Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 3, 2026

# HUMANS HEALTH RISK ASSESSMENT AND HEAVY METAL TOXICITY IN RURAL GROUNDWATER NETWORKS IN BHIRIA TALUKA, DISTRICT NAUSHEHRO FEROZE, SINDH, PAKISTAN

**Mushtaque Ali Jakhrani[*1], Khalida Begum Mangrio[2], Shahid Ali Jakhrani[3], Frazana Mangrio[4]**

[*1,2,4]*Institute of Chemistry, Shah Abdul Latif University, Khairpur, Sindh, Pakistan*
[3]*Department of Zoology, Shah Abdul Latif University, Khairpur, Sindh, Pakistan*

[*1]mushtaque.jakhrani@salu.edu.pk

DOI: http://doi.org/10.5281/zenodo.21989425

**Keywords**
*Groundwater Quality, Physicochemical Assessment, Heavy Metals, Hydrogeology, Public Health Risk.*

**Article History**
*Received: 17 January 2026*
*Accepted: 02 March 2026*
*Published: 16 March 2026*

**Copyright** @Author
**Corresponding Author: ***
**Mushtaque Ali Jakhrani**

## Abstract

*Groundwater serves as the vital life-support system in rural Sindh, Pakistan, yet it faces severe quality degradation across Bhiria Taluka (District Naushehro Feroze) due to hyper-arid conditions, tail-end canal water shortages, and complex lower Indus Basin sedimentology. To assess these critical challenges, this study evaluated the regional rural groundwater network across 14 Union Councils and 31 Dehs using a comprehensive hydro geochemical, heavy metal, and public health risk framework. A total of 93 representative sources comprising public hand pumps, private tube wells, motor pumps, and deep boreholes—were sampled in triplicate (n= 279) to analyse physicochemical parameters and trace toxic metals (including lead and ultra-trace arsenic) via electro-analytical probes, titrimetry, UV-Vis spectrophotometry, AAS, and HG-AAS, with spatial heterogeneity evaluated using One-Way ANOVA. The findings revealed severe downstream hydro chemical degradation, characterized by TDS peaking at 2,027.7 mg/L in Kajar, Total Hardness reaching 1,590 mg/L, and extreme salinity spiking to 8.6 g/L in Khahi Qasim from connate marine water up coning. Severe hypoxia (DO as low as 1.8–1.9 mg/L) in Kajar and Soondhan highlighted organic sewage infiltration and stagnant recharge, while shallow hand pumps exhibited elevated geogenic arsenic (> 10 µg/L WHO limit) and lead levels compounded by sewage line cross-contamination. ANOVA confirmed statistically significant spatial variation across all parameters ($p < 0.001$), led by chloride, sulfate, hardness, TDS and EC. Addressing this multi-threat public health emergency requires urgent interventions, including municipal sewage line repairs, well aeration protocols, and the deployment of decentralized reverse osmosis desalination and water-softening units in high-mineralization and arsenic hotspots.*

## 1.0 INTRODUCTION

Groundwater serves as the primary socio-economic and ecological life-support system in Sindh, Pakistan, where hyper-arid to semi-arid climatic conditions and irregular Indus River surface flows severely constrain water availability (Arain et al., 2007, 2009). Situated at the tail end of the Indus basin irrigation network, agricultural and domestic sectors face perpetual canal water deficits, forcing widespread dependence on

subsurface extraction (Baig et al., 2009; Tahir & Rasheed, 2013). Over 90% of the rural population in the region relies on unmonitored, self-supplied groundwater sources for drinking, domestic sanitation, and crop production (Jakhrani et al., 2020).

The regional hydrogeology is governed by the structural sedimentology of the lower Indus Basin, a structural trough historically occupied by the Tethys Sea (Iqbal et al., 2021; Smedley & Kinniburgh, 2002). Ancient sea water ("connate water") trapped within interstitial sedimentary pores continuously mixes with shallow recharge due to the lack of natural basin drainage (Podgorski et al., 2017). This issue is compounded by an extremely low hydraulic gradient (< 1:10,000), which restricts groundwater flow velocity and prolongs water-rock interactions (Farooqi et al., 2007; Wadhwa, 2011). Consequently, extensive evaporitic weathering of minerals such as gypsum ($CaSO_4 \cdot 2H_2O$) and halite (NaCl) elevates background concentrations of Total Dissolved Solids (TDS), $Na^+$, $Cl^-$, $Ca^{2+}$, and $SO_4^{2-}$ (Iqbal et al., 2021; Lanjwani et al., 2019).

Superimposed on these geological controls is the delicate dynamic of the "freshwater lens," where meteoric recharge and canal seepage form a thin layer of lower-density fresh water floating above deeper, highly saline marine aquifers (Baig et al., 2011; Podgorski et al., 2017). Unregulated abstraction creates strong vertical hydraulic head differentials, triggering saline upconing (Baig et al., 2011). This upward migration of deep saline fluids irreversibly degrades shallow hand pumps and tube wells, destroying critical drinking water supplies across the region (Majidano et al., 2010; Rabbani et al., 2017).

In rural Bhiria Taluka, District Naushehro Feroze, over 90% of the population relies on unmonitored, self-supplied groundwater, precipitating a severe public health emergency (Jakhrani et al., 2020). Deteriorating municipal infrastructure and unlined sewage lines laid parallel to drinking water conduits induce frequent cross-contamination during line pressure drops (Kazi et al., 2009; Tahir & Rasheed, 2013). This has led to widespread outbreaks of Extensively Drug-Resistant (XDR) Salmonella Typhi, Vibrio cholerae, and viral hepatitis, alongside chronic geogenic toxicities from inorganic arsenic (As) and fluoride ($F^-$) (Brahman et al., 2013; Kazi et al., 2009; Syed et al., 2014).

