

Hydrogeochemical Assessment of Groundwater Quality in Gulshan-e-Iqbal, Karachi, Pakistan

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KEYWORDS

Groundwater quality; hydrogeochemistry; Water Quality Index; Piper diagram; carbonate dissolution; sewage contamination; Karachi; Pakistan; Ca–Na–Cl facies; urban aquifer

ABSTRACT

Rapid urbanisation and the absence of piped water infrastructure in many districts of Karachi have increased dependence on shallow groundwater; yet systematic hydrogeochemical assessments of individual town-level aquifers remain scarce. This study presents a comprehensive evaluation of groundwater quality in Gulshan-e-Iqbal Town, District East, Karachi, Pakistan, a densely populated coastal urban area underlain by the Miocene Gaj and Oligocene Nari Formations. Groundwater samples were collected from eleven boreholes and hand pumps distributed across the town and analysed for physicochemical parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, calcium (Ca^{2+}), chloride (Cl^-), and bicarbonate (HCO_3^-) using standard titration, spectroscopic, and electrochemical methods. Results were benchmarked against World Health Organization (WHO) and Pakistan National Environmental Quality Standards (NEQS) guidelines. EC varied from 0.86 to 2.47 mS/cm, indicating a broad gradient in dissolved ion concentrations across the sampling sites. Total hardness ranged from 210.77 to 1176.43 ppm (mean: 646.69 ppm), classifying most groundwater as hard to very hard, attributable to active carbonate mineral dissolution from the aquifer lithology. Chloride concentration exceeded the WHO aesthetic guideline of 250 ppm; the spatial uniformity of this exceedance, combined with the sewage odour recorded at seven sites, implicates leaking urban sewage infrastructure as the dominant anthropogenic chloride source. Bicarbonate concentrations (50.97–172.89 ppm) indicate predominantly geogenic alkalinity generated through CO_2 –water–rock interaction along the groundwater flow path. A strong positive correlation between EC and TDS confirmed the internal consistency of the dataset, while the dominance of Ca^{2+} in controlling hardness reflects carbonate weathering as the primary geochemical process. Water Quality Index (WQI) analysis classified 73% of samples as poor and 18% as very poor, with only one site (S7) meeting acceptable quality thresholds. The thresholds. The Piper diagram classification identified a mixed Ca–Na–Cl hydrochemical facies, indicating that groundwater chemistry is transitioning from natural geogenic control toward anthropogenic and salinity-driven modification, consistent with coastal urban aquifer degradation. These findings confirm that the groundwater of Gulshan-e-Iqbal Town is largely unsuitable for direct consumption without treatment.

1. Introduction:

Groundwater is a vital resource for drinking, watering crops, and household needs. Groundwater is defined as water that seeps through soil layers to saturate sediments and subterranean rock formations (Abanyie et al., 2023). In regions where surface water is scarce or contaminated, it often serves as the primary water source and is a vital natural resource for household uses, irrigation, and potable water (Akram et al., 2020; Shahab, 2016). A complicated interaction between natural and man-made factors, such as the chemical weathering of rocks, local geology, climate, and the infiltration of municipal and industrial waste, affects the hydrochemistry (Akram et al., 2020; Khan, 2020). Over-exploitation, untreated sewage discharge, and seawater intrusion seriously impair groundwater quality in rapidly urbanizing coastal megacities like Karachi (Khan, 2020; Sohail, 2022). Groundwater is vulnerable to chemical pollutants that are often difficult to detect by taste or odor, even though natural filtration through soil layers can remove a significant amount of microbiological contaminants.

Despite being one of the most densely populated towns in Karachi, Gulshan-e-Iqbal has received remarkably little attention in the hydrogeochemical literature, and the quality of its groundwater remains poorly characterized at the local scale. The present study was therefore undertaken with four specific objectives: to characterize the major ion chemistry of groundwater across the town, to evaluate its suitability for drinking through Water Quality Index (WQI) analysis, to classify the prevailing hydrochemical facies using Piper diagram interpretation, and to identify the natural and anthropogenic sources responsible for the observed contamination patterns. Throughout, measured ion concentrations were evaluated against the drinking water standards set by the World Health Organization (WHO) and Pakistan's National Environmental Quality Standards (NEQS), providing a dual-framework benchmark for assessing potability. Comparable Karachi and peri-urban groundwater studies have also reported groundwater quality deterioration and suitability concerns (Asif et al., 2020; Khan, 2019; Taryab et al., 2022).

