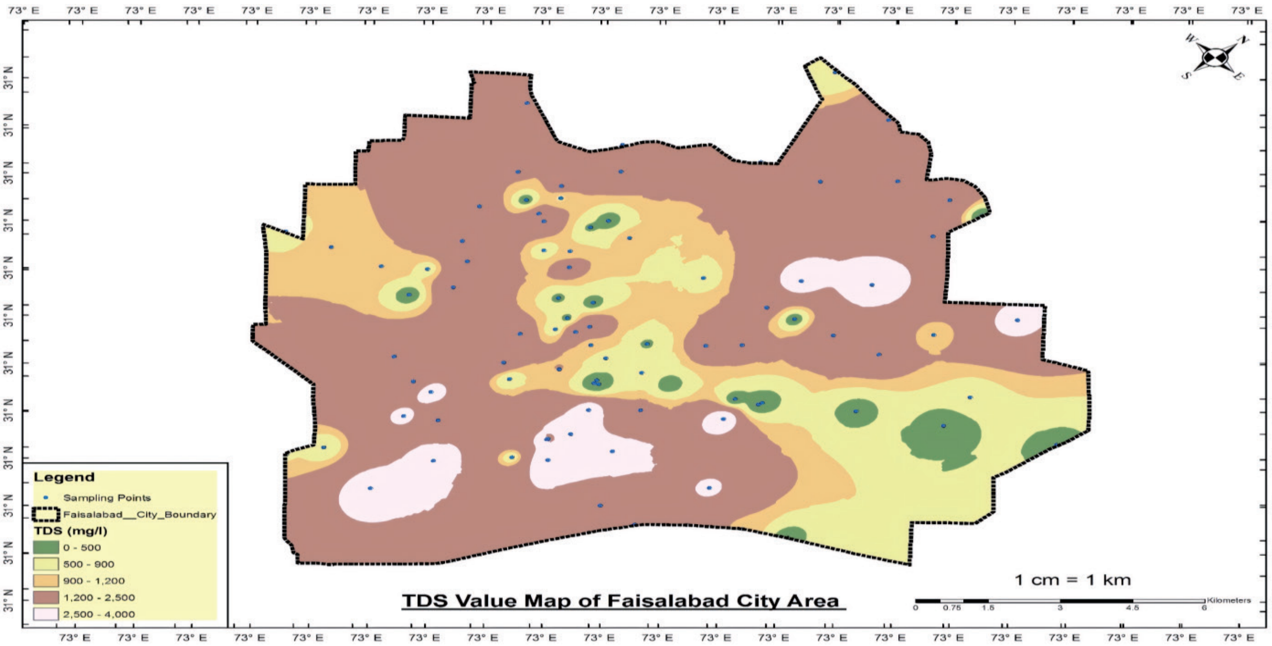

Fig. 4. Spatial variation of TDS in the study area of Faisalabad city.