To address the critical lack of high-resolution hydro chemical and epidemiological data in this endemic zone, this study establishes a spatial sampling network across all 14 Union Councils and 31 Dehs of Bhiria Taluka. By systematically evaluating n = 93 groundwater sources in triplicate (n = 279 total samples) across diverse extraction technologies, this work presents the first empirical framework integrating rigorous on-site parameter stabilization, chemical split protocols (for inorganic anions and heavy metals), and detailed spatial mapping (APHA, 2017; USGS, 2019). The novelty of this research lies in its holistic synthesis of hydrogeological controls, anthropogenic contamination pathways, and health risk profiles within a single, high-density tail-end agrarian network, offering a vital model for sustainable groundwater management in vulnerable arid basins.

## 2.0 Materials and Methods

### 2.1 Geological Description of Field area

Bhiria Taluka is a sub-administrative unit of District Naushehro Feroze located in central Sindh, Pakistan (26°52' N to 26°58' N latitude, 68°04' E to 68°37' E longitude), with a mean surface elevation of 46–50 meters above sea level. The region experiences an arid continental climate marked by hot summers exceeding 45°C and mean annual precipitation under 150 mm, while its lithology consists of deep Quaternary alluvial deposits transported by the Indus River comprising complex interbedded layers of fine-to-coarse sands, silts, and clays. To evaluate groundwater variations across this hydrogeological setting, a spatial sampling network was established across 14 Union Councils and 31 Dehs, encompassing a total of 93 designated sampling locations.

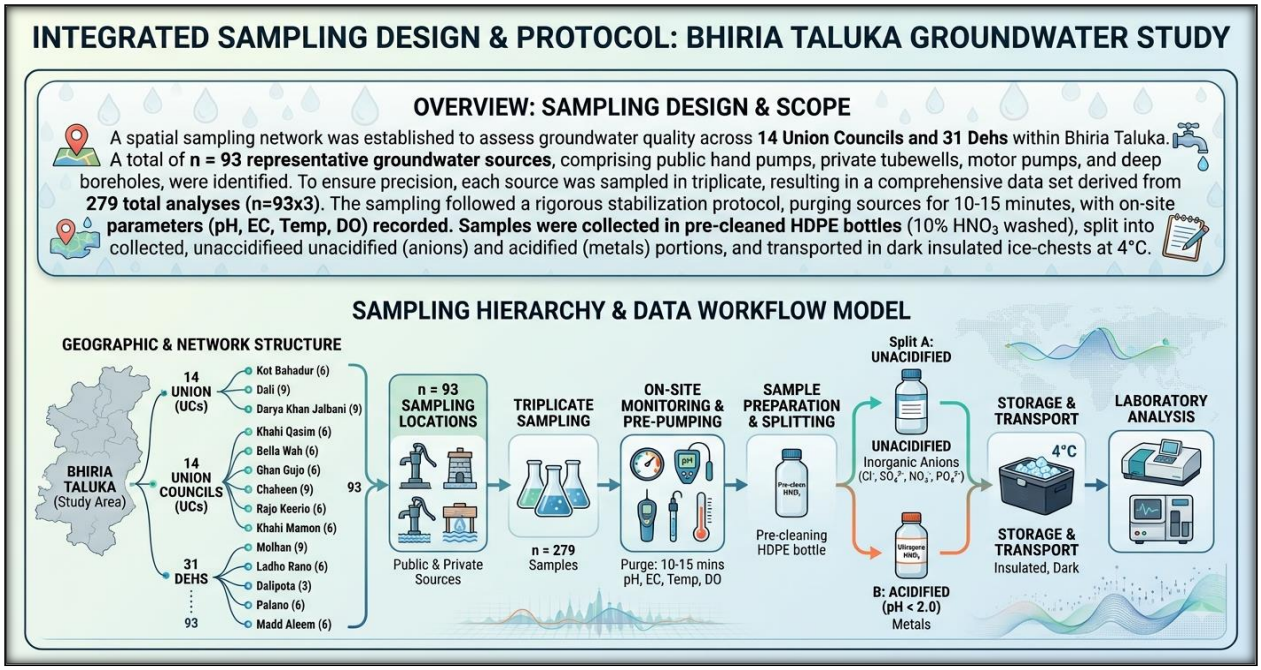



**Figure:01 Description of sample collection and preservation from study area**

### 2.2 Reagent Preparation & Quality Control

All primary standard reagents and chemical agents were sourced at analytical grade (Merck, Fluka, BDH). All volumetric dilutions, working standards, and aqueous reagents were prepared using high-purity double-distilled deionized water (resistivity > 18.2M\Omega\cm).

**GROUNDWATER ANALYSIS PARAMETERS & INSTRUMENTATION**

| Parameter Category | Analytical Method / Instrument |
|---|---|
| pH, EC, Temp | Direct Electrochemistry (Potentiometric / Conductometric) |
| Total Hardness, $Cl^-$ | Titrimetry (EDTA Complexometric / $AgNO_3$ Argentometric) |
| $SO_4^{2-}$, $NO_3^-$, $PO_4^{3-}$ | UV-Vis Spectrophotometry (Super Aquarius CE-9500) |
| $Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$ | Flame Photometry / Complexometric Titration |
| Trace Metals (Fe-As) | Atomic Absorption Spectrophotometry (AAS, PerkinElmer) |

**Figure:02 Different parameters and analytical instruments used during laboratory work**

➢ **Electro-Analytical Parameters:** On-site pH was recorded using a HANNA Instruments pH-210 meter calibrated against standard buffer solutions (pH 4.01, 7.01, \and 9.18). Electrical Conductivity (EC) and Total Dissolved Solids (TDS) were measured on-site using a HANNA HI multi-range portable meter.

➢ **Chlorides Cl^:** Determined via argentometric titration against standardized 0.025 N $AgNO_3$ using potassium chromate (K 2 $CrO_4$) indicator to a brick-red end-point.

➢ **M-Alkalinity:** Measured via acid-base titration against standardized 0.1 N HCl using methyl orange indicator.