2. Study area:

The research site is in Gulshan-e-Iqbal Town, District East, Karachi, Sindh province, Pakistan (Figure 1).

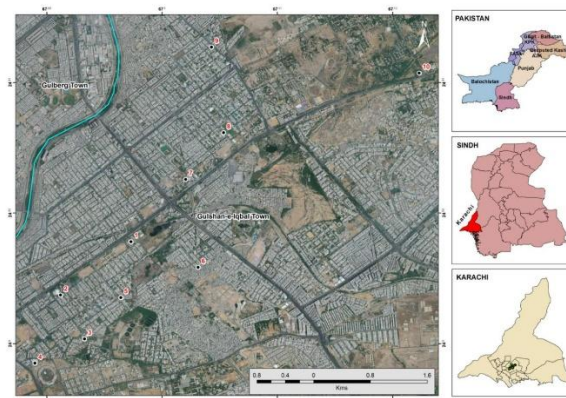


Figure 1: Study Area Map

The geological framework of the region features significant exposure of the Nari and Gaj Formations, originating from the Oligocene and Miocene epochs, respectively (Naseem, 1996; Sohail, 2022). The stratigraphic units consistently extend from the western shoreline of Karachi to northern Sindh, exhibiting a series of asymmetrical folds and anticlines that primarily tilt southwestward (Sohail, 2022). This structural arrangement affects groundwater flow patterns and the likelihood of pollutant movement within the aquifer system. The Gaj Formation, mostly composed of argillaceous limestone, sandstone, and shale, dramatically affects groundwater infiltration and solute transport dynamics (Rafi, 2019). The Nari formation is distinguished by interlayers of siltstone, limestone, and shale.

3. Material and methods:

Groundwater samples were systematically collected from various boreholes and hand pumps across Gulshan-e-Iqbal Town, ensuring representative spatial distribution to capture potential variations in hydrochemical parameters.

3.1. Chemicals and Laboratory Apparatus:

All reagents employed in the analyses were of analytical grade, and glassware was meticulously cleaned with deionized water and oven-dried prior to use.

Only Pyrex (IsoLab, Germany) glassware was used. The various chemicals employed in the physicochemical analysis of water samples include ethylenediamine tetraacetic acid (EDTA), silver nitrate (AgNO_3), sodium hydroxide (NaOH), ammonium chloride (NH_4Cl), potassium chromate (K_2CrO_4), barium chloride (BaCl_2), sodium chloride (NaCl), potassium chloride (KCl), hydrochloric acid (HCl), Eriochrome Black T (EBT), and methyl orange.

3.2 Acquisition of groundwater samples

Groundwater samples from 11 boreholes at various sites inside Gulshan-e-Iqbal Town, Karachi, are shown in Fig. 2. Samples from all these sources were gathered to evaluate groundwater quality. Groundwater sampling was conducted using polyethylene bottles. The bottles were initially rinsed with distilled water and subsequently rinsed two or three times with the sampling water before collection.

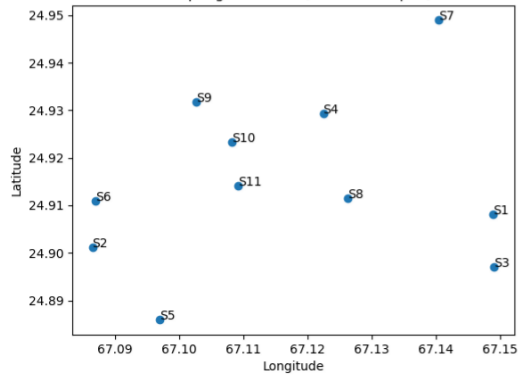


Fig. 2. Spatial distribution of groundwater sampling locations in Gulshan-e-Iqbal Town, Karachi.

