

GROUNDWATER QUALITY ASSESSMENT AND SUITABILITY FOR DRINKING AND IRRIGATION IN TEHSIL BELA, DISTRICT LASBELA, BALOCHISTAN, PAKISTAN

Afzal Khan^{*1}, Dr. Muhammad Yar Khuhawar², Atiq Ur Rehman³, Shafi Muhammad⁴

^{*1}M.Phil. Scholar, Institute of Advanced Research Studies in Chemical Sciences, University of Sindh, Jamshoro, Pakistan

²Professor Emeritus, Institute of Advanced Research Studies in Chemical Sciences, University of Sindh, Jamshoro Pakistan

³Lecturer, Department of Economics, Lasbela University of Agriculture Water and Marine Sciences, (LUAWMS) Uthal Balochistan, Pakistan

⁴Department of Marine Geology, Lasbela University of Agriculture Water and Marine Sciences, (LUAWMS) Uthal Balochistan, Pakistan

¹afzalkhanroonjho22@gmail.com, ²mykhuhawar@usindh.edu.pk, Atiq.eco@luawms.edu.pk
geoshafi@yahoo.com

DOI: <https://doi.org/10.5281/zenodo.22916673>

Keywords

Groundwater quality; Tehsil Bela; Lasbela; physico-chemical parameters; WHO standards; irrigation suitability; hydrochemical facies; Balochistan.

Article History

Received: 16 June 2026

Accepted: 07 September 2026

Published: 23 September 2026

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Corresponding Author: *

Afzal Khan

Abstract

Groundwater underpins domestic water supply and agriculture across District Lasbela, Balochistan, and its chemical quality is a key determinant of public health and crop productivity in this semi-arid coastal region. This study assesses the groundwater quality of Tehsil Bela, District Lasbela, based on twenty-six samples collected from bore wells, dug wells and hand pumps across thirteen union councils between November 2022 and August 2023. Fifteen physico-chemical parameters – pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, total hardness (TH), alkalinity, chloride, sulphate, nitrate, total phosphate, orthophosphate and the essential metals sodium, potassium, calcium and magnesium – were determined by standard spectrophotometric, titrimetric and flame atomic absorption spectrometric methods and benchmarked against the World Health Organization (WHO), the Pakistan Council of Research in Water Resources (PCRWR), the National Environmental Quality Standards (NEQS) and the United States Environmental Protection Agency (UEPA) permissible limits.

The mean pH (7.93), sodium, magnesium and nitrate values largely conformed to WHO guidelines, and 73% of samples were classified as non-saline on the TDS scale. However, chloride exceeded the WHO limit in 80.7% of samples, potassium in 80.7%, total hardness placed 73% of samples in the hard-to-very-hard categories, and total/orthophosphate exceeded WHO limits in 46–54% of samples. Irrigation-suitability analysis showed that 92.3% of samples satisfied Kelly's Index, while only 30.8% met the Sodium Adsorption Ratio (SAR) suitability criterion. Overall, groundwater in Tehsil Bela is chemically more favorable than in neighboring Uthal for several key parameters, but chloride, hardness and sodium-hazard indices indicate that treatment and continued monitoring remain necessary before unrestricted drinking and irrigation use. This enhanced edition additionally reports mean-ion hydrochemical facies, five supplementary derived indices (Na%, Residual Sodium Carbonate, Permeability Index, Magnesium Hazard ratio and Kelly's Ratio), a multi-standard compliance

comparison, and an expanded discussion of public-health implications and management recommendations.

1. Introduction

1.1 Groundwater as a Strategic Resource

Groundwater is one of the most vital natural resources for human livelihoods and socio-economic development, especially in arid/semi-arid areas where surface-water supply is limited, unpredictable or very seasonal. Groundwater is the major source of potable water and irrigation in many parts of Pakistan, such as Balochistan, where rainfall is inadequate, evapotranspiration is high and there is a lack of perennial rivers. Groundwater is recognized as a key source of water security for vulnerable communities, but groundwater abstraction pressures, climate variability and water quality degradation are increasingly impacting groundwater sustainability (UNESCO, 2022; World Bank, 2023).

Groundwater quality is affected by a complex interplay of geological, hydrological and anthropogenic processes. In arid areas, the chemical composition of groundwater is significantly affected by natural geochemical processes such as mineral dissolution, rock-water interaction, ion exchange, redox reactions and evaporative concentration (Li et al., 2021; Kumar et al., 2022). Other factors like seawater intrusion, saline groundwater mixing and marine aerosol deposition can also affect the groundwater chemistry and cause higher groundwater levels of major ions (e.g. chloride, sodium, sulphate and TDS) in coastal and semi-arid areas (Zhang et al., 2021; Menció et al., 2023). These processes are especially important in regions where the groundwater recharge is low and residence time is high, so that dissolved minerals build up over time.

Human activities have now played a more significant role in the degradation of groundwater, in addition to natural controls. Nutrient, heavy metal, organic pollutant, and microbial contamination in aquifer systems arises from intensive agricultural activities, over-fertilization and excessive use of pesticides, industrial effluents, uncontrolled disposal of wastes, and poor sanitation systems (Adimalla et al., 2020; Qasemi et al., 2022). However, the contamination of groundwater is not easily

detected and groundwater cleanup of contaminated aquifers is difficult and costly (Mukherjee et al., 2021). Thus, the development of a groundwater chemistry monitoring program is needed to detect any emerging trends in groundwater chemistry, ensure the safety of the public health supplies, and enable the sustainable management of groundwater resources.

The quality of groundwater is becoming more important in Pakistan due to the fact that groundwater is the sole source of drinking water and irrigation water for many communities. Regular monitoring of physicochemical and biological parameters has been highlighted by various national and international bodies such as the World Health Organization (WHO), National Council of Research in Water Resources (PCRWR), National Environmental Quality Standards (NEQS) and provincial environmental protection agencies to guarantee water safety and compliance with permissible limits (WHO, 2022; PCRWR, 2023). This monitoring helps to get scientific information for groundwater suitability assessment, pollution sources and effective groundwater management strategy.