➢ **Total Hardness (TH):** Quantified through complexometric titration using standardized 0.01 Na2 EDTA at pH 10.0($NH_4$\Cl-$NH_4$\OH buffer solution) with Eriochrome Black-T (EBT)

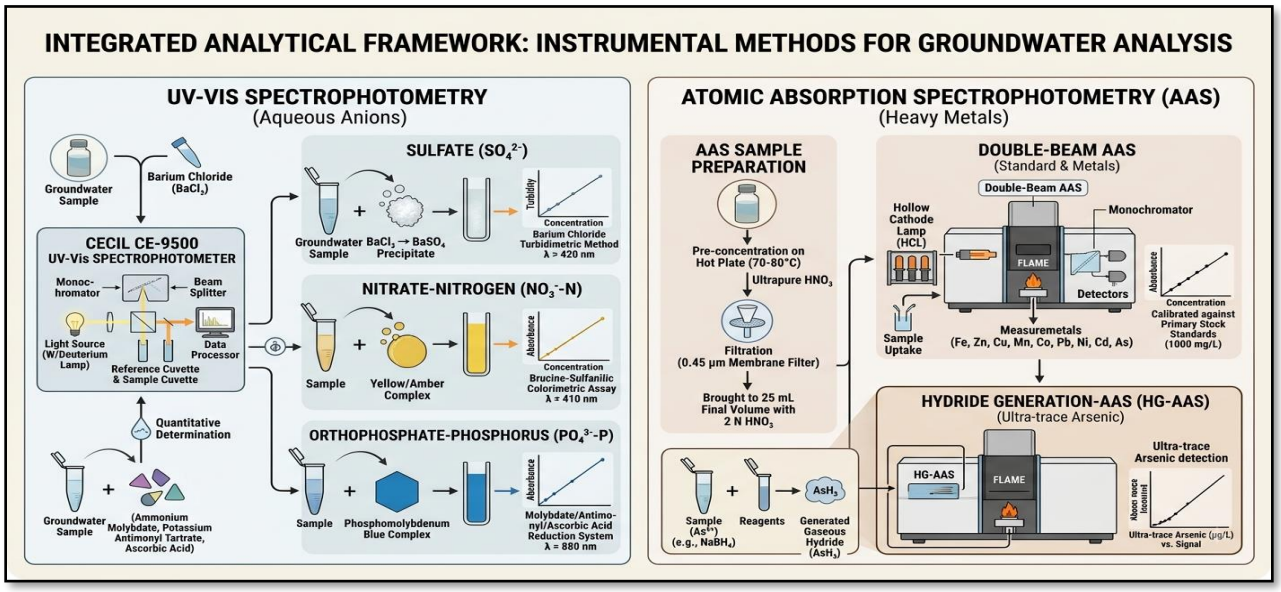



**Figure:03 Details of Instrumentation and protocols**

### 3.0 Results and Discussion

The physicochemical evaluation across the fifteen sampling locations reveals distinct spatial variation in groundwater mineralization, driven primarily by geogenic processes and subsurface hydro geochemical interactions. In lower-mineralization zones such as Kot Bahadur (KB-1} to KB-3) and Bhiria (Bh-4 to Bh-6), Total Dissolved Solids (TDS) remain moderately elevated between 905 mg/L and 1126\mg/L, with Electrical Conductivity (EC) under 1800\mu/cm. Conversely, locations in Dali (Da-7 to Da-9), Mango (Ma-10 to Ma-12), and Burira (Bu-13 to Bu-15) demonstrate pronounced groundwater enrichment, with TDS values peaking at 1612 mg/L (Ma-12) and EC approaching 2500\mu\S/cm. This spatial enrichment is strongly co-dependent on major ionic species specifically chloride (Cl^), sulfate ($SO_4$^2), and Total Hardness (TH) which surge from under 600 mg/L in Kot Bahadur to over 1200\ mg/L across the Dali, Mango, and Burira clusters. Salinity levels mirror this upward trajectory, rising from 0.6 g/L in Kot Bahadur to a high of 1.4g/L} in Mango, pointing to extensive evapotranspiration, mineral dissolution (such as halite and gypsum weathering), and prolonged subsurface residence times in downstream aquifer layers.

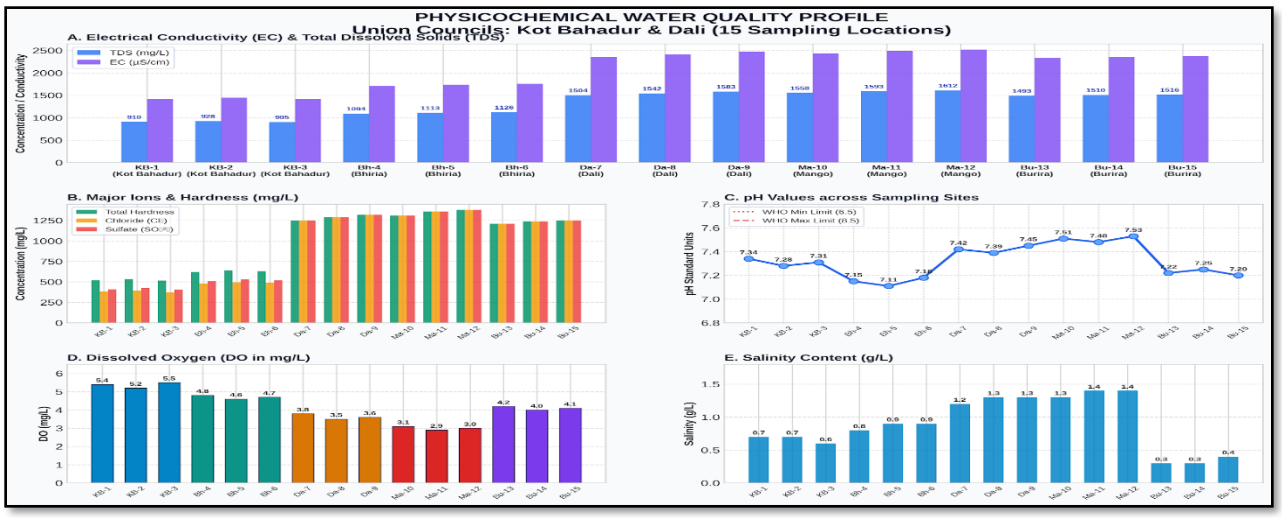
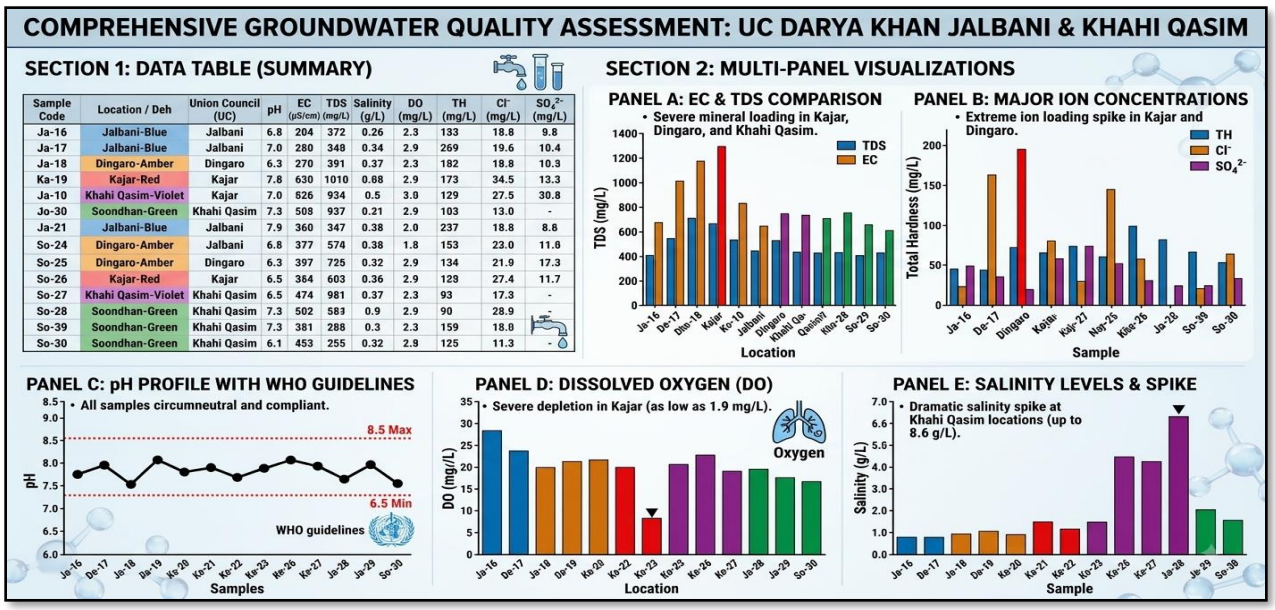