3.3. Analysis of water samples:

Water samples were analyzed using both traditional and instrumental methods. A Cole-Palmer Digi-sense digital pH/mV/ORP meter assessed TDS, pH, and electrical conductivity. Calcium, chloride, and bicarbonate ions were titrated. Sulfate is measured using the gravimetric method, and AAS quantifies sodium, potassium, and magnesium with precision and accuracy (Latif, 2024). These analyses were very precise and accurate. Turbidity, total hardness, and fluoride were measured using advanced techniques (Ullah, et al., 2022). Use of a calibrated multi-parameter probe to quantify total dissolved solids allowed in situ by pH and electrical conductivity measurements (Ghani, 2022). After cleaning plastic jars with distilled water to prevent contamination, bore pumps were flushed for 10 minutes before sample capture to ensure representative water collection (Akram et al., 2020). Ultra-pure nitric acid was used to acidify samples for trace metal analysis to a pH below 2, preventing precipitation and adsorption onto container walls until laboratory examination.

4. RESULTS AND DISCUSSION:

4.1. Physicochemical Analysis

Physicochemical analyses of the groundwater samples revealed several key parameters that indicate the overall water quality in the study area. (Tables 1 & 2) Specifically, parameters such as pH, electrical conductivity, total dissolved solids, hardness, and various ionic concentrations were systematically evaluated to determine their compliance with established drinking water standards. These findings are critical for assessing the potability of the groundwater and identifying potential health risks associated with its consumption. Charts graphically represent the variation in the concentration of different cations and anions (Figs. 3, 5, 6, 7, and 8).

The analytical results for physicochemical parameters, including pH, electrical conductivity, and total dissolved solids, along with major cations and anions, are tabulated and discussed in relation to the World Health Organization (WHO) and national drinking water guidelines (Kumar et al., 2014; Selvakumar et al., 2014; Selvam et al., 2012).

Gulshan Iqbal Groundwater Quality Data with International Standards														
Sample	Location	Latitude	Longitude	Date	Depth (m)	pH	EC (µS/cm)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na+K (mg/L)	Cl (mg/L)	SO4 (mg/L)	Hardness (mg/L)
S1	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S2	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S3	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S4	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S5	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S6	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S7	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S8	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S9	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S10	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
S11	24.90	67.10	67.10	2025	10	7.5	120	120	10	5	10	10	10	35
WHO Guidelines (2011)														
						6.5-8.5	<2500	<500	<100	<100	<200	<100	<100	<300
Pakistan Standards (PSQ)														
						6.5-8.5	<2500	<500	<100	<100	<200	<100	<100	<300

Table 1: Physicochemical analysis of samples in study area

These results provide a comprehensive overview of the groundwater's chemical composition.

Gulshan Iqbal Water Quality Statistics with International Standards								
Parameter	Mean	Min	Max	Median	Std. Deviation	WHO Guideline	Pakistan NEQS	Status (Mean vs WHO)
pH	7.07	6.81	7.39	7.07	0.18	6.5–8.5	6.5–8.5	Within Range
TDS (ppm)	835.56	547.55	1146.22	834.09	241.99	600 (acceptable) 1000 (max)	1000	Above Acceptable (< WHO max 1000)
EC (mS/cm)	1.51	0.86	2.47	1.29	0.59	No guideline (TDS linked)	No limit	No Standard
Hardness (ppm)	646.69	210.77	1176.43	668.36	341.88	500 (max)	500	Exceeds
Ca (ppm)	141.42	86.93	204.67	135.95	42.68	No health guideline	No limit	No Standard
Cl (ppm)	329.65	235.58	419.64	322.43	61.06	250 (taste)	250	Exceeds
HCO ₃ (ppm)	99.09	50.97	172.89	93.69	39.52	No guideline	No limit	No Standard

Table 2. Statistical summary of parameters with international standards

4.1.1. pH:

pH is an essential parameter for evaluating the quality of drinking water. The pH of drinking water must be maintained within an acceptable range. The WHO guidelines are based on the premise that acidic water possesses corrosive characteristics, whereas basic water develops a bitter flavor. A water sample that meets drinking water quality standards according to WHO guidelines is most acceptable (Table 2). The pH values recorded in this study (6.81–7.39), which are slightly acidic to neutral, indicate a diminished likelihood of corrosive effects and aesthetic issues associated with alkalinity, thereby enhancing the overall palatability and non-aggressiveness of the groundwater (Gulgundi & Shetty, 2018). The narrow pH range indicates a stable buffering capacity in the aquifer system, preventing major changes that could impact water treatment processes or the health of the ecosystem. This stability is further supported by the mean pH of 7.5, which falls within the permissible limits set by the WHO and NSDQW, minimizing concerns about taste alteration or plumbing corrosion (Ismaila et al., 2020). Chemically, pH 7 refers to neutral. neither acidic nor alkaline. It is the ideal condition for drinking water. Health-wise, this range poses no direct health risk. The human body maintains blood pH around 7.4, and drinking water in this range causes no disruption.