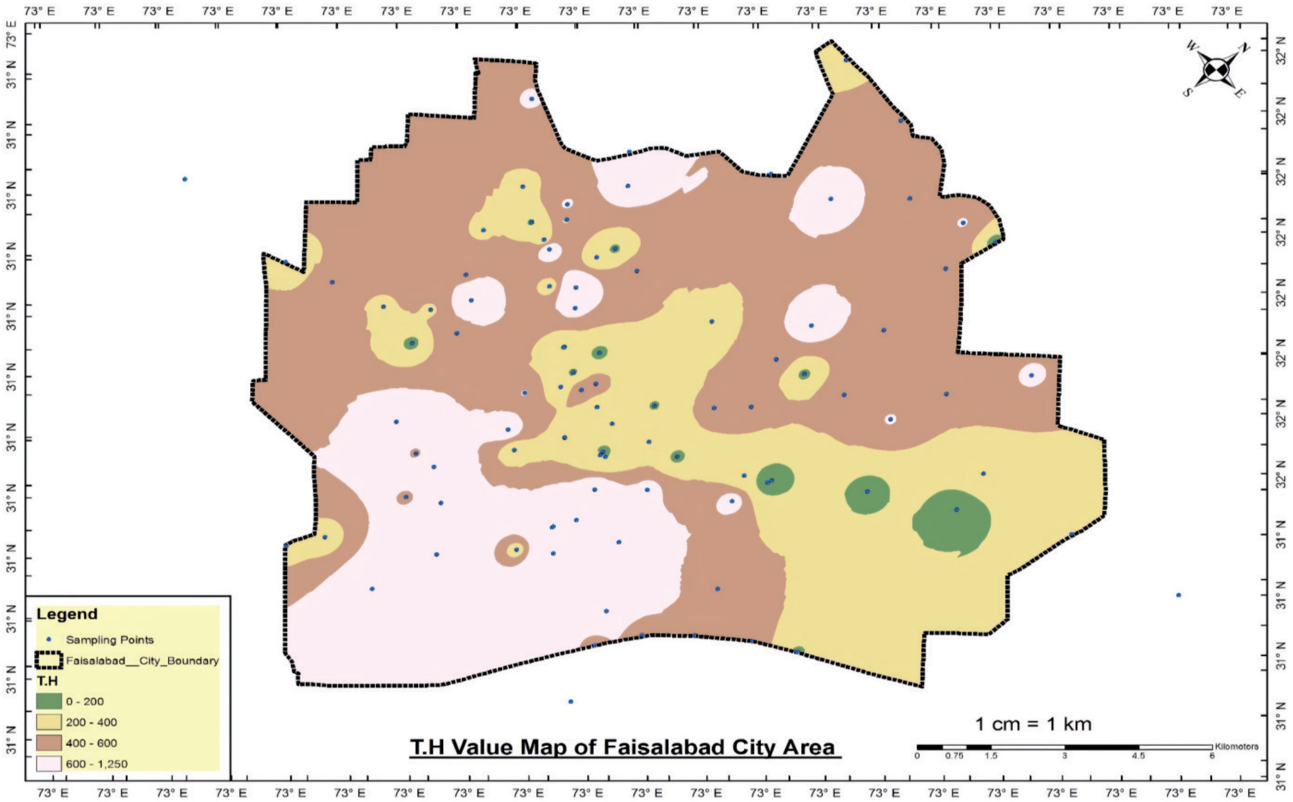

Fig. 5. Spatial variation of TH in the study area of Faisalabad city.

Bicarbonate (HCO_3^{-1})

Bicarbonate (HCO_3^-) in groundwater principally reflects carbonic acid weathering and dissolution of carbonate minerals (e.g., calcite, dolomite); at circumneutral to slightly alkaline pH, it typically dominates total alkalinity and tracks lithology, residence time, and CO_2 inputs from soils [37]. In the present study, HCO_3^- ranged from 68-1400 mg L^{-1} (mean 437 mg L^{-1}), indicating carbonate-influenced hydrochemical facies with zones of elevated alkalinity (Fig. 8). The WHO does not set a health-based guideline value for bicarbonate;