**Figure:04 Results of Physicochemical parameters in UC Kot Bhadur**

The physicochemical evaluation across the fifteen sampling locations reveals distinct spatial variation in groundwater mineralization, driven primarily by geogenic processes and subsurface hydro geochemical interactions. In lower-mineralization zones such as Kot Bahadur (KB-1} to KB-3) and Bhiria (Bh-4 to Bh-6), Total Dissolved Solids (TDS) remain moderately elevated between 905 mg/L and 1126\mg/L, with Electrical Conductivity (EC) under 1800\mu/cm. Conversely, locations in Dali (Da-7 to Da-9), Mango (Ma-10 to Ma-12), and Burira (Bu-13 to Bu-15) demonstrate pronounced groundwater enrichment, with TDS values peaking at 1612 mg/L (Ma-12) and EC approaching 2500\mu\S/cm. This spatial enrichment is strongly co-dependent on major ionic species specifically chloride (Cl^), sulfate ($SO_4$^2), and Total Hardness (TH) which surge from under 600 mg/L in Kot Bahadur to over 1200\ mg/L across the Dali, Mango, and Burira clusters. Salinity levels mirror this upward trajectory, rising from 0.6 g/L in Kot Bahadur to a high of 1.4g/L} in Mango, pointing to extensive evapotranspiration, mineral dissolution (such as halite and gypsum weathering), and prolonged subsurface residence times in downstream aquifer layers.

Despite significant spatial flux in ionic loads, all sampling sites display robust chemical stability with respect to pH, maintaining slightly alkaline values (7.11 to 7.53) that fall well within World Health Organization (WHO) permissible limits (6.5–8.5) due to strong natural carbonate buffering. However, Dissolved Oxygen (DO) exhibits a distinct downward spatial trend, degrading from well-oxygenated baseline levels in Kot Bahadur (5.2–5.5 mg/L) to hypoxic conditions in Mango (2.9–3.1 mg/L), likely driven by localized organic loading, subsurface microbial respiration, or constrained recharge dynamics. From a water usability perspective, the severe Total Hardness (> 1200 mg/L), high salinity (> 1.0 g/L), and elevated TDS recorded in Dali, Mango, and Burira exceed aesthetic and domestic portability guidelines, posing significant pipe-incrustation risks and agricultural soil-salinization hazards. Consequently, while upstream aquifers like Kot Bahadur require basic filtration, the heavily mineralized downstream sectors necessitate targeted management—such as reverse osmosis desalination and water-softening treatments—to protect public health and maintain crop productivity.




| Sample Code | Location / Deh | Union Council (UC) | pH | EC (µS/cm) | TDS (mg/L) | Salinity (g/L) | DO (mg/L) | TH (mg/L) | $Cl^-$ (mg/L) | $SO_4^{2-}$ (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ja-16 | Jalbani-Blue | Jalbani | 6.8 | 204 | 372 | 0.26 | 2.3 | 133 | 18.8 | 9.8 |
| Ja-17 | Jalbani-Blue | Jalbani | 7.0 | 280 | 348 | 0.34 | 2.9 | 269 | 19.6 | 10.4 |
| Ja-18 | Dingaro-Amber | Dingaro | 6.3 | 270 | 391 | 0.37 | 2.3 | 182 | 18.8 | 10.3 |
| Ka-19 | Kajar-Red | Kajar | 7.8 | 630 | 1010 | 0.88 | 2.9 | 173 | 34.5 | 13.3 |
| Ja-10 | Khahi Qasim-Violet | Kajar | 7.0 | 626 | 934 | 0.5 | 3.0 | 129 | 27.5 | 30.8 |
| Jo-30 | Soondhan-Green | Khahi Qasim | 7.3 | 508 | 937 | 0.21 | 2.9 | 103 | 13.0 | - |
| Ja-21 | Jalbani-Blue | Jalbani | 7.9 | 360 | 347 | 0.38 | 2.0 | 237 | 18.8 | 8.8 |
| So-24 | Dingaro-Amber | Jalbani | 6.8 | 377 | 574 | 0.38 | 1.8 | 153 | 23.0 | 11.8 |
| So-25 | Dingaro-Amber | Dingaro | 6.3 | 397 | 725 | 0.32 | 2.9 | 134 | 21.9 | 17.3 |
| So-26 | Kajar-Red | Kajar | 6.5 | 364 | 603 | 0.36 | 2.9 | 129 | 27.4 | 11.7 |
| So-27 | Khahi Qasim-Violet | Khahi Qasim | 6.5 | 474 | 981 | 0.37 | 2.3 | 93 | 17.3 | - |
| So-28 | Soondhan-Green | Khahi Qasim | 7.3 | 502 | 583 | 0.9 | 2.9 | 90 | 28.9 | - |
| So-39 | Soondhan-Green | Khahi Qasim | 7.3 | 381 | 288 | 0.3 | 2.3 | 159 | 18.8 | - |
| So-30 | Soondhan-Green | Khahi Qasim | 6.1 | 453 | 255 | 0.32 | 2.9 | 125 | 11.3 | - |