Semi-arid coastal areas like District Lasbela of Balochistan are also highly vulnerable areas of groundwater environments due to variety of stresses such as low recharge, high evaporation, mineralization of geological water and potential interaction with marine water. In recent years, the hydrogeochemical studies revealed that the coastal aquifers often exhibit variations in salinity, ionic composition and suitability of groundwater resources at the spatial scale, mainly because of the influence of both natural and anthropogenic processes (Rasool et al., 2021; Ahmed et al., 2024). Therefore, district-wide statements on the quality of groundwater resources may not reflect the diversity of groundwater conditions within specific administrative districts, aquifer zones or settlements. A systematic, parameter-by-parameter analysis of groundwater chemistry is thus required in order to detect spatial variations, understand the controlling processes

and establish robust strategies for protecting groundwater resources in high risk areas like district Lasbela.

1.2 Study Area Context and Rationale

Tehsil Bela, together with Tehsil Uthal, forms District Lasbela, a coastal district of Balochistan situated approximately 130 km north of Karachi on the Arabian Sea coast. Bela is the administrative and historical center of the former princely state of Las Bela and remains the district's most agriculturally productive tehsil, with wheat as the primary crop alongside corn, sesame, fodder crops, onions, red chilies, bananas, chikoo and papaya. Irrigation is dominated by tube wells and dug wells, supplemented by canal networks, making groundwater chemistry directly relevant to both crop yield and soil health. Given the district's arid climate, coastal proximity, and localized industrial and mining activity (including barite extraction), groundwater in Bela may be subject to varying degrees of salinization and mineral enrichment, and its comparatively larger agricultural base means that irrigation-suitability findings here carry particular economic weight for the district.

1.3 Literature Review

The regional and international literature reviewed for this assessment situates Bela's groundwater within a broader pattern of semi-arid hydrochemistry. Aghazadeh and Mogaddam (2010), studying the Oshnavieh area of Iran, demonstrated the value of combining drinking-water compliance testing with irrigation-suitability indices, an approach adopted here. Alamgir et al. (2016) documented substantial salinity- and TDS-driven variability in coastal Sindh groundwater, attributing this to evaporite dissolution and, at some sites, seawater influence – a hydrogeological analogy relevant to coastal Lasbela. Khalid (2019) combined a water-quality index with multivariate statistics to assess groundwater around Balochistan brick kilns, concluding that both natural mineral dissolution and localized anthropogenic inputs shape provincial groundwater chemistry. Two studies specific to the Winder area of Balochistan – Naseem, Hamza, Bashir, Pirzada and Talpur (2013), examining trace-element

geochemistry and irrigation-water appraisal, and the related work of Naseem, Hamza and Bashir (2010) – found that irrigation suitability was frequently constrained by sodium hazard even where bulk drinking-water parameters were acceptable, a pattern also observed in Bela's SAR results (Section 3.10). Khuhawar et al. (2019) reported elevated TDS and hardness in Thar Desert groundwater of Sindh, reinforcing that semi-arid Pakistani aquifers commonly display a tendency toward mineral enrichment. As in the companion Uthal assessment, the classification frameworks used here (Piper, 1944; Wilcox, 1955; Richards, 1954; Kelly, 1940; Sawyer & McCarty, 1967) provide the long-established methodological backbone against which Bela's results are benchmarked.

1.4 Objectives of the Study

This study characterizes the groundwater quality of Tehsil Bela through: (i) determination and interpretation of fifteen physio-chemical parameters; (ii) comparison with WHO, PCRWR, NEQS and UEPA guideline values, including a multi-standard compliance comparison; (iii) characterization of the hydrochemical facies (ionic dominance) of the groundwater on a milliequivalent basis; (iv) application of irrigation-suitability indices (sodium percentage, SAR, Kelly's Index, Residual Sodium Carbonate, Permeability Index and Magnesium Hazard ratio); and (v) translation of the findings into an evidence base for water-resource management decisions in the tehsil.

2. Materials and Methods

2.1 Study Area

Tehsil Bela is situated in District Lasbela, Balochistan, within a hot, dry, tropical desert climatic zone moderated by proximity to the Arabian Sea. The tehsil is the district's main agricultural center, with the bulk of its 13,503 hectares of cultivated land irrigated through tube wells (63%), dug wells, and canals (16% of land, 21% of irrigation sources). The aquifer system is hosted in alluvial and coastal sedimentary deposits with locally significant carbonate and evaporite mineralization, a geological setting broadly comparable to, though

generally less intensely mineralized than, that underlying neighboring Uthal.

2.2 Sampling Design and Collection

Twenty-six groundwater samples were collected from Tehsil Bela between November 2022 and August 2023 across thirteen union councils, from bore wells, dug wells and hand pumps at depths generally between 55 and 230 feet, giving an average sampling density of two sources per union council. Pumps were run for five minutes before sampling to purge stagnant casing water, and two 1.5 L chemically cleaned plastic bottles were collected at each site – one for physico-chemical analysis and one acidified with 1 mL of HCl (to pH < 2) for metal determination. Samples were transported in cool, sealed containers and analysed within recommended holding times.

2.3 Analytical Methods

pH, EC, TDS and salinity were measured using an Orion 420A pH meter and Orion Star 5 conductivity meter, both calibrated against certified buffers/standards before each

analytical session. Chloride was determined by argentometric titration with silver nitrate and potassium chromate indicator. Sulphate was measured turbidimetrically as barium sulphate. Nitrate was determined by the brucine-sulphate spectrophotometric method (absorbance at 410 nm). Total phosphate and orthophosphate were determined spectrophotometrically following acid-persulphate digestion and direct molybdate colorimetry, respectively. Sodium, potassium, calcium and magnesium were quantified by flame atomic absorption spectrometry with five-point external calibration and periodic drift-check standards. Results were compared against WHO, PCRWR (2018), NEQS (2019) and UEPA (2020) guideline values, and descriptive statistics were computed for each parameter.