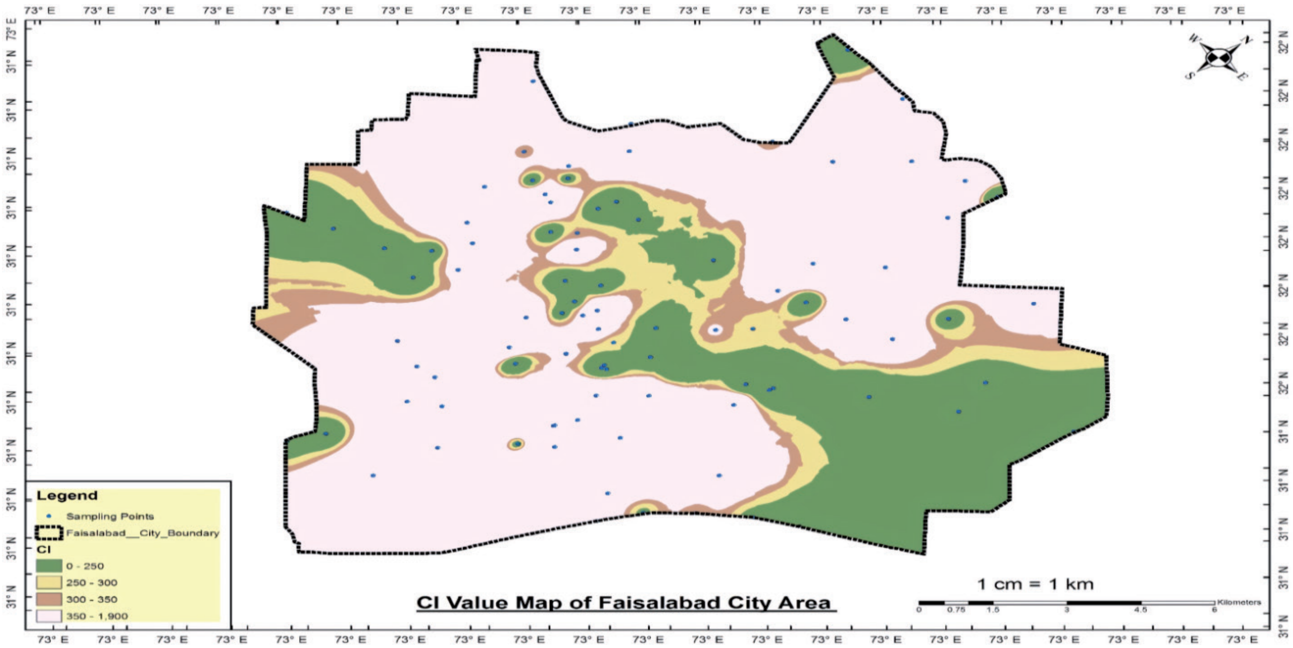

Fig. 6. Variation of Cl^- in the area of Faisalabad city.

related concerns are chiefly acceptability/operational (taste, scaling) rather than direct toxicity [24]. Consistent with WHO's approach, Pakistan's national standards emphasize overall alkalinity/TDS management and do not prescribe a specific numeric limit for HCO_3^- [38].

Calcium (Ca^{+2})

Calcium in groundwater is predominantly geogenic, released through dissolution of carbonate minerals (calcite, dolomite) and, locally, sulfate minerals (e.g., gypsum/anhydrite); its distribution is further shaped by rock-water interaction and ion-exchange processes

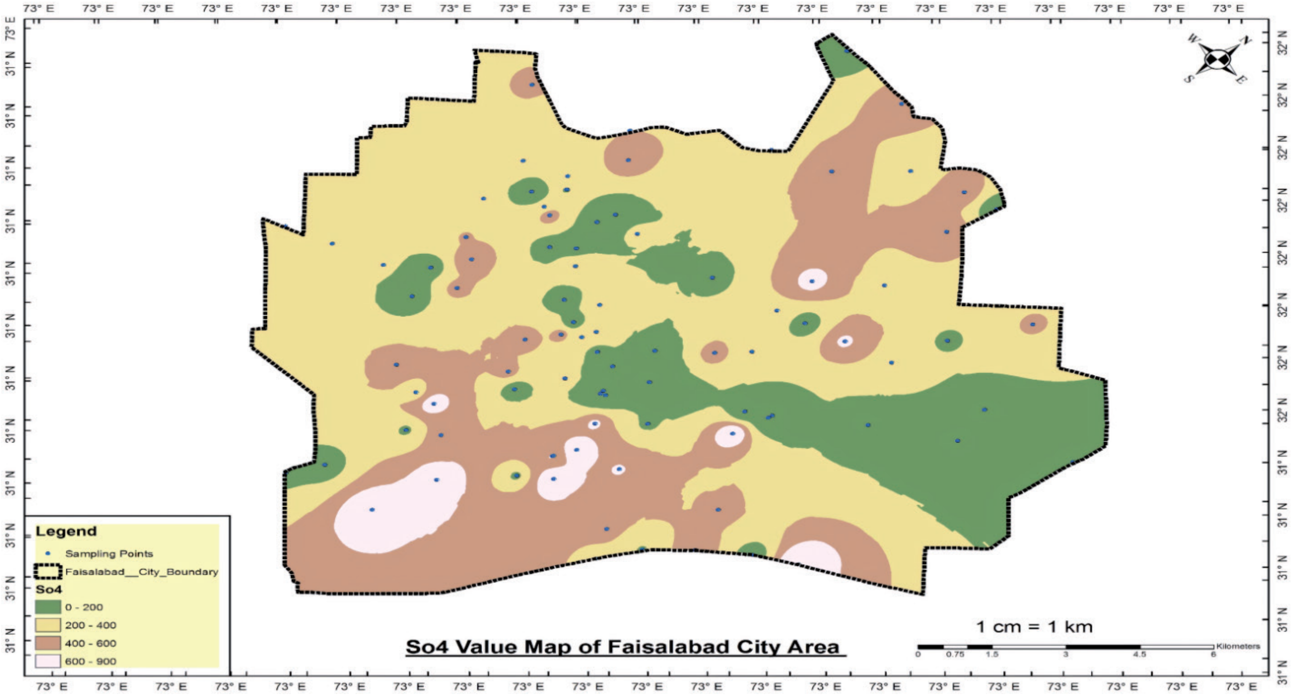

Fig. 7. Variation of SO_4^{-2} in the study area of Faisalabad city.