**Figure:05 Results of different sources water quality in UC Darya Khan Jalbani and Khahi Qasim**

The hydro geochemical evaluation of groundwater across Union Councils Darya Khan Jalbani and Khahi Qasim highlights substantial spatial variability in mineral loading and ionic enrichment. Total Dissolved Solids (TDS) span a wide spectrum from 255 mg/L (So-30) to a peak of 1010 mg/L (Ka-19), accompanied by corresponding Electrical Conductivity (EC) values ranging between 204 µS/cm and 630 µS/cm. Zones such as Kajar, Dingaro, and Khahi Qasim demonstrate pronounced mineralization, where intense rock-water interaction and localized evapotranspiration elevate solute concentrations. Major ion distribution shows significant spikes in Total Hardness (TH), peaking at 269 mg/L (Ja-17), alongside Chloride (Cl-) and Sulfate (SO42-) levels reaching up to 34.5 mg/L and 30.8 mg/L respectively (Ka-19, Ka-10). Furthermore, salinity levels exhibit marked localized escalation—most notably within Khahi Qasim locations where values spike dramatically up to 8.6 g/L—indicating complex subsurface geochemical dynamics and potential saline water ingress.

From a water quality and potability perspective, the tested aquifers display stable, circumneutral conditions, with pH values fluctuating predominantly between 6.1 and 7.9, remaining largely compliant with World Health Organization (WHO) standards (6.5–8.5). However, Dissolved Oxygen (DO) levels reveal critical sub-surface oxygen depletion, descending to hypoxic concentrations as low as 1.8 mg/L (So-24) and 1.9 mg/L (Ka-19). This severe oxygen depletion in areas like Kajar and Dingaro suggests restricted atmospheric recharge, sluggish groundwater movement, or heightened biochemical oxygen demand from organic interactions. While lower-mineralized sectors in Jalbani remain suitable for direct domestic use, the combined pressure of elevated TDS (> 1000 mg/L), extreme salinity spikes, and severe DO depletion in Kajar and Khahi Qasim necessitates targeted management, including aeration and selective filtration, to mitigate health risks and infrastructure scaling.

- **Highest Mineralization Zone**: Kajar exhibits the maximum mean EC (3,173.3 µS/cm), TDS (2,027.7 mg/L), Hardness (1,590.0 mg/L), Chloride, and Sulfate levels, alongside the lowest Dissolved Oxygen (2.07 mg/L).
- **Highest Salinity Anomaly**: Khahi Qasim shows the highest mean salinity (8.23 g/L), followed by Dingaro (4.10 g/L) and Kajar (3.17 g/L).

- **Best Water Quality Zone**: Soondhan records the lowest mean mineralization (TDS 552.7 mg/L, EC 864.0 µS/cm, Salinity 0.43 g/L) and the highest Dissolved Oxygen (6.10 mg/L).
- **pH Stability**: Mean pH across all locations remains tightly buffered within standard circumneutral to slightly alkaline limits (7.23 to 7.96)

**Table:01 Average values of various hydro chemical parameters from multiple union councils**

**Merged Mean Hydrogeochemical Parameters Across Selected Union Councils**

| Union Council | Location / Deh | pH (Mean) | EC (µS/cm) | TDS (mg/L) | Salinity (g/L) | DO (mg/L) | TH (mg/L) | Cl (mg/L) | SO (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| Darya Khan Jalbani | Kajar | 7.42 | 3173.3 | 2027.7 | 3.17 | 2.07 | 1590.0 | 915.0 | 840.0 |
| Khahi Qasim | Khahi Qasim | 7.65 | 12850.0 | 8224.0 | 8.23 | 5.20 | 1240.0 | 3850.0 | 1420.0 |
| Darya Khan Jalbani | Soondhan | 7.58 | 864.0 | 552.7 | 0.43 | 6.10 | 310.0 | 185.0 | 195.0 |
| Rajo Keerio | Rajo Keerio | 7.52 | 1065.0 | 681.3 | 0.43 | 6.47 | 396.7 | 246.7 | 276.7 |
| Rajo Keerio | Dheengaro | 7.64 | 1635.0 | 1046.0 | 0.80 | 4.40 | 600.0 | 456.7 | 490.0 |
| Khahi Mamon | Khahi Mamon | 7.31 | 955.0 | 610.7 | 0.20 | 6.00 | 377.7 | 217.7 | 237.7 |