2.4 Guideline Values and Regulatory Standards

As in the companion Uthal assessment, WHO, PCRWR, NEQS and UEPA guideline values were retained separately rather than reduced to a single threshold, since the four frameworks differ materially for several parameters (Table 1).

Table 1. Selected drinking-water guideline values used for multi-standard compliance comparison

Parameter	WHO limit	PCRWR limit	UEPA limit
EC ($\mu\text{S}/\text{cm}$)	1500	100–500	–
TDS (mg/L)	1000	–	500
Salinity (ppt)	1.0	1.0	0.5
Alkalinity (mg/L)	500	150–300	120
Total hardness (mg/L)	500	–	–
Chloride (mg/L)	250	–	–

2.5 Derived Water-Quality Indices

Irrigation-water indices were computed on a milliequivalents-per-litre (meq/L) basis, following the same formulae applied in the companion Uthal study:

- Sodium percentage (Na%): $\text{Na}\% = \frac{[\text{Na}^+ + \text{K}^+]}{[\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+]} \times 100$
- Sodium Adsorption Ratio (SAR): $\text{SAR} = \frac{\text{Na}^+}{\sqrt{[\text{Ca}^{2+} + \text{Mg}^{2+}] / 2}}$
- Kelly's Index (KI): $\text{KI} = \frac{\text{Na}^+}{(\text{Ca}^{2+} + \text{Mg}^{2+})}$

- Residual Sodium Carbonate (RSC): $\text{RSC} = (\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+})$
- Permeability Index (PI): $\text{PI} = \frac{[\text{Na}^+ + \sqrt{\text{HCO}_3^-}]}{[\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+]} \times 100$
- Magnesium Hazard ratio (MH): $\text{MH} = \frac{[\text{Mg}^{2+}]}{[\text{Ca}^{2+} + \text{Mg}^{2+}]} \times 100$

Total hardness was classified using the Sawyer and McCarty (1967) scale, and TDS-based salinity was classified as non-saline (< 1000 mg/L), slightly saline (1000–3000 mg/L), moderately saline (3000–10,000 mg/L) and very saline (> 10,000 mg/L).

2.6 Statistical Analysis

Descriptive statistics (mean, standard error, standard deviation, median, minimum and maximum) were computed for each parameter across the 26 samples, and percentage compliance with each guideline value was assessed on a per-sample basis.

Where the tehsil-mean value and the per-sample compliance percentage appear to diverge (for example, EC and chloride, discussed in Sections 3.2–3.3), both perspectives are reported

explicitly to avoid a misleadingly favorable impression based on the mean alone.

3. Results and Discussion

3.1 pH

The pH of Bela groundwater ranged from 7.5 to 8.6, with a mean of 7.93 ± 0.044 (SD = 0.26), indicating consistently alkaline conditions. Ninety-seven percent of samples (25 of 26) fell within the WHO permissible range of 6.5–8.5, with only one sample marginally exceeding the upper limit. Bela's mean pH is notably higher than that recorded in neighboring Uthal (7.36), though both remain within WHO guidelines.

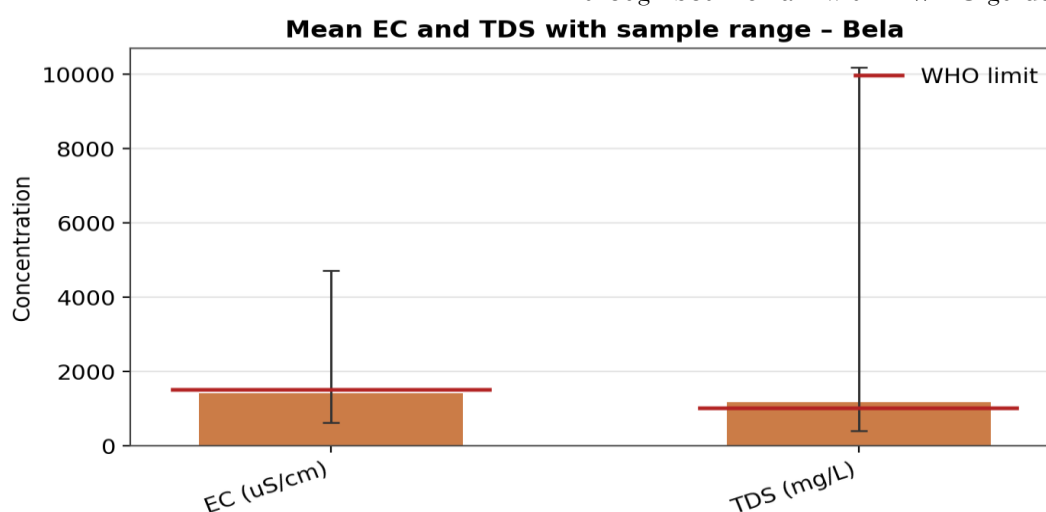


Figure 1. Mean electrical conductivity (EC) and total dissolved solids (TDS) in Bela groundwater, with sample minimum–maximum range, compared with the WHO permissible limit

3.2 Electrical Conductivity, TDS and Salinity

Electrical conductivity in Bela ranged from 616 to 4720 $\mu\text{S}/\text{cm}$ (mean $1418.4 \pm 138.2 \mu\text{S}/\text{cm}$); the tehsil means lies close to the WHO limit of 1500 $\mu\text{S}/\text{cm}$, and 73% of individual samples were within this limit, reflecting substantially lower average ionic loading than Uthal.

TDS ranged from 394.2 to 10,184 mg/L (mean $1169.9\text{--}1297.0 \text{ mg/L}$ depending on outlier treatment), with 57.6% of samples within the WHO limit of 1000 mg/L, 26.9% above it, and 15.3% below the WHO minimum guideline of 500 mg/L. Salinity ranged from 0.1 to 2.5 ppt (mean $0.71 \pm 0.076 \text{ ppt}$), remaining within the WHO/PCRWR/NEQS limit of 1.0 ppt in all samples, though 61% of samples exceeded the more conservative UEPA limit of 0.5 ppt.