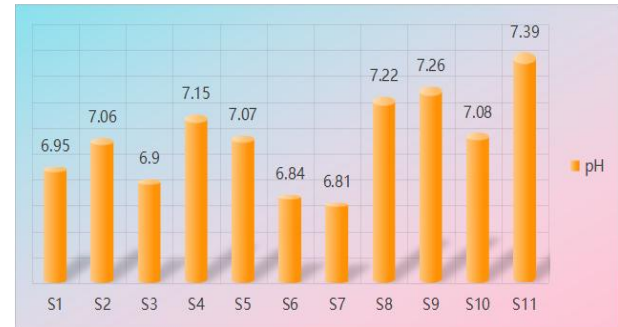


Figure 3: Variation of pH in water samples from different locations, Gulshan-e-Iqbal Town

4.1.2 Electrical Conductivity

Electrical conductivity acts as an indirect indicator of total dissolved solids and salinity in water, directly correlating with the concentration of ionized chemicals in solution (P. Kumar, 2024; V. Kumar, 2014). The EC values in the examined samples varied from 0.86 to 2.47 mS/cm (Tables 1 & 2), reflecting a broad range of dissolved inorganic components (Egbueri, 2019). The EC values ranged from 0.86 to 2.47 mS/cm, indicating a broad variation in dissolved inorganic ion concentrations across sampling sites. While lower EC values (S7, S11) suggest relatively fresh groundwater, elevated values in S2, S6, and S10 indicate significant ionic enrichment, likely attributed to geogenic dissolution and anthropogenic contamination (Fig. 4). These findings are consistent with corresponding TDS and hardness values, confirming EC as a reliable indicator of overall mineralization in the study area. Further investigation into specific ionic contributions to the elevated EC in these samples would elucidate the precise nature of the mineralization process.

EC Value (mS/cm)	Water Class	Interpretation
< 0.75	Low mineralization	Very fresh, low salt
0.75 – 1.5	Moderate mineralization	Acceptable for drinking
1.5 – 3.0	High mineralization	Marginal for drinking, ok for irrigation
> 3.0	Very high mineralization	Generally unsuitable for drinking

Fig. 4: Water class classification according to EC



Figure 5: Conductivity Variation of Water Samples from Different Locations, Gulshan-e-Iqbal Town

EC Relationship with Other Parameters:

EC strongly correlates with your other measurements:

- **TDS** — S6 has EC 2.47 mS/cm and TDS 1077 ppm (both high & consistent)
- **Hardness**—High EC samples tend to show elevated hardness due to Ca^{2+} and Mg^{2+} ions
- **Cl^-** — Chloride ions are major conductivity contributors; S6 also has Cl 365 ppm

4.1.3 Total Dissolved Solids (TDS):

Total Dissolved Solids are the aggregate concentration of all dissolved organic and inorganic compounds in water; they affect water palatability and can signal contaminants (Shinwari, 2025). Natural geological formations, agricultural runoff, industrial discharges, and urban wastewater can cause high TDS levels, which indicate a complex interaction of environmental and anthropogenic factors that affects water quality. In the study area, the range of TDS is revealing an exceptionally wide inter-sample variability (Tables 1 & 2).



Fig. 6: Variation of total dissolved solids (TDS) in Groundwater Samples

4.1.4 Calcium:

Groundwater contains calcium, a vital alkaline earth metal, derived from the decomposition of calcium-rich rocks such as calcite, dolomite, and gypsum found in geological formations. The hardness of water and its appropriateness for domestic, industrial, and agricultural applications are contingent upon its concentration in groundwater. Calcium is essential for bone formation, but its excessive concentration may lead to gastrointestinal distress and the accumulation of scale in pipes and appliances (Rao, 2018).