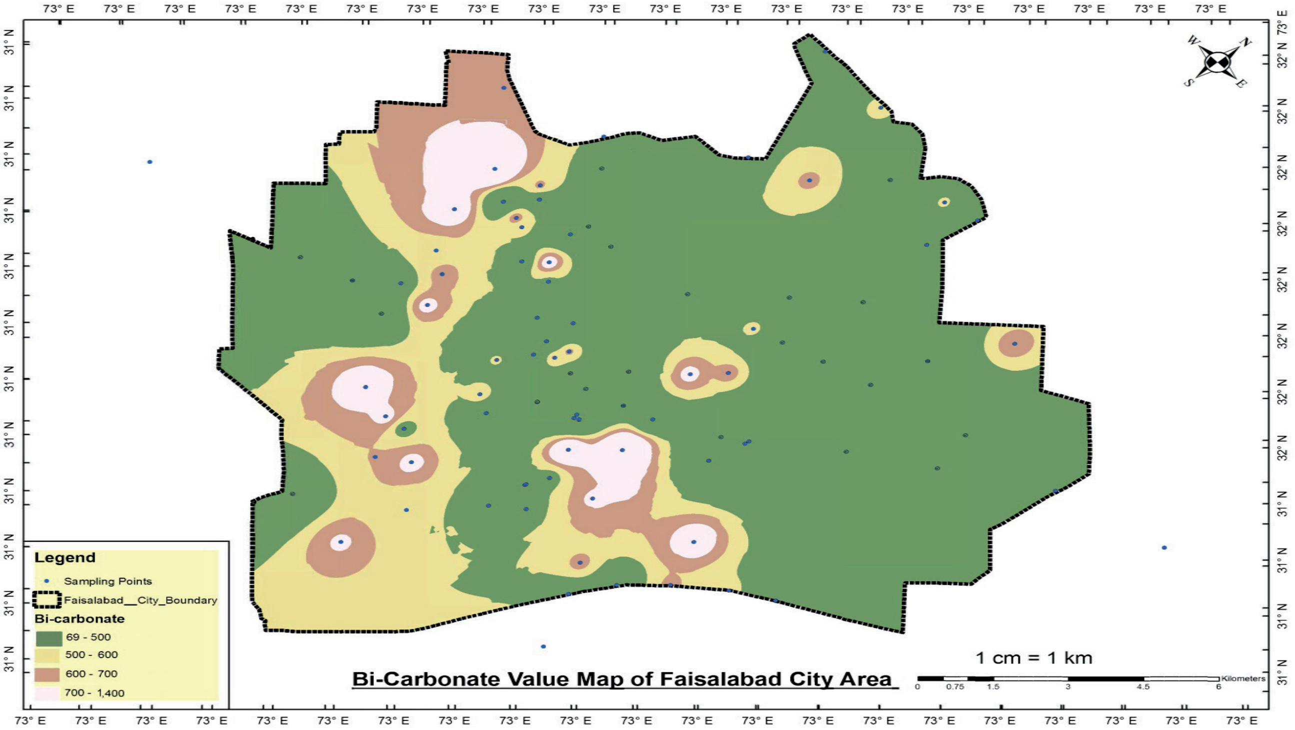

Fig. 8. Variation of HCO_3^{-1} in the study area of Faisalabad city.