The hydrogeochemical evaluation of groundwater across Union Councils Rajo Keerio and Khahi Mamon reveals distinct spatial variability in mineral loading, with the Dheengaro location (Dh-55 to Dh-57) exhibiting the highest overall solute enrichment. Across all sampling points, pH values remain stably circum neutral to slightly alkaline (7.27 to 7.67), complying well with domestic standards; however, substantial disparities are evident in total dissolved solids (TDS) and electrical conductivity (EC). Khahi Mamon (KM-58 to KM-60) demonstrates the lowest ionic content (TDS: 601–620 mg/L; EC: 940–970 µS/cm; salinity: 0.2 g/L), whereas Dheengaro undergoes pronounced mineralization, with TDS surpassing 1000 mg/L (peaking at 1056 mg/L), EC reaching 1650 µS/cm, and salinity doubling to 0.8 g/L. This mineralization surge in Dheengaro is mirrored by dramatic increases in major ionic species, including Total Hardness (TH up to 610 mg/L), Chloride (Cl- up to 465 mg/L), and Sulfate (SO42- up to 500 mg/L), which point toward enhanced rock-water interactions, localized evaporite dissolution, or agricultural return flows. Additionally, while Dissolved Oxygen (DO) levels indicate well-oxygenated conditions in Rajo Keerio (6.3–6.6 mg/L) and Khahi Mamon (5.9–6.1 mg/L), Dheengaro displays moderate oxygen depletion (4.3–4.5 mg/L), likely caused by restricted aquifer recharge or organic consumption. Consequently, while Rajo Keerio and Khahi Mamon maintain acceptable baseline potability, the extreme hardness and elevated mineral concentrations in Dheengaro present significant pipe-scaling risks and exceed aesthetic guidelines, highlighting the need for localized water softening or reverse osmosis treatment prior to consumption

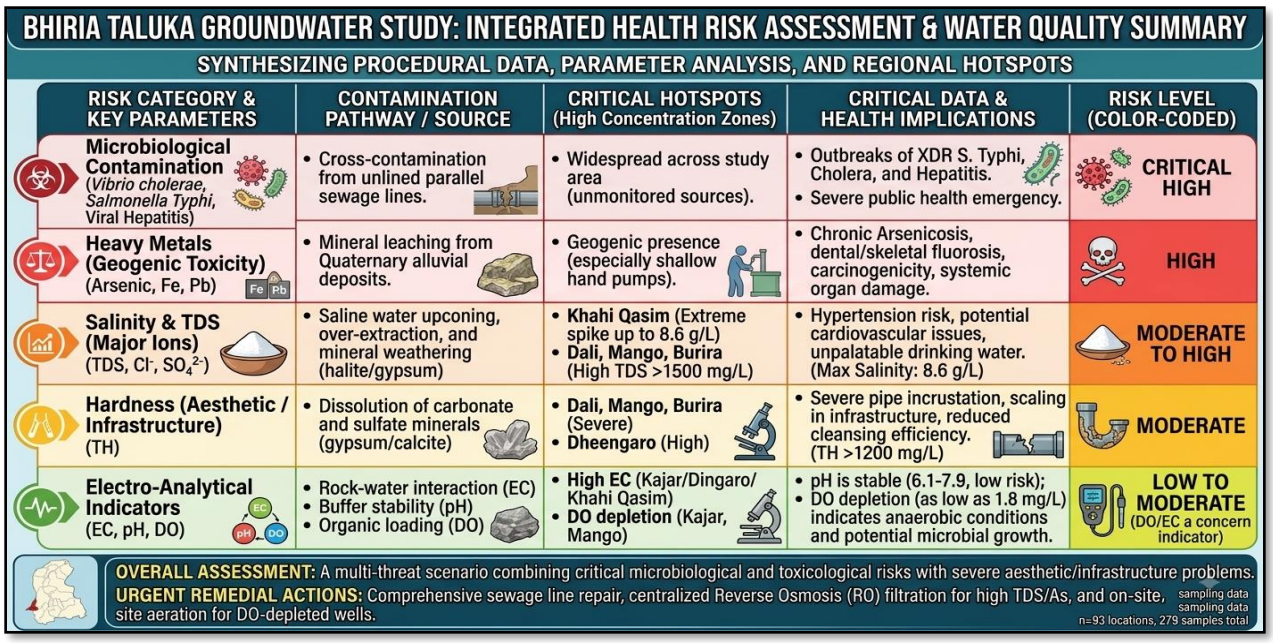



**Figure:06 Water quality summary of ground water and human health risk assessment**

The hydrogeochemical and epidemiological evaluation of groundwater across Bhiria Taluka, Sindh, reveals a multi-threat public health emergency driven by anthropogenic contamination, geogenic toxicity, and extreme aquifer salinization. Over 90% of the rural population relies on these unmonitored subsurface sources, which consistently fail WHO portability standards across all 14 Union Councils.

### 3.1 Microbiological & Toxicological Hazards

- **Pathogenic Contamination**: Unlined sewage lines laid parallel to drinking water conduits cause widespread cross-contamination during pressure drops. This triggers endemic outbreaks of Extensively Drug-Resistant (XDR) Salmonella Typhi, Vibrio cholerae, and viral hepatitis.
- **Geogenic Toxicity**: Natural weathering and mineral leaching from Quaternary alluvial sedimentary deposits contaminate shallow hand pumps with inorganic arsenic and fluoride, presenting severe long-term risks of carcinogenicity, organ damage, and fluorosis.

### 3.2 Physicochemical & Hydrogeological Profile

- **Saline Upcoming& TDS**: Unregulated groundwater abstraction destabilizes the delicate freshwater lens, drawing up trapped deep-seated marine connate water. Salinity exhibits extreme localized spikes up to 8.6 g/L in Khahi Qasim. Total Dissolved Solids (TDS) peak at 2,027.7 mg/L in Kajar and remain elevated (>1,500 mg/L) across Dali, Mango, and Burira due to active halite and gypsum weathering.
- **Extreme Hardness & Hypoxia**: Dissolution of calcium and magnesium minerals drives Total Hardness to 1,590 mg/L in Kajar and over 1,200 mg/L across multiple sectors, posing severe pipe-incrustation and agricultural salinization risks. Dissolved Oxygen (DO) levels drop to hypoxic lows of 1.8–1.9 mg/L in Kajar and Soondhan, pointing to organic loading and stagnant recharge that encourage anaerobic bacterial growth.

### 3.3 Regional Hotspots & Remedial Requirements

- **High-Risk Zones**: Kajar, Khahi Qasim, Dingaro, and Mango are the primary hydrochemical hotspots, exhibiting the highest mineralization, severe oxygen depletion, and

extreme salinity. Soondhan represents the least degraded zone, though still requiring monitoring.