In the study area, calcium concentrations range from 86.93 to 204.67 ppm (Tables 1 & 2). WHO or NEQS has not established any health-based guidelines for calcium in drinking water, as calcium at typical groundwater concentrations is not considered harmful to human health. However, the observed calcium concentrations are notably elevated and contribute substantially to the high total hardness values recorded across most sampling sites. Calcium, alongside magnesium, potassium, and sodium, consistently exhibits strong positive correlations with EC and TDS in groundwater systems, which reflects its origin from common mineral dissolution pathways (Asghari et al., 2018).

The ions that contribute to hardness and alkalinity primarily derive from the dissolution of geological minerals into rainwater and groundwater. Surface and groundwater sources in regions with carbonate-rich formations are particularly prone to elevated levels of hardness and alkalinity due to the dissolution of bicarbonates and carbonates.

The highest calcium concentrations were recorded at S11 (204.67 ppm), S3 (181.54 ppm), and S8 (196.53 ppm), while the lowest occurred at S7 (86.93 ppm). The inverse relationship between calcium and total hardness at S7 where hardness is the lowest (210.77 ppm) despite moderate depth (121.23 feet) which may

suggest a lithological variation or a dilution effect from recharge in that particular zone. The dissolution of carbonate rock significantly affects calcium concentrations in groundwater, as Ca^{2+} is released into solution when carbonate minerals undergo weathering due to dissolved carbonic acid. ([Rohani-Ghadikolaei et al., 2017](#))

4.2.2 Chloride

The principal source of chloride in groundwater consists of industrial and domestic discharges containing chloride salts, as well as contributions from specific geological formations. Chloride concentrations in the Gulshan Iqbal groundwater samples range from 235.58 to 419.64 ppm, with a mean of 329.65 ppm (Tables 1 & 2). The WHO aesthetic guideline for chloride in drinking water is 250 ppm, a threshold primarily based on taste rather than health. Critically, all eleven sampled wells exceeded this guideline, with a mean value of 329.65 ppm representing a 32% exceedance. The maximum value of 419.64 ppm was recorded at S2, while even the lowest value (S4: 235.58 ppm) is marginally below the threshold, confirming that chloride enrichment is a pervasive and spatially uniform concern across the entire study area.

Chloride movement is not retarded by interaction with soils, sediments, and rocks, making it a reliable indicator of other types of contamination with anomalously high concentrations serving as an advance warning of the presence of other potentially more toxic contaminants. Elevated chloride concentrations exceeding the WHO maximum have been reported as a consequence of the discharge of municipal sewage, road runoff, and industrial waste, and alluvial aquifers in urban settings are particularly vulnerable to such inorganic anthropogenic inputs due to their high permeability and shallow depth. The spatial uniformity of elevated chloride across all sites, combined with the widespread "slight sewage" odor reported at seven of eleven sampling locations, strongly implies that leaking sewage infrastructure is the principal chloride source in the Gulshan Iqbal aquifer—a contamination mode well-documented in densely urbanized South Asian cities. Excess chloride in groundwater is widely recognized as an index of anthropogenic pollution and serves as a reliable tracer for groundwater contamination of sewage origin ([Kelly et al., 2012](#), [Nemčić-Jurec et al., 2022](#))

4.2.3 Bicarbonate

Carbonate is an inherent constituent of all mineral waters. Mineral water derived from limestone-rich regions generally possesses elevated bicarbonate levels. Bicarbonate is essential for acid buffering and contributes to the clean, refreshing flavor of mineral

water. Bicarbonate concentrations in the study area ranged from 50.97 to 172.89 ppm (Tables 1 & 2). No WHO or Pakistan NEQS health-based guideline limit has been established for bicarbonate in drinking water; however, though elevated levels are known to affect the palatability and corrosive properties of water. Bicarbonate and carbonate are generated by the action of carbon dioxide in water on carbonate rocks such as limestone and dolomite, producing an alkaline chemical environment; in large amounts, bicarbonate may affect the taste of water or influence its corrosiveness toward distribution infrastructure. (NGWA, 1999)