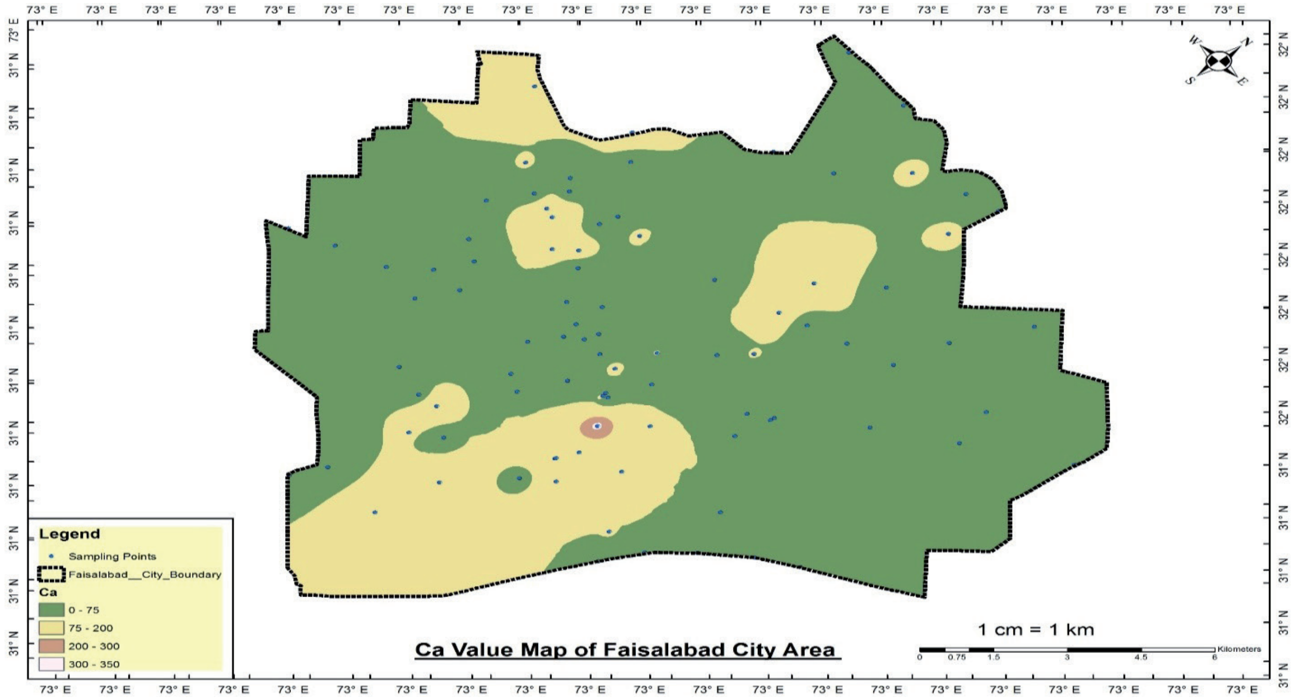

Fig. 9. Variation of Ca^{+2} in the study area of Faisalabad city.

[39]. In the present study area, Ca^{2+} ranged from 16 to 323 mg L^{-1} (mean 65 mg L^{-1}; range 307 mg L^{-1}) as shown in Fig. 9. No health-based guideline value is set for calcium in the WHO GDWQ (2022), and Pakistan's NDWQS similarly do not specify a calcium limit; potability is typically assessed via total hardness (threshold 500 mg L^{-1} as $CaCO_3$) [40].

Magnesium (Mg^{2+})

Magnesium (Mg^{2+}) is ubiquitous in natural waters, predominantly derived from the dissolution of dolomite and ferromagnesian silicates; together with Ca^{2+} it is a principal contributor to water hardness and related scaling/taste issues [41]. In the present study area, Mg^{2+} ranged from 5 to 242 mg L^{-1} (Fig. 10). Although the WHO Guidelines for Drinking-water Quality do not set a health-based guideline value for Mg^{2+}, elevated concentrations can impair palatability and – particularly where sulfate is high – produce an osmotic (laxative) effect in unaccustomed consumers [25, 36]. For regulatory context, Pakistan's specification for bottled drinking water (PS:4639) sets an operational cap of 50 mg L^{-1} for Mg^{2+} [6].

Sodium Na^{+}

Sodium (Na^{+}) is highly soluble and commonly present in groundwater; at elevated levels, it chiefly affects palatability rather than odor, with an average taste threshold near 200 mg L^{-1} and no health-based WHO guideline value [24]. Evidence from cohort and population studies indicates that saline (sodium-rich) drinking water can elevate blood pressure and may adversely affect renal markers, particularly in vulnerable groups (e.g., those with hypertension, heart disease, or kidney disorders) [42]. In the present study area, Na^{+} ranged from 10-1411 mg L^{-1} (Fig. 11), meaning a substantial fraction of samples exceeded the taste-based benchmark of ~200 mg L^{-1}, underscoring the need for source protection and desalination/softening measures where exceedances occur [43].

Water Quality Index (WQI)

The Water Quality Index (WQI) in the study area ranged from 20.53 to 170.36 (Table 1). Based on the classification adopted in this study, 1% of samples were excellent, 15% good, 23% poor, 19% very poor, and 42% unsuitable (for drinking). Overall, 84% of samples fell below the "good" category (poor + very poor + unsuitable), indicating widespread deterioration of groundwater quality across the area.