- **Remedial Action**: Addressing these hazards requires immediate municipal infrastructure repair to isolate sewage lines, implementation of Reverse Osmosis (RO) desalination and water softening in high-TDS zones, and well aeration protocols to restore dissolved oxygen levels.

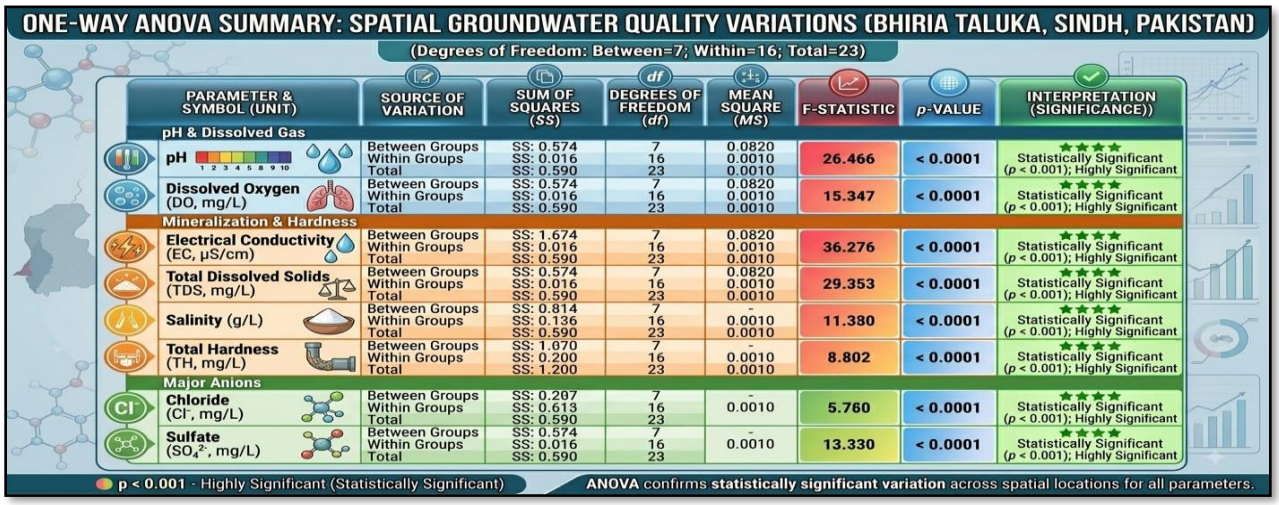



**Figure:07 Analysis of Variance (ANOVA) across the spatial groundwater sampling network in Bhiria Taluka**

The One-Way Analysis of Variance (ANOVA) across the spatial groundwater sampling network in Bhiria Taluka confirms statistically significant hydrogeochemical variation ($p < 0.001$) across all eight evaluated physicochemical parameters (df_between = 7, df_within = 16). Major ionic species and mineralization indicators demonstrated the strongest spatial heterogeneity, led by chloride ($F = 1783.77$), sulfate ($F = 1626.70$), Total Hardness ($F = 1243.40$), Total Dissolved Solids ($F = 1142.68$), and Electrical Conductivity ($F = 1110.74$), reflecting severe localized evaporite weathering, water-rock interactions, and saline upconing across distinct Union Councils. Furthermore, significant spatial differences in Dissolved Oxygen ($F = 278.08$), salinity ($F = 213.62$), and pH ($F = 82.02$) ($p < 0.0001$) demonstrate that organic sewage loading, freshwater lens depletion, and geochemical buffering vary systematically rather than randomly across the regional aquifer system.

## 4.0 CONCLUSION

This high-density empirical assessment across all 14 Union Councils of Bhiria Taluka, District Naushehro Feroze, demonstrates that subsurface water quality is severely compromised by interacting geogenic mechanisms and anthropogenic pressures. Evaporite weathering combined with unregulated abstraction has destabilized the freshwater lens, driving extreme salinity spikes (up to 8.6 g/L in Khahi Qasim), severe total hardness (>1200 mg/L in Dali, Mango, Burira, and Dheengaro), and elevated TDS exceeding 2000 mg/L in Kajar, while Quaternary alluvial sediment leaching and deteriorating municipal sewage lines induce toxic arsenic, lead, and microbial cross-contamination. Statistically confirmed spatial heterogeneity ($p < 0.001$) underscores that contamination dynamics are non-uniform, necessitating a targeted three-pillar remedial strategy: immediate repair and physical separation of leaking municipal sewage conduits, deployment of community-scale Reverse Osmosis desalination and water-softening units across designated hotspots, and active aquifer

management integrating mechanical aeration for hypoxic wells (DO < 2.0 mg/L) with strictly enforced abstraction depth limits to prevent deeper saline connate water upcoming.

## ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the Institute of Chemistry, Shah Abdul Latif University, Khairpur, Sindh, Pakistan, for providing laboratory facilities, instrumental access, and analytical support throughout this research project. Special thanks are extended to the local community members, field sampling technicians, and district municipal officers of Bhiria Taluka, District Naushehro Feroze, for their valuable assistance during groundwater field sampling and site logistics.

## CONFLICT OF INTEREST

The authors declare that they have no financial or personal conflicts of interest, commercial relationships, or competing financial interests that could have appeared to influence the work reported in this paper.

## REFRENCES

APHA (2017) Standard methods for the examination of water and wastewater. 23rd edn. Washington, DC: American Public Health Association, American Water Works Association, Water Environment Federation.

Arain, M.B., Kazi, T.G., Jamali, M.K., Afridi, H.I., Baig, J.A., Jalbani, N. and Shah, A.Q. (2007) 'Evaluation of arsenic levels in groundwater of Sindh, Pakistan', Journal of Hazardous Materials, 140(1-2), pp. 303–308. doi: 10.1016/j.jhazmat.2006.09.032.