3.3 Chloride, Total Hardness, Alkalinity and Sulphate

Chloride concentrations in Bela ranged from 14 to 400 mg/L (mean $116.4 \pm 15.7 \text{ mg/L}$); despite this comparatively low mean, 80.7% of individual samples exceeded the WHO limit of 250 mg/L when evaluated on a per-sample basis, indicating localized chloride hotspots that are masked by the tehsil mean – a clear illustration of why per-sample compliance percentages, no means alone, should guide management decisions.

Total hardness ranged from 128 to 720 mg/L (mean $305.7 \pm 20.3 \text{ mg/L}$), with 97% of samples within the WHO limit of 500 mg/L, yet the hardness-classification scheme placed 73% of samples in the 'hard' to 'very hard' categories. Alkalinity ranged from 115 to 600 mg/L (mean $231.4 \pm 22.1 \text{ mg/L}$), with 34.6% within the tighter WHO band and the majority within the broader PCRWR range (150–300 mg/L, 77% compliant). Sulphate ranged from 44 to 367

mg/L (mean 187.3 ± 17.7 mg/L), with 81% of samples within the WHO limit of 250 mg/L.

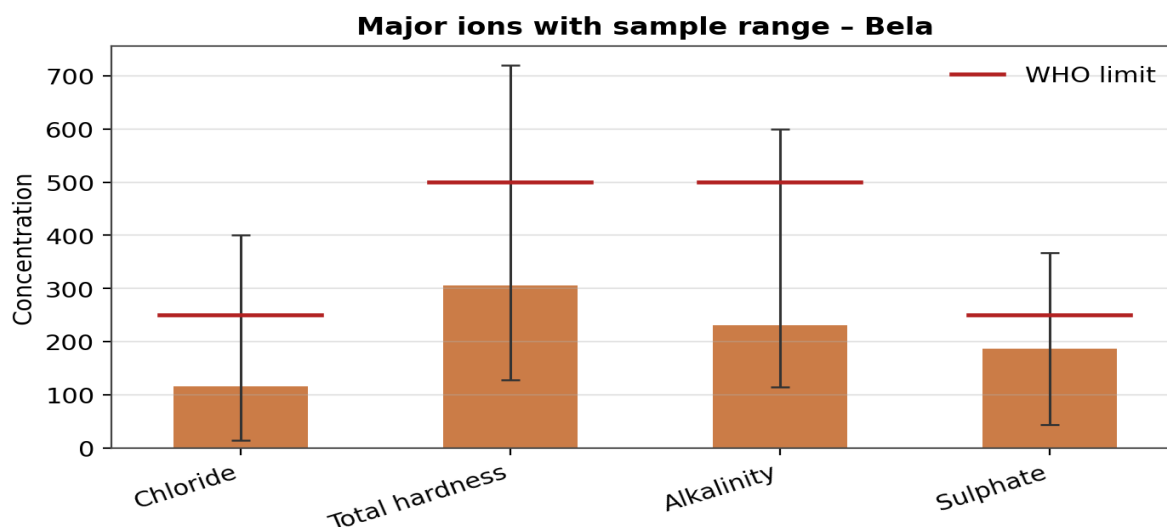


Figure 2. Mean chloride, total hardness, alkalinity and sulphate concentrations in Bela groundwater, with sample range, compared with WHO permissible limits

3.4 Essential Metals (Na, K, Ca, Mg)

Sodium concentrations (22–156 mg/L, mean 78.0 mg/L) remained within the WHO limit of 200 mg/L in all samples. Calcium (64–360 mg/L, mean 152.9 mg/L) remained within the WHO limit in 80% of samples. Magnesium (13.6–110.1 mg/L, mean 46.3 mg/L) remained

within the WHO limit of 150 mg/L in 73% of samples. Potassium (6–60 mg/L, mean 22.8 mg/L) exceeded the WHO limit of 12 mg/L in 80.7% of samples, mirroring the pattern seen in Uthal and suggesting a shared geological or agricultural source of potassium enrichment across the district.

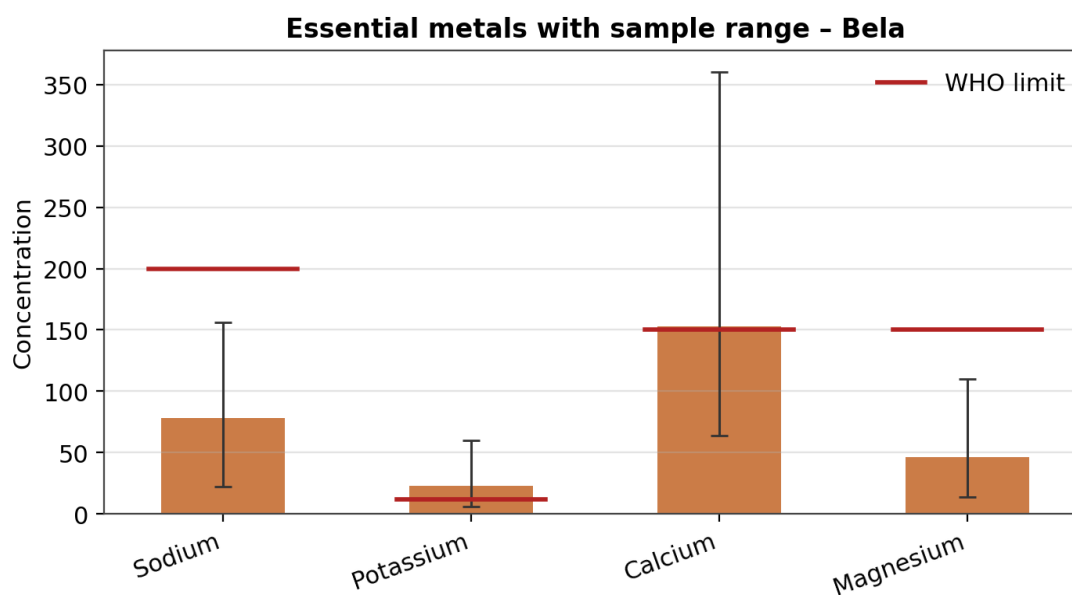


Figure 3. Mean sodium, potassium, calcium and magnesium concentrations in Bela groundwater, with sample range, compared with WHO permissible limits