Discussion

Faisalabad, the textile hub of Pakistan, hosts numerous dyeing units and textile mills within the city limits. Most of these industries discharge untreated effluents directly into the environment, which has become the principal cause of groundwater deterioration. The combined effects of industrial effluents, unregulated abstraction, and limited natural recharge have significantly degraded water quality in the central and southern parts of the city. In contrast,

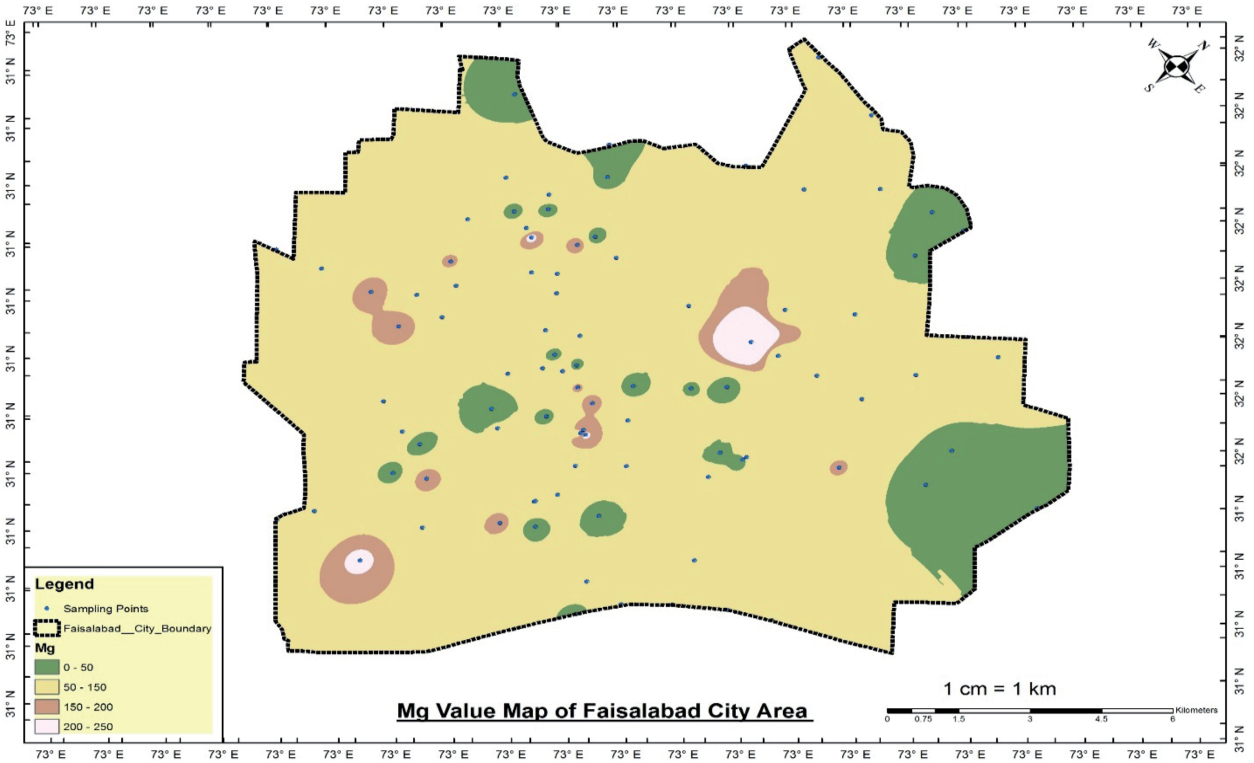

Fig. 10. Variation of Mg^{2+}in the study area of Faisalabad city.