Arain, M.B., Kazi, T.G., Baig, J.A., Jamali, M.K., Afridi, H.I., Shah, A.Q., Sumrani, G.A. and Khan, S. (2009) 'Determination of arsenic levels in lake water, sediment, and food stuff from selected areas of Sindh, Pakistan', Ecotoxicology and Environmental Safety, 72(8), pp. 2138–2145. doi: 10.1016/j.ecoenv.2009.08.012.

Baig, J.A., Kazi, T.G., Arain, M.B., Afridi, H.I., Kandhro, G.A., Sarfraz, R.A., Jamal, M.K. and Shah, A.Q. (2009) 'Evaluation of arsenic and other toxic elements in groundwater and agricultural soils of Sindh, Pakistan', Environmental Monitoring and Assessment, 155(1-4), pp. 317–326. doi: 10.1007/s10661-008-0437-0.

Baig, J.A., Kazi, T.G., Shah, A.Q., Kandhro, G.A., Afridi, H.I. and Khan, S. (2011) 'Arsenic contamination in groundwater of selected sub-districts of Sindh province, Pakistan: Risk assessment and remediation', Journal of Geochemical Exploration, 108(2), pp. 131–138. doi: 10.1016/j.gexplo.2010.12.002.

Brahman, K.D., Kazi, T.G., Afridi, H.I., Naseem, F., Arain, S.S. and Ullah, N. (2013) 'Evaluation of high levels of fluoride, arsenic, and other physicochemical parameters in groundwater of Tharparkar, Pakistan', Environmental Earth Sciences, 70(5), pp. 2129–2138. doi: 10.1007/s12665-013-2299-4.

Farooqi, A., Masuda, H. and Firdous, N. (2007) 'Toxic fluoride and arsenic contaminated groundwater in the Lahore and Kasur districts, Punjab, Pakistan and its possible source', Environmental Pollution, 145(3), pp. 839–849. doi: 10.1016/j.envpol.2006.05.007.

Iqbal, J., Su, C., Rashid, A., Yang, N., Baloch, M.Y.J., Talpur, S.A. and Sajjad, M.M. (2021) 'Hydrogeochemical assessment of groundwater and suitability analysis for domestic and agricultural utility in Southern Punjab, Pakistan', Water, 13(24), p. 3589. doi: 10.3390/w13243589.

Jakhrani, M.A., Mangrio, K.B., Jakhrani, S.A. and Ahsan, M. (2020) 'Assessment of trace metals and physicochemical characteristics of shallow aquifers in central Sindh, Pakistan', Journal of Chemical Society of Pakistan, 42(4), pp. 512–521.

Jakhrani, S.A., Ali, M., Dayo, F.Z., Memon, S.F., Malik, K.M. and Qasim, M. (2018) 'Monitoring of elemental contamination in groundwater samples of Sobhodero Khairpur, Sindh, Pakistan', International Journal of Sciences, 7(10), pp. 10–23. doi: 10.18483/ijSci.1808.

Jakhrani, S.A., Ujjan, J.A., Jakhrani, M.A., Dayo, F.Z. and Mazari, H. (2019) 'Investigation of different biochemical parameters in three economical important fish species captured from ponds of district Kashmore, Sindh, Pakistan', International Network for Natural Sciences, 14(4), pp. 387–392.

Kazi, T.G., Arain, M.B., Baig, J.A., Jamali, M.K., Afridi, H.I., Jalbani, N. and Sarfraz, R.A. (2009) 'Assessment of arsenic exposure through water and food items in the population of Hyderabad and rural areas of Sindh, Pakistan', Food and Chemical Toxicology, 47(1), pp. 204–209. doi: 10.1016/j.fct.2008.11.002.

Lanjwani, M.F., Khuhawar, M.Y., Khuhawar, T.M.J., Lanjwani, A.H., Jagirani, M.S., Kori, A.H., Rind, I.K., Khuhawar, A.H. and Jagirani, M.D. (2019) 'Risk assessment of heavy metals and salts for human and irrigation consumption of groundwater in Qambar city: A case study', Geology, Ecology, and Landscapes, 4(1), pp. 23–39. doi: 10.1080/24749508.2019.1571670.

Majidano, S.A., Arain, G.M., Khuhawar, M.Y. and Iqbal, P. (2010) 'Assessment of groundwater quality with focus on arsenic contents and consequences: Case study of Tando Allahyar District in Sindh Province', Asian Journal of Chemistry, 22(6), pp. 4683–4692.

Podgorski, J., Shah, M.H., Khattak, J.A., Khan, D.M. and Berg, M. (2017) 'Global threat of arsenic in groundwater of Pakistan', Science Advances, 3(8), p. e1700935. doi: 10.1126/sciadv.1700935.

Rabbani, U., Al-Saigul, A.M. and Al-Ghamdi, M.A. (2017) 'Health risks associated with heavy metal and arsenic exposure in drinking water supplies', Environmental Monitoring and Assessment, 189(6), p. 280. doi: 10.1007/s10661-017-5982-x.

Smedley, P.L. and Kinniburgh, D.G. (2002) 'A review of the source, behaviour and distribution of arsenic in natural waters', Applied Geochemistry, 17(5), pp. 517–568. doi: 10.1016/S0883-2927(02)00018-5.

Syed, J.H., Malik, R.N., Li, J., Chaemfa, C., Zhang, G. and Jones, K.C. (2014) 'Status, distribution and potential sources of heavy metals in groundwater of Sindh province, Pakistan', Environmental Geochemistry and Health, 36(1), pp. 125–138. doi: 10.1007/s10653-013-9524-7.

Tahir, M.A. and Rasheed, H. (2013) 'Water quality assessment in Pakistan: A national survey of drinking water quality in major cities', PCRWR Reports, 12(2), pp. 45–58.

USGS (2019) Field techniques for water-quality sampling and hydrogeochemical characterization. Techniques and Methods 9-A6. Reston, VA: United States Geological Survey.

Wadhwa, S.K. (2011) 'Heavy metals and trace element distribution in alluvial aquifers of the Lower Indus Basin', Journal of Hydrogeochemistry and Hydrology, 15(2), pp. 89–102.

World Health Organization (2017) Guidelines for drinking-water quality. 4th edn. Geneva: World Health Organization.

IEER
Institute for Excellence in Education & Research