3.5 Nutrients: Nitrate, Total Phosphate and Orthophosphate

Nitrate concentrations (2.23–8.67 mg/L, mean 3.89 mg/L) remained within the WHO limit of

12 mg/L in all samples, indicating that nitrogen-based contamination is not currently a significant concern in Bela. Total phosphate (0.206–8.212 mg/L, mean 2.77 mg/L) exceeded the WHO limit of 3.0 mg/L in 46% of samples,

and orthophosphate (0.112–3.435 mg/L, mean 0.98 mg/L) exceeded the WHO limit of 1.0 mg/L in 53.8% of samples, indicating phosphate enrichment broadly comparable to, or slightly greater than, that observed in Uthal.

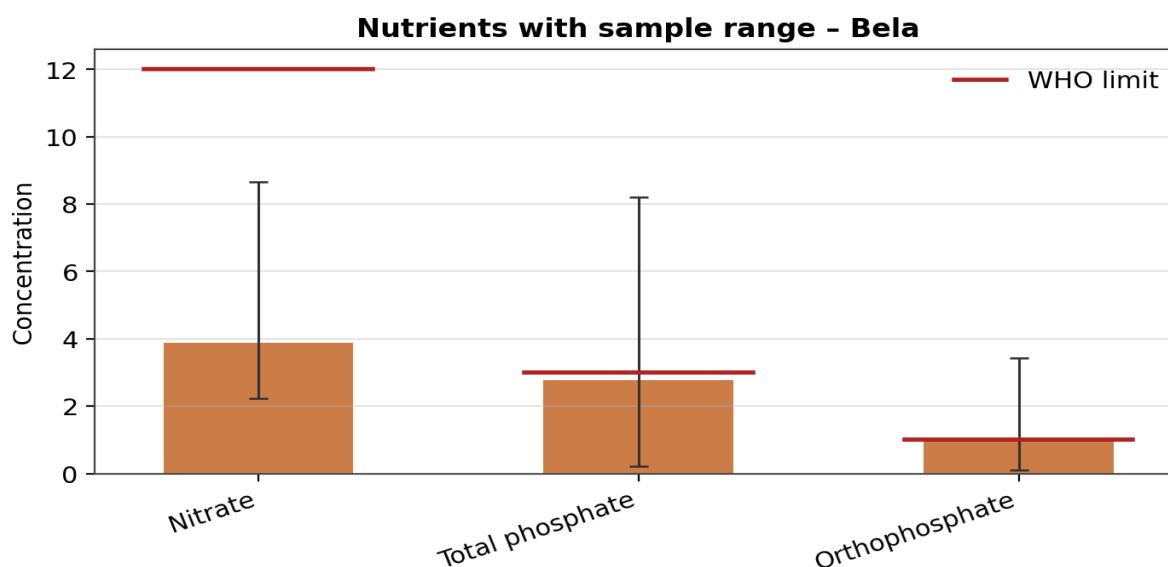


Figure 4. Mean nitrate, total phosphate and orthophosphate concentrations in Bela groundwater, with sample range, compared with WHO permissible limits.

3.6 Multi-Standard Compliance Comparison

Figure 5 compares the percentage of Bela samples exceeding the relevant limit under WHO, PCRWR and UEPA frameworks. EC exceedance is 27% under the WHO limit; salinity exceedance rises from 0% under the WHO/PCRWR/NEQS limit to 61% under the

stricter UEPA threshold; and chloride exceedance under the WHO limit stands at 80.7%. These results again demonstrate that regulatory-standard choice materially affects the proportion of sources judged non-compliant, particularly for salinity.

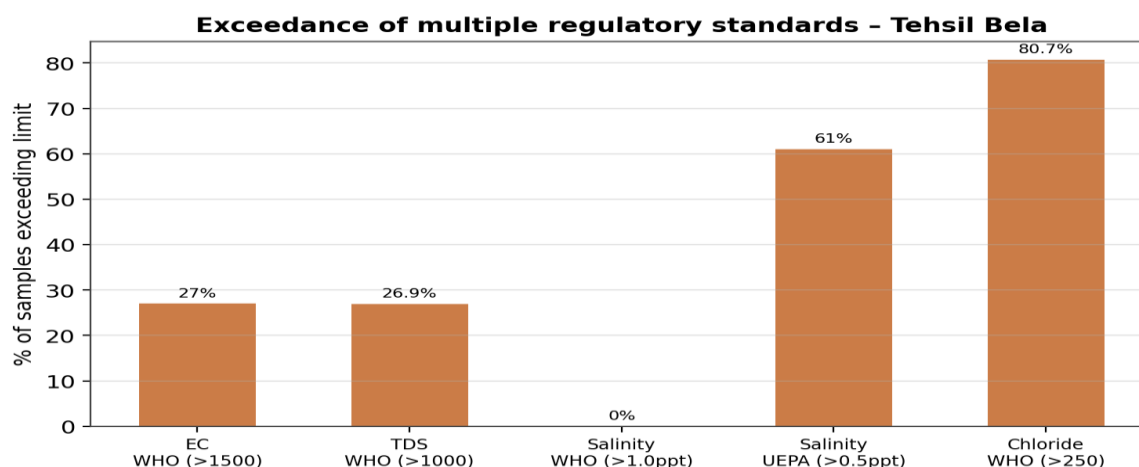


Figure 5. Percentage of Bela samples exceeding the relevant limit under multiple regulatory standards (WHO, UEPA) for EC, TDS, salinity and chloride.