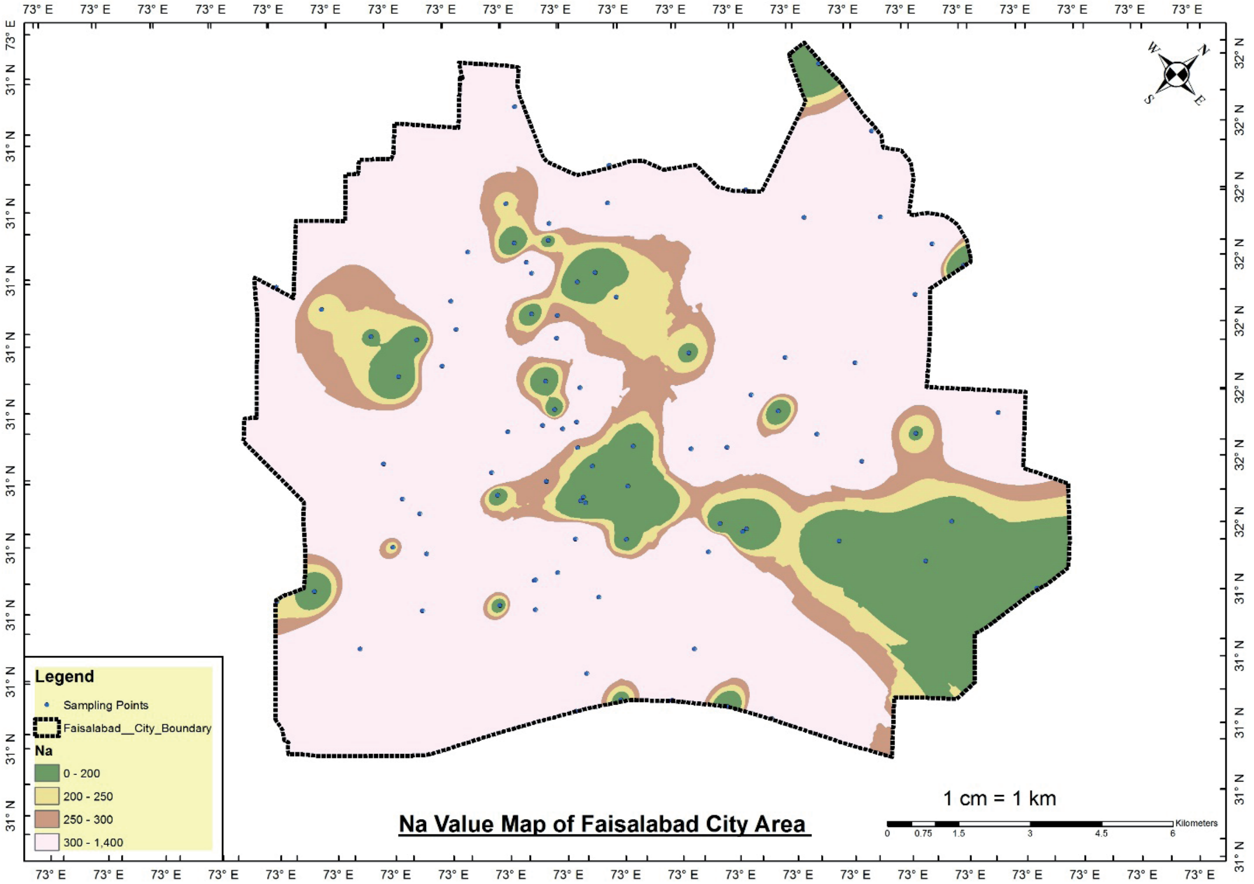

Fig. 11. Spatial Variation of Na^+ in the study area of Faisalabad city.

Table 1. Details of Water Quality Index rate of analyzed samples.

Sample No.	Index Rate	Water Quality	Sample No.	Index Rate	Water Quality
1	74.926	Poor	51	110.34	Unsuitable
2	126.441	Unsuitable	52	106.499	Unsuitable
3	119.441	Unsuitable	53	51.651	Poor
4	68.153	Poor	54	72.022	Poor
5	43.736	Good	55	108.84	Unsuitable
6	44.751	Good	56	53.156	Poor
7	104.366	Unsuitable	57	107.217	Unsuitable
8	47.541	Good	58	102.725	Unsuitable
9	88.467	Very poor	59	144.298	Unsuitable
10	108.202	Unsuitable	60	52.264	Poor
11	60.57	Poor	61	95.38	Very poor
12	38.22	Good	62	60.918	Poor
13	101.815	Unsuitable	63	69.902	Poor
14	106.856	Unsuitable	64	56.151	Poor
15	150.822	Unsuitable	65	94.368	Very poor
16	151.265	Unsuitable	66	78.325	Very poor
17	134.172	Unsuitable	67	93.248	Very poor
18	51.949	Poor	68	99.104	Very poor
19	117.604	Unsuitable	69	79.245	Very poor
20	110.883	Unsuitable	70	72.625	Poor
21	20.532	Excellent	71	52.527	Poor
22	149.379	Unsuitable	72	66.99	Poor
23	114.455	Unsuitable	73	98.803	Very poor
24	110.664	Unsuitable	74	72.882	Poor
25	76.919	Very poor	75	112.14	Unsuitable
26	118.632	Unsuitable	76	106.895	Unsuitable
27	86.987	Very poor	77	48.718	Good
28	170.358	Unsuitable	78	103.914	Unsuitable
29	129.129	Unsuitable	79	110.3	Unsuitable
30	114.399	Unsuitable	80	90.559	Very poor
31	42.49	Good	81	66.177	Poor
32	48.848	Good	82	109.539	Unsuitable
33	42.579	Good	83	114.563	Unsuitable
34	45.765	Good	84	61.115	Poor
35	45.772	Good	85	100.564	Unsuitable
36	121.066	Unsuitable	86	81.867	Very poor
37	47.103	Good	87	52.726	Poor
38	150.566	Unsuitable	88	49.051	Good
39	53.419	Poor	89	49.205	Good