The primary source of natural alkalinity, of which bicarbonate is the dominant component, is carbon dioxide from the atmosphere and soil gases that dissolves in infiltrating water; bicarbonate is subsequently released through the dissolution of carbonate minerals along the groundwater flow path. The relatively moderate and consistent bicarbonate concentrations observed across the study area suggest a predominantly geogenic origin through carbonate mineral weathering and CO_2 -water-rock interaction in the shallow aquifer, rather than anthropogenic enrichment. The highest bicarbonate values were recorded at S5 (172.89 ppm) and S1 (134.26 ppm), both of which also exhibit very high hardness values, supporting the geochemical coupling of HCO_3^- with calcium dissolution from carbonate-bearing aquifer materials. (Fig. 7) As groundwater moves through the aquifer and reacts with carbonate and silicate minerals, dissolved carbonic acid is progressively consumed while bicarbonate concentrations increase, reflecting the degree of water-rock interaction along the flow path. The lower bicarbonate concentrations observed at sites such as S10 (50.97 ppm) and S7 (61.88 ppm) may indicate shorter subsurface residence times or reduced contact with carbonate lithologies at those well locations.

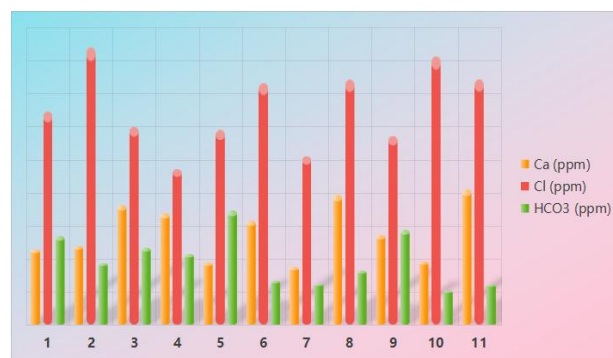


Figure 7: Concentration trends of major ions (Ca^{2+} , Cl^- , HCO_3^-) showing hydrogeochemical variations across sampling sites.

4.2.4 Hardness

Total hardness in the study area ranged from 210.77 to 1176.43 ppm, with a mean of 646.69 ppm and a standard deviation of 341.88 ppm, revealing an exceptionally wide inter-sample variability (Tables 1 & 2). The WHO guideline value for total hardness is 500 ppm. The mean value of 646.69 ppm exceeds this threshold, and a majority of samples—including S1 (1176.43 ppm), S5 (1172.61 ppm), S2 (933.26 ppm), S6 (708.24 ppm), S3 (668.36 ppm), and S9 (751.02 ppm)—significantly surpass the permissible limit, classifying the groundwater at these sites as very hard (Fig. 8). The hardness of water is primarily attributable to the presence of alkaline earth elements, particularly calcium and magnesium, and groundwater in areas with carbonate-bearing lithologies typically exhibits hard to very hard water characteristics as a result of ongoing mineral dissolution (Prasanth et al., 2012). Hard water causes scale buildup in pipes and household appliances, diminishes their efficiency and lifespan, and reduces the effectiveness of soap and detergents, leading to residue buildup and decreased cleaning performance. From a health perspective, while moderate hardness has been associated with reduced cardiovascular disease risk, very hard water over prolonged consumption may contribute to urolithiasis and gastrointestinal disturbances. The extremely high hardness values recorded at S1 and S5, both shallow wells (63.65 and 86.08 feet, respectively) with a "slight sewage" odor, suggest that the hardness at these sites may reflect not only natural carbonate dissolution but also enrichment from organic waste decomposition products percolating through the shallow vadose zone.



Fig. 8: Hardness variation in water samples from different locations of Gulshan-e-Iqbal Town

4.2.5 Temperature

The mean water sample temperature in our study area was 30°C, ranging from 30.4°C to 31.9°C. This study location met the WHO 30°C temperature requirement. Thermal properties affect gas and

mineral solubility, which affects groundwater hydrogeochemical dynamics. Thermal variability can affect microbial growth and water treatment efficiency. Elevated water temperatures accelerate chemical processes, decrease dissolved oxygen, and stimulate bacterial growth, degrading water quality and requiring stronger disinfection. Temperature and dissolved mineral content, particularly carbonates and bicarbonates, might affect water quality metrics, which could cause scaling or corrosion (Khalid, 2020).

