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PHYSICOCHEMICAL ASSESSMENT OF DRINKING WATER QUALITY IN TEHKAL BALA, PESHAWAR, PAKISTAN, WITH REFERENCE TO NATIONAL STANDARDS

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Abstract
The present study evaluated the physicochemical quality of drinking water in the residential area of Tehkal Bala, Peshawar, Pakistan, with reference to the National Standards for Drinking Water Quality (NSDWQ) of Pakistan. A total of twenty household water samples were collected and analyzed for key physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, total hardness, calcium hardness, magnesium hardness, alkalinity, and chloride, using standard analytical procedures. The results indicated that most parameters namely pH (6.86–7.12), EC, TDS, turbidity, alkalinity, and chloride were within the permissible limits prescribed by NSDWQ, suggesting that the water is generally suitable for domestic consumption.
However, magnesium hardness consistently exceeded the recommended NSDWQ threshold across all sampling locations, representing a systematic deviation from compliance. This persistent elevation is likely attributable to geogenic processes associated with the local aquifer lithology. In addition, one sampling point exhibited marginally elevated calcium hardness, though it remained within acceptable limits at most locations. Although the whole physicochemical quality of the drinking water was classified as potable, the widespread exceedance of magnesium hardness raises concerns regarding potential long-term health implications associated with chronic exposure. The study recommends detailed hydrogeochemical investigations to identify the source and mobilization mechanisms of magnesium, the implementation of routine water quality monitoring programs, and the adoption of appropriate point-of-use treatment technologies, such as ion-exchange systems, for affected households. Strengthening public awareness and regulatory oversight is also essential to safeguard public health and ensure sustainable access to safe drinking water.

Introduction
Water is far more than a basic necessity; it is the very engine of human settlement and the foundation upon which societies build their economic and social fabric (Thakur et al., 2024). History shows us that the fate of great civilizations has been intimately tied to their access to reliable water. Yet, despite its apparent abundance, the freshwater available for our direct use makes up less than one percent of the Earth's total water

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(Mekonnen et al., 2024). Within this critical sliver lies groundwater, stored in complex and often fragile aquifer systems a finite resource that is alarmingly susceptible to overextraction and irreversible degradation, with emerging challenges in geochemical balance such as shifts in hardness and metal concentrations. This precious water is part of the global hydrological cycle, a natural process now under severe stress from human activity and climatic shifts, with studies noting its increasing vulnerability to pollution pathways (Nsabimana et al., 2022).

As water travels through this cycle, its purity is continuously compromised. In our modern world, a heavy human footprint comprised of industrial effluents laden with heavy metals (Khan et al., 2020), agricultural runoff rich in nitrates and pesticides, and untreated urban wastewater (Murtaza & Zia, 2012) creates a dangerous cocktail of contaminants. This pollution threatens not only human health, through waterborne diseases and longterm exposure to toxins (Azizullah et al., 2011), but also destabilizes entire aquatic ecosystems (Cornelius et al., 2017). We now face a convergence of pressures: rapid population growth, sprawling urbanization that paves over natural recharge zones, and intensive agriculture, all pushing water systems toward a tipping point. Compounding this is climate change, which is intensifying the hydrological cycle, leading to more extreme and erratic precipitation. In regions like South Asia, this manifests as devastating floods followed by prolonged droughts, severely undermining both water availability and quality (Parvaze et al., 2023). Recent research emphasizes that these climatic extremes directly exacerbate groundwater depletion and concentrate pollutants, creating a dual crisis of scarcity and contamination, further complicated by transboundary water management challenges (Ahmadzai et al., 2018; Vinca et al., 2021).

This crisis is starkly evident in Khyber Pakhtunkhwa (KP), Pakistan. While official statistics may report access to "improved" water sources for a majority, these figures often mask a harsh reality of inequality and unsafe conditions (Natasha et al., 2020). KP relies on a mix of rivers including the vital Kabul River system springs, and groundwater wells, but these sources are compromised by dilapidated infrastructure, a lack of functional treatment facilities (Hussain et al., 2013;Reshteen et al.,2024), and direct contamination from local activities. Empirical studies consistently show that a significant portion of water in Pakistan's urban and rural centers is contaminated with fecal coliforms, heavy metals like arsenic and lead (Rasool et al., 2016; Ullah et al., 2019), excessive salinity, and other harmful substances (Rashid et al., 2019).

Despite this growing body of literature, critical research gaps persist for KP, hindering effective local solutions. Existing studies often provide only isolated snapshots of contamination in specific towns or major cities, leaving a pronounced lack of comprehensive data across diverse settings (Khan et al., 2020). A particularly understudied yet critical zone is the periurban interface areas in rapid transition where urban pollution meets rural infrastructure limits. The present study focused on physiochemical analysis in the study area, representing a vital microcosm of the pressures facing KP, yet no dedicated, integrated water quality study for this community exists.