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40	93.31	Very poor	90	105.118	Unsuitable
41	123.603	Unsuitable	91	98.694	Very poor
42	46.964	Good	92	58.614	Poor
43	143.688	Unsuitable	93	49.517	Good
44	114.731	Unsuitable	94	83.362	Very poor
45	71.868	Poor	95	74.004	Poor
46	97.031	Very poor	96	76.593	Very poor
47	97.63	Very poor	97	74.614	Very poor
48	130.536	Unsuitable	98	137.825	Unsuitable
49	52.193	Poor	99	71.967	Poor
50	103.296	Unsuitable			

comparatively better quality in Gatwala and the eastern zones is attributed to recharge from the Rakh Branch Canal, which dilutes contaminants. The analysis identifies Maqbool Road and Satyana Road as critical hotspots of contamination resulting from textile dyeing discharges.

To reverse this trend, the study recommends a multi-tiered strategy that includes: (i) strict enforcement of industrial effluent pretreatment before discharge into open drains; (ii) promotion of wastewater recycling and decentralized treatment systems to lessen the pollutant load on aquifers; (iii) artificial recharge measures, such as infiltration basins and canal-seepage enhancement; (iv) controlled abstraction through licensing and volumetric metering; and (v) establishment of a GIS-based monitoring and reporting framework for continuous assessment of groundwater quality.

Considering the hydrogeological characteristics of the Faisalabad aquifer – average recharge rate of about 10-15% per year and relatively high transmissivity – visible improvements in salinity, hardness, and chloride concentrations are expected within 8-10 years if groundwater extraction is reduced by 20-30% and pollution-control measures are effectively implemented. This recovery timeframe aligns with findings from similar semi-arid urban aquifers worldwide. The discussion further connects these outcomes with the Punjab Water Policy (2018) and Sustainable Development Goal 6 (Clean Water and Sanitation), emphasizing that sustainable groundwater governance in Faisalabad demands coordinated action among WASA, the Environmental Protection Department, and local industries.

Conclusions

This study provides the first multi-year, GIS-based Water Quality Index (WQI) assessment of groundwater in Faisalabad city, Pakistan, offering a cohesive and data-driven answer to the research question on its suitability for drinking purposes. The analysis of 1,188 samples collected between 2015 and 2020 revealed that 84% of the city's groundwater falls within poor to unsuitable quality categories, primarily due to elevated electrical conductivity, total dissolved solids, and hardness levels influenced by industrial effluents and over-extraction. These results not only validate the spatial trends identified through ArcGIS-IDW mapping but also demonstrate the robustness of the weighted arithmetic WQI approach for evaluating aquifer health in semi-arid, industrialized environments. In the broader scientific context, this research advances existing knowledge by coupling long-term field data with spatial modeling to identify contamination hotspots and potential recharge zones, thereby filling a major gap in urban groundwater quality monitoring in Pakistan.

The findings provide an empirical foundation for policy and management actions, including strict enforcement of industrial effluent pretreatment, establishment of decentralized wastewater-recycling systems, and implementation of controlled abstraction and artificial-recharge programs. Furthermore, considering the aquifer's recharge characteristics, measurable improvement in groundwater quality may require 8-10 years under reduced pumping and pollution-control conditions. Future work should integrate numerical flow and solute-transport modeling, heavy-metal risk assessment, and continuous monitoring frameworks to support adaptive management. Overall, the study contributes a replicable GIS-WQI methodology that can guide sustainable groundwater-resource planning not only in Faisalabad but also in other rapidly urbanizing regions across South Asia, aligning with the objectives of the Punjab Water Policy (2018) and Sustainable Development Goal 6 (Clean Water and Sanitation).

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Conflict of Interest

The authors declare no conflict of interest.

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