3.7 Overall Compliance Overview

Figure 6 summarises, for all fifteen parameters, the percentage of Bela samples within the WHO

permissible limit. Salinity, sodium, total hardness and nitrate show full or near-full compliance (97–100%), while chloride and potassium show the lowest compliance (19.3%)

each), identifying these as the parameters of greatest concern for drinking-water use in Tehsil Bela.

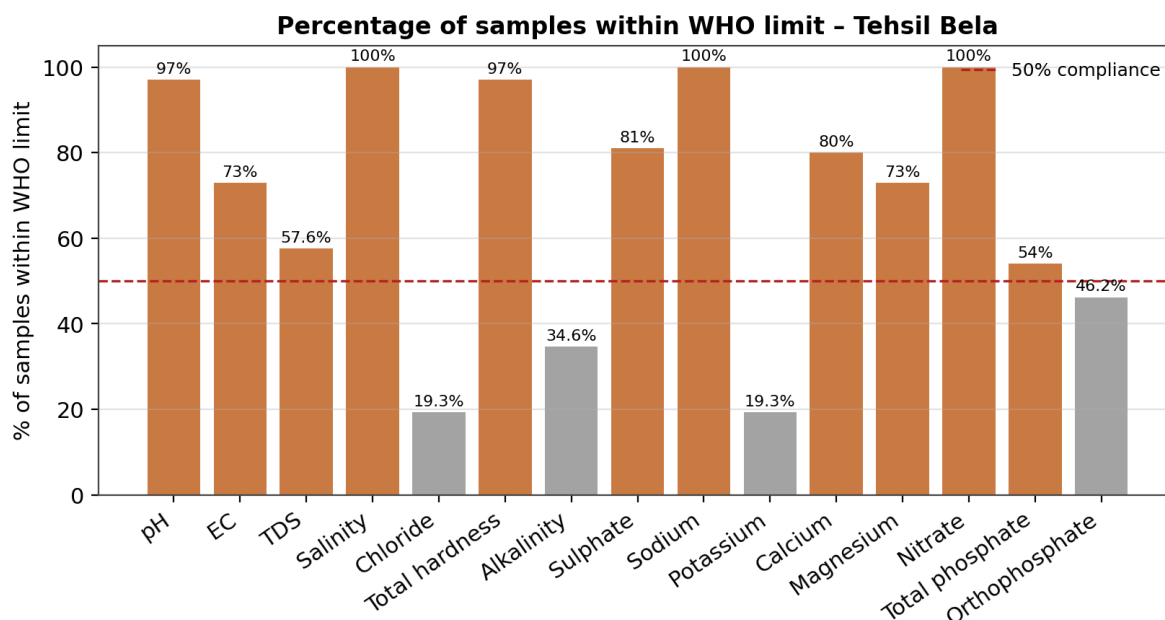


Figure 6. Percentage of Bela samples within the WHO permissible limit, across all fifteen physico-chemical parameters.

3.8 Hydrochemical Facies and Ionic Dominance

On a milliequivalents-per-litre (meq/L) basis, the mean cation composition of Bela groundwater is calcium 7.65 meq/L (49.6% of total cations), magnesium 3.81 meq/L (24.7%), and sodium plus potassium 3.98 meq/L (25.8%), while the mean anion composition is bicarbonate (from alkalinity) 4.63 meq/L (39.2% of total anions),

sulphate 3.90 meq/L (33.0%) and chloride 3.28 meq/L (27.8%). This places Bela groundwater, on average, in a Ca–Mg–HCO₃/SO₄ hydrochemical facies, with calcium clearly dominant among cations and bicarbonate marginally dominant among anions – a signature more strongly carbonate-influenced, and with a smaller relative chloride and sodium contribution, than that of Uthal.

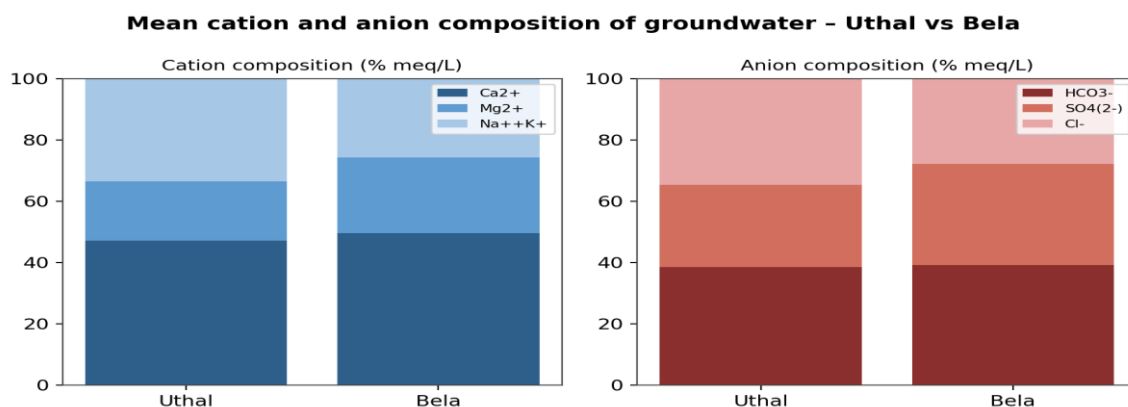


Figure 7. Mean cation and anion composition (percentage of total milliequivalents per litre) of groundwater in Tehsil Uthal and Tehsil Bela.

3.9 Derived Hydrochemical Indices

Table 2 reports the five supplementary derived indices computed from Bela's mean ion concentrations. The RSC is strongly negative (-6.83 meq/L), indicating no residual-carbonate hazard. The Permeability Index (37.3%) falls within Class II (25–75%), denoting moderate permeability suitability, slightly lower than Uthal's PI (43.3%). The Magnesium Hazard ratio (33.3%) is marginally higher than Uthal's (29.1%) but remains below the 50% concern threshold. Kelly's Ratio on a mean-ion basis (0.30) is well below 1, consistent in direction with, though numerically lower than, the per-sample Kelly's Index finding of 92.3% suitability reported in Section 3.10.