Furthermore, while research often isolates specific contaminants like microbes or heavy metals, few studies concurrently analyze the full suite of physical, chemical, and biological parameters from the same water sources to assess cumulative risk. There is also a lack of detailed investigation into the precise sources and pathways of pollution at the village level, where contributors could range from localized sewage seepage to agricultural runoff (Murtaza & Zia, 2012). The impact of climate variability on contaminant mobilization in such specific aquifer systems remains unexplored, and the practical evaluation of affordable remediation technologies such as adsorption or coagulation using local materials for water with the unique chemical profile of a periurban village is notably absent (Zahra & Naseem, 2012; Zaman et al., 2019).

To directly address these gaps, this study conducts a comprehensive assessment of drinking water in Tehkal Bala, Peshawar. It aims to move beyond broad generalizations to provide an empirical, multiparameter profile of water quality at the

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community level. The primary objectives are to determine the concentration levels of key contaminants against safety standards, identify and apportion the specific pollution sources affecting this periurban context, and generate evidencebased insights. Ultimately, the findings are intended to bridge the gap between broad policy and actionable, localized intervention strategies (Ali & Nabeel, 2023), offering a crucial case study for designing resilient and equitable water management solutions for similar settlements across Khyber Pakhtunkhwa and contributing to wider national water security efforts.

Description of the Study Area

This research focuses on Tehkal Bala, a peri-urban village situated in the immediate vicinity of the University of Peshawar, Khyber Pakhtunkhwa, Pakistan (Figure 1). The selection of this site is strategic, as it embodies the critical challenges of a transitional zone experiencing pressure from adjacent urban expansion while maintaining rural characteristics in infrastructure and water management. The area is representative of communities where groundwater, typically accessed via household storage tanks and wells, is the primary drinking water source, making it vulnerable to localized contamination pathways. For this study, a total of twenty (n=20) water samples were systematically collected from household storage tanks across the village using a randomized sampling strategy to ensure spatial representativeness and minimize sampling bias.

Materials and Methods

Study Area and Sample Collection

Drinking water samples were collected from Tehkal Bala, a peri-urban village adjacent to the University of Peshawar, Khyber Pakhtunkhwa, Pakistan (Figure 1). A total of twenty (n=20) samples were obtained from household water storage tanks using a randomized sampling strategy to ensure spatial representativeness.

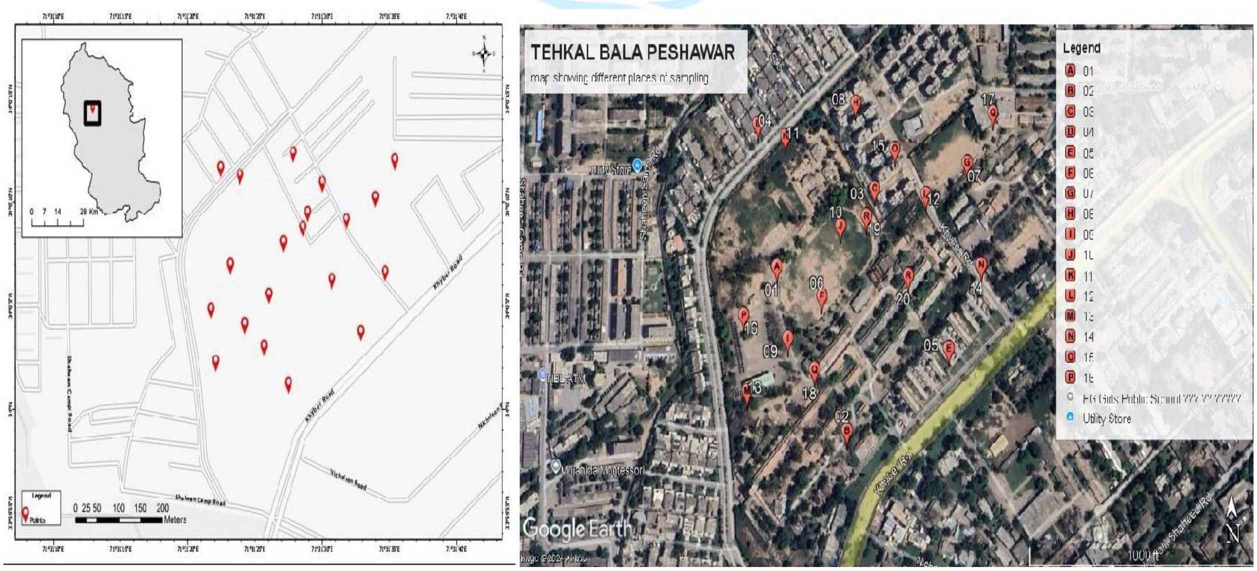

Figure 1. Geographical location of the study area, Tehkal Bala, a peri-urban village situated adjacent to the University of Peshawar, Khyber Pakhtunkhwa, Pakistan.

Sample Collection, Preservation, and Transportation

Water samples were collected in pre-cleaned, high-density polyethylene (HDPE) bottles of 1-liter capacity. Prior to sampling, each bottle was rinsed three times with the source water. Immediately after collection, samples were labeled, coded, placed in an insulated cooler at approximately 4°C, and transported to the laboratory for analysis. In-situ measurements of pH, electrical conductivity (EC), and temperature were performed within four hours of collection. For other analyses, samples

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were preserved according to standard methods (e.g., refrigeration for microbiological tests, acidification for metal analysis) and stored at 4°C until processing.