5.1 Water Quality Index Analysis:

The Water Quality Index (WQI) analysis shows that the groundwater quality in Gulshan-e-Iqbal Town is predominantly compromised (Table 3). A significant proportion of the samples (73%) fall within the *poor* category, indicating that the water is unsuitable for direct consumption without proper treatment (Table 4). Additionally, 18% of the samples are classified as *very poor*, further emphasizing the severity of water quality deterioration and the associated health risks. Only one sample (S7) falls within the acceptable or *good* category, highlighting the limited availability of potable groundwater in the study area. Overall, these findings clearly indicate a serious degradation of groundwater quality in Gulshan-e-Iqbal, likely influenced by a combination of natural geochemical processes and anthropogenic activities. (Tables 3 & 4)

Sample-wise WQI — Gulshan Iqbal Groundwater Study		
Sample	WQI	Classification
S1	165	Poor
S2	210	Very Poor
S3	145	Poor
S4	120	Poor
S5	230	Very Poor
S6	180	Poor
S7	95	Good
S8	105	Poor
S9	190	Poor
S10	140	Poor
S11	115	Poor

Colour key: Excellent (teal) | Good (green) | Poor (amber) | Very Poor (orange) | Unfit (red)

Table 3: WQI of Water Samples in the Study Area

WQI Classification — Gulshan Iqbal Groundwater Study		
Category	WQI Range	% Samples
Excellent	< 50	0%
Good	50 – 100	9%
Poor	100 – 200	73%
Very Poor	200 – 300	18%
Unfit	> 300	0%

Colour key: Excellent (teal) | Good (green) | Poor (amber) | Very Poor (orange) | Unfit (red)

Table 4 WQI Classification Summary

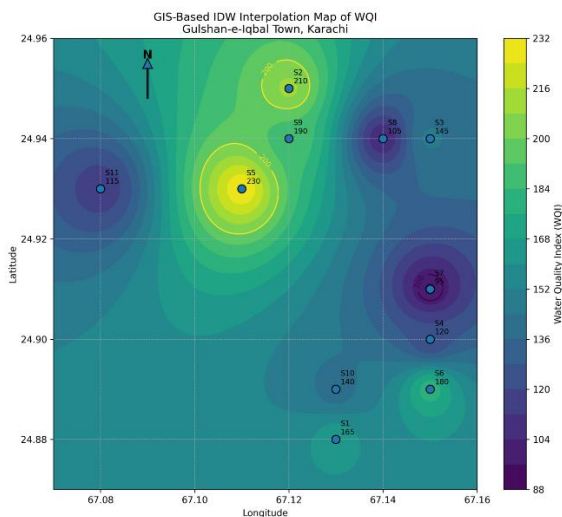


Fig. 8 GIS-based interpolation map of WQI in the Gulshan-e-Iqbal area

5.1.2 Hydrochemical analysis:

The hydrochemical analysis shows a strong positive correlation between electrical conductivity (EC) and total dissolved solids (TDS), which confirms the internal consistency and reliability of the dataset, as both parameters are governed by the concentration of dissolved ions in groundwater. Furthermore, the dominance of calcium in controlling total hardness indicates that the groundwater chemistry is significantly influenced by carbonate mineral dissolution, particularly from limestone and dolomite formations. In addition, the elevated chloride concentrations observed in several samples suggest the impact of anthropogenic activities such as urban waste disposal and sewage infiltration. This enrichment of chloride may also be partly attributed to seawater mixing, considering Karachi's coastal setting, which enhances the

possibility of saline intrusion into the groundwater system. (Table 5)

Parameters	Relationship	Interpretation
TDS – EC	Strong (+0.91)	Dissolved ions control conductivity
Hardness – Ca	Strong (+0.85)	Hardness mainly due to calcium
Cl – TDS	Moderate (+0.65)	Salinity influence
HCO ₃ – Ca	Moderate (+0.52)	Carbonate weathering
EC – Cl	Moderate (+0.60)	Ionic enrichment

Table 5: Key Correlations (r values)

Correlation analysis reveals strong positive relationships between the following variables:

- **TDS and EC** → confirms ionic control of conductivity
- **Hardness and Ca²⁺** → indicates carbonate mineral dissolution
- **Cl⁻ with TDS/EC** → suggests salinity and anthropogenic influence

These relationships indicate that groundwater chemistry is governed by both **natural geochemical processes and urban contamination sources**.