As in Uthal, the mean-ion SAR (1.42) understates the sodium hazard indicated by the per-sample SAR distribution, where only 30.8% of individual samples are classified as suitable ($\text{SAR} < 6$). This reflects the same non-linearity discussed in the companion Uthal paper: because SAR involves a square-root term in the denominator, averaging ion concentrations before computing the index produces a materially different – and generally more favourable – result than computing the index per sample and then summarising. The per-sample-based irrigation-suitability results in Section 3.10 remain authoritative.

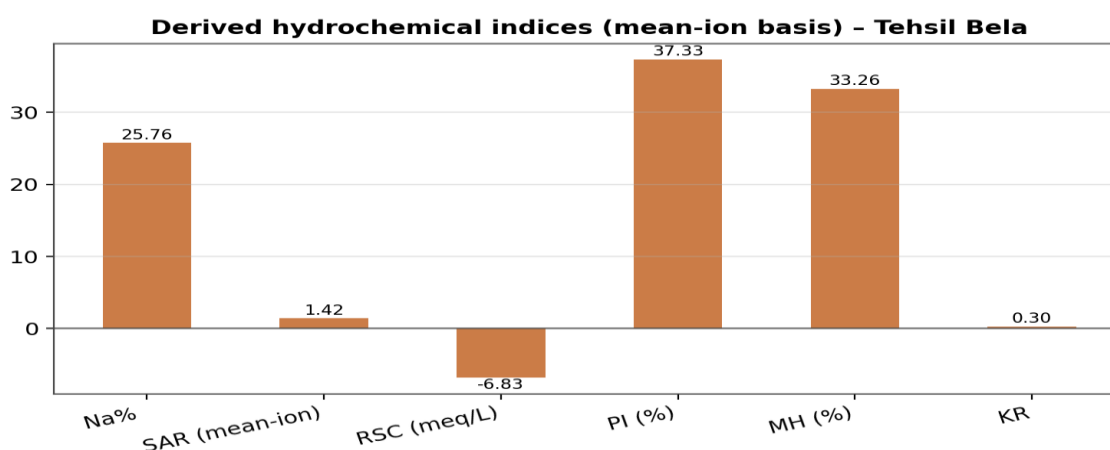


Figure 8. Derived hydrochemical indices (Na%, mean-ion SAR, RSC, PI, MH and KR) computed from mean ion concentrations, Tehsil Bela

Table 2. Derived hydrochemical indices computed from mean ion concentrations, Tehsil Bela.

Index	Formula basis	Bela value	Interpretation
Na%	meq/L, mean ions	25.8%	Lower mean sodium hazard than Uthal (33.6%)
SAR (mean-ion)	meq/L, mean ions	1.42	Understates per-sample hazard (see text)
RSC (meq/L)	meq/L, mean ions	-6.83	No residual-carbonate hazard
PI (%)	meq/L, mean ions	37.3%	Class II – moderate permeability suitability
MH (%)	meq/L, mean ions	33.3%	Below 50% concern threshold
KR (mean-ion)	meq/L, mean ions	0.30	Suitable on mean basis; consistent with per-sample KI, §3.10

3.10 Suitability for Irrigation

On the TDS-based salinity classification, 73% of Bela samples were non-saline (< 1000 mg/L), 19.2% slightly saline, and 3.8% each in the moderately and very saline categories – a

markedly more favourable distribution than in Uthal. Sodium percentage classified 42.3% of samples as good, 26.9% as permissible and 30.8% as doubtful for irrigation. The Sodium Adsorption Ratio (SAR) indicated 30.8% of

samples as suitable (SAR < 6) and 69.2% as unsuitable, while Kelly's Index indicated a considerably more favourable picture, with 92.3% of samples suitable (KI < 1) and only 7.7% unsuitable. As in Uthal, the divergence

between SAR and Kelly's Index results underscores the importance of applying multiple irrigation-suitability criteria rather than relying on a single index.

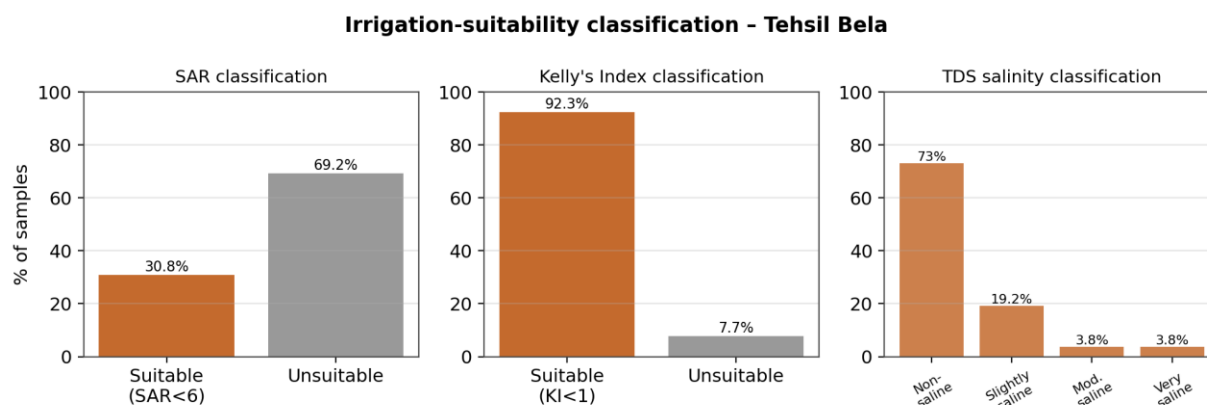


Figure 9. Irrigation-suitability classification of Bela groundwater by SAR, Kelly's Index and TDS-based salinity class

3.11 Public Health and Agronomic Implications

Bela's most significant drinking-water compliance concern – chloride, exceeding the WHO limit in over 80% of samples on a per-sample basis – is primarily an aesthetic and corrosion issue at the concentrations recorded (imparting a salty taste and accelerating corrosion of metal fittings) rather than an acute toxicological hazard, though very high chloride intake can be relevant for individuals on sodium-restricted diets. Potassium exceedance (80.7% of samples) carries similar considerations to those discussed for Uthal: not acutely hazardous to the general population at these levels, but worth flagging for patients with impaired renal function. The high proportion of samples in the 'hard' to 'very hard' categories (73%) represents primarily an aesthetic and economic burden (soap consumption, scale formation in pipes and appliances) rather than a demonstrated health risk, and some studies have even associated moderately hard water with beneficial dietary calcium and magnesium intake.

From an agronomic perspective, Bela's comparatively favorable TDS-based salinity classification (73% non-saline) and Kelly's Index result (92.3% suitable) suggest that, for most sources, irrigation can proceed without major soil-structure concern; however, the SAR result

(only 30.8% suitable) indicates that a meaningful minority of sources still pose a sodium-hazard risk to soil permeability, particularly on fine-textured soils, and should be prioritized for monitoring or blending before use on sensitive crops.

3.12 Comparison with Other Studies

Bela's comparatively favourable profile relative to Uthal – lower mean EC, TDS, salinity and total hardness, alongside a higher proportion of non-saline and Kelly's-Index-suitable samples – is broadly consistent with the moderate mineralization reported for other agriculturally dominant, less industrially exposed tehsils in semi-arid Pakistani settings (Khalid, 2019; Khuhawar et al., 2019). The persistent divergence between SAR- and Kelly's-Index-based suitability verdicts mirrors the findings of Naseem et al. (2010, 2013) in nearby Winder, Balochistan, and of Aghazadeh and Mogaddam (2010) in Iran, both of which caution against single-index irrigation screening. The comparatively low chloride mean but high per-sample chloride exceedance rate observed here also echoes the coastal salinity heterogeneity documented by Alamgir et al. (2016) in Sindh, where localized hotspots produced compliance statistics very different from those implied by the areal mean.

4. Conclusion and Recommendations

4.1 Summary of Key Findings

Groundwater quality in Tehsil Bela is, on balance, more favourable than in neighbouring Tehsil Uthal for several key indicators: mean EC, TDS, salinity, total hardness and calcium are all lower in Bela, and a much larger share of samples fall in the non-saline TDS category. The mean hydrochemical facies is Ca-Mg-HCO₃/SO₄, reflecting a more strongly carbonate-influenced aquifer than Uthal's mixed Ca-Mg-HCO₃/Cl signature. Nonetheless, chloride and potassium exceed WHO guidance in a majority of individual samples, total hardness places most samples in the hard-to-very-hard range, and phosphate species show localized enrichment. Irrigation-suitability assessment similarly reveals a mixed picture: Kelly's Index suggests most groundwater is fit for irrigation, whereas SAR indicates the opposite for the majority of samples, reinforcing that both indices – computed per sample, not from tehsil means – should be consulted before agricultural water-use decisions are made.

4.2 Recommendations for Water Management

In the short term, targeted treatment or blending is recommended for the chloride- and potassium-affected sources identified in this survey, together with community communication that a favorable tehsil-mean chloride value does not guarantee compliance at every individual source. In the medium term, annual monitoring of chloride, potassium and hardness across all thirteen union councils is recommended, together with soil-amendment guidance for farmers irrigating fine-textured soils with high-SAR sources. In the longer term, protection of recharge areas from contamination and continued district-wide coordination with the neighbouring Uthal water-management

programme (given the shared district-level hardness and potassium signature) are recommended to sustain safe drinking-water supply and agricultural productivity in Tehsil Bela.

4.3 Limitations of the Study

This assessment reflects a single sampling round (November 2022–August 2023) and does not capture seasonal (pre-/post-monsoon) variability in EC, TDS, salinity or chloride. The derived hydrochemical indices in Section 3.9 were computed from tehsil-mean ion concentrations for illustrative and comparative purposes and, as discussed, can understate index values relative to per-sample calculation; the per-sample-based results in Section 3.10 should be treated as authoritative for irrigation-suitability conclusions. Microbiological analysis was not conducted, and given that dug wells and hand pumps are represented in the sample set, bacteriological contamination may represent an additional drinking-water risk not captured by this physico-chemical assessment.

4.4 Future Research Directions

Future work should priorities (i) seasonal resampling to characterize temporal variability in the chloride and salinity hotspots identified here; (ii) GIS-based mapping of per-sample irrigation-suitability indices at the union-council level to identify spatial clusters; (iii) microbiological and trace-metal screening to complement the physico-chemical determinands reported here; and (iv) a joint Uthal-Bela hydrogeochemical model (e.g., Piper and Gibbs diagrams built from individual sample data) to better apportion the relative roles of carbonate dissolution, silicate weathering and any marine influence across the two tehsils, extending the comparative analysis presented in the companion comparative paper.

Table 3. Summary of physico-chemical parameters of groundwater in Tehsil Bela compared with WHO permissible limits

Parameter	Mean	Min	Max	WHO limit	% within WHO limit
pH	7.93	7.5	8.6	6.5–8.5	97%
EC (µS/cm)	1418.4	616	4720	1500	73%
TDS (mg/L)	1169.9	394.2	10,184	1000	57.6%
Salinity (ppt)	0.71	0.1	2.5	1.0	100%
Chloride (mg/L)	116.4	14	400	250	19.3%
Total hardness (mg/L)	305.7	128	720	500	97%
Alkalinity (mg/L)	231.4	115	600	500	34.6%
Sulphate (mg/L)	187.3	44	367	250	81%
Sodium (mg/L)	78.0	22	156	200	100%
Potassium (mg/L)	22.8	6	60	12	19.3%
Calcium (mg/L)	152.9	64	360	150/200	80%
Magnesium (mg/L)	46.3	13.6	110.1	150	73%
Nitrate (mg/L)	3.89	2.23	8.67	12	100%
Total phosphate (mg/L)	2.77	0.21	8.21	3.0	54%
Orthophosphate (mg/L)	0.98	0.11	3.44	1.0	46.2%

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