	pH	TDS	EC	Hardness	Ca	Cl	HCO ₃
pH	1	-0.34	-0.51	-0.16	0.47	0.18	0.05
TDS	-0.34	1	0.19	0.08	-0.29	-0.28	0.09
EC	-0.51	0.19	1	0.12	-0.3	0.52	-0.33
Hardness	-0.16	0.08	0.12	1	-0.29	-0.02	0.79
Ca	0.47	-0.29	-0.3	-0.29	1	0.09	-0.2
Cl	0.18	-0.28	0.52	-0.02	0.09	1	-0.46
HCO ₃	0.05	0.09	-0.33	0.79	-0.2	-0.46	1

Table 6: Correlation Matrix (Hydrochemical Relationships)

5.1.3 Piper Diagram Interpretation of Water Samples:

The Piper diagram interpretation of the groundwater samples indicates a clear dominance of alkaline earth metals in the cation field, with calcium (Ca²⁺) and magnesium (Mg²⁺) being the most abundant ions (Fig. 9)

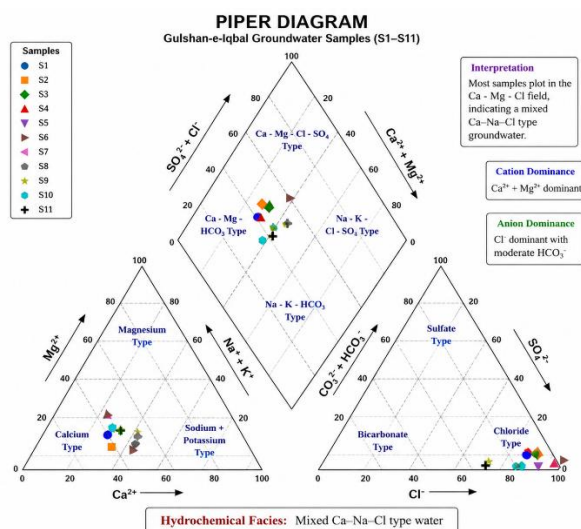


Fig. 9: Piper Diagram and its interpretation

This reflects the significant influence of carbonate mineral dissolution on groundwater chemistry. In the anion field, chloride (Cl^-) is the dominant species, accompanied by moderate concentrations of bicarbonate (HCO_3^-). This combination suggests that while natural geochemical processes such as rock–water interaction contribute to the hydrochemical composition, there is also a notable influence of salinity and possible anthropogenic inputs, leading to a chloride-enriched groundwater system.

5.1.4 Hydrochemical Facies:

The classification of groundwater as mixed Ca–Na–Cl type water indicates a complex hydrochemical system in which no single ion pair dominates completely, and the water chemistry reflects the combined influence of multiple geochemical and environmental processes.

In this facies, both calcium (Ca^{2+}) and sodium (Na^+) are important cations, while chloride (Cl^-) is the dominant anion. The presence of calcium suggests that the groundwater is influenced by carbonate rock weathering, particularly the dissolution of limestone and dolomite. At the same time, the significant contribution of sodium indicates processes such as ion exchange, in which calcium in the water is replaced by sodium from clay minerals or by mixing with saline sources.

The dominance of chloride is particularly important, as it often reflects external influences beyond natural rock–water interaction. Elevated chloride concentrations are commonly associated with urban contamination (sewage, industrial discharge) and, in coastal regions like Karachi, may also indicate seawater intrusion or saline

mixing. This combination suggests that the groundwater system is undergoing a transition from natural geochemical control toward anthropogenic and salinity-driven modification.

Overall, the mixed Ca–Na–Cl facies represents an evolved groundwater type, where initial recharge water has been significantly altered through interaction with geological formations and human activities. This type of water is generally associated with deteriorating water quality, which aligns with your WQI results showing predominantly poor groundwater conditions in the study area.

CONCLUSION:

The groundwater of Gulshan-e-Iqbal Town is predominantly characterized by poor to very poor water quality, with elevated hardness, TDS, and chloride concentrations. WQI results indicate that over 90% of samples are unsuitable for direct drinking without treatment. Correlation analysis reveals that groundwater chemistry is primarily controlled by carbonate weathering and ionic dissolution processes, while elevated chloride levels suggest anthropogenic contamination and possible saline intrusion. A Piper diagram classification confirms a mixed Ca–Na–Cl hydrochemical facies, indicating a transition from natural geogenic processes to an influence.

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