Analytical Methods for Physicochemical Parameters

All physicochemical analyses were conducted following standard protocols as outlined in Standard Methods for the Examination of Water and Wastewater. Specific methods and procedures are detailed below.

pH

The hydrogen ion concentration (pH) was measured potentiometrically using a calibrated digital pH meter (Model, Manufacturer). The meter was calibrated daily using standard buffer solutions of pH 4.0, 7.0, and 9.2. Measurements were performed by immersing the combined glass electrode in a 100 mL beaker containing the sample, and the stabilized reading was recorded.

Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

Electrical conductivity, a measure of the water's capacity to convey an electric current, was determined using a calibrated conductivity meter (Model, Manufacturer). The meter was standardized with a 0.01 M potassium chloride (KCl) solution. Total Dissolved Solids (TDS) were estimated from the EC measurement using an instrument-specific conversion factor, as well as verified gravimetrically. For the gravimetric method, a known volume of filtered sample was evaporated in a pre-weighed china dish at 105°C until a constant weight was achieved.

Turbidity

Turbidity, quantifying the light-scattering properties of suspended particles, was measured nephelometrically in Nephelometric Turbidity Units (NTU) using a digital turbidity meter (Model, Manufacturer). The instrument was calibrated with standard formazin suspensions of 0, 1, 10, 100, and 1000 NTU prior to analysis.

Total Hardness, Calcium, and Magnesium

Total hardness (as mg/L $CaCO_3$) was determined by titration with 0.01 M Ethylenediaminetetraacetic acid (EDTA) using Eriochrome Black-T (EBT) as an indicator at a pH of 10.0, maintained by an ammonium chloride/ammonium hydroxide buffer. Calcium hardness was determined separately by titrating with EDTA at pH 12–13 (adjusted using NaOH) using murexide indicator. Magnesium hardness was calculated as the difference between total hardness and calcium hardness.

Chloride (Cl^-)

Chloride concentration was determined by argentometric titration. A 20 mL aliquot of the sample was titrated against standardized 0.0141 N silver nitrate ($AgNO_3$) solution, using potassium chromate (K_2CrO_4) as an indicator. The endpoint was indicated by the appearance of a brick-red precipitate of silver chromate.

Total Alkalinity

Total alkalinity (as mg/L $CaCO_3$) was determined by acid-base titration. A 20 mL sample was titrated with 0.02 N sulfuric acid (H_2SO_4) using a mixed indicator (methyl orange) to an endpoint of pH 4.5, indicated by a color change from yellow to orange-red.

Statistical Analysis

Data for each physicochemical parameter were expressed as mean ± standard deviation (SD) based on triplicate analyses from six service stations. Statistical analyses were conducted using IBM SPSS Statistics v.26 and Microsoft Excel to ensure accuracy and consistency. One-way Analysis of Variance (ANOVA) was applied to assess significant differences ($p < 0.05$) among stations. The mean values were compared against the Pakistan National Environmental Quality Standards (NEQS) for industrial effluents.

Results and Discussion

Analysis of Physical Parameters

pH

In present study, the pH values of the twenty samples ranged from 6.86 to 7.12, with a mean

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value of 7.02 ± 0.06 (Figure 2). These results indicate that the drinking water in Tehkal Bala is neutral to very slightly alkaline. The pH values of all analyzed groundwater samples were within the guideline range of 6.5–8.5 recommended by the Pakistan National Standards for Drinking Water (NSDW) and the World Health Organization (WHO), indicating chemically stable groundwater conditions across the study area. This near-neutral pH plays a critical role in controlling water rock interactions and has direct implications for drinking-water safety. Specifically, such conditions reduce the corrosivity of groundwater, thereby limiting the dissolution and mobilization of metals from aquifer materials and distribution infrastructure, including lead, copper, and zinc elements frequently reported in contaminated urban and peri-urban groundwater systems in Pakistan (Khan et al., 2020; Rasool et al., 2016).

From a treatment and public-health perspective, near-neutral pH conditions also enhance the efficiency of chlorine-based disinfection by optimizing hypochlorous acid formation, should disinfection be applied at centralized facilities or at the household level. The consistently narrow pH range, reflected by a low standard deviation (0.06), suggests a well-buffered hydrochemical system. This buffering capacity is most likely governed by carbonate mineral equilibria, particularly calcite dissolution–precipitation reactions, which are characteristic of alluvial aquifers in the region and consistent with previous groundwater investigations in northern Pakistan (Rashid et al., 2019).

Moreover, the absence of extreme acidic or alkaline values implies limited influence from acute anthropogenic inputs such as industrial effluents, acid-generating wastes, or intense organic matter decomposition in the vicinity of the sampling sites. This contrasts with groundwater systems reported near industrial estates, where significant pH perturbations have been attributed to unregulated discharge and localized contamination (Lokhande et al., 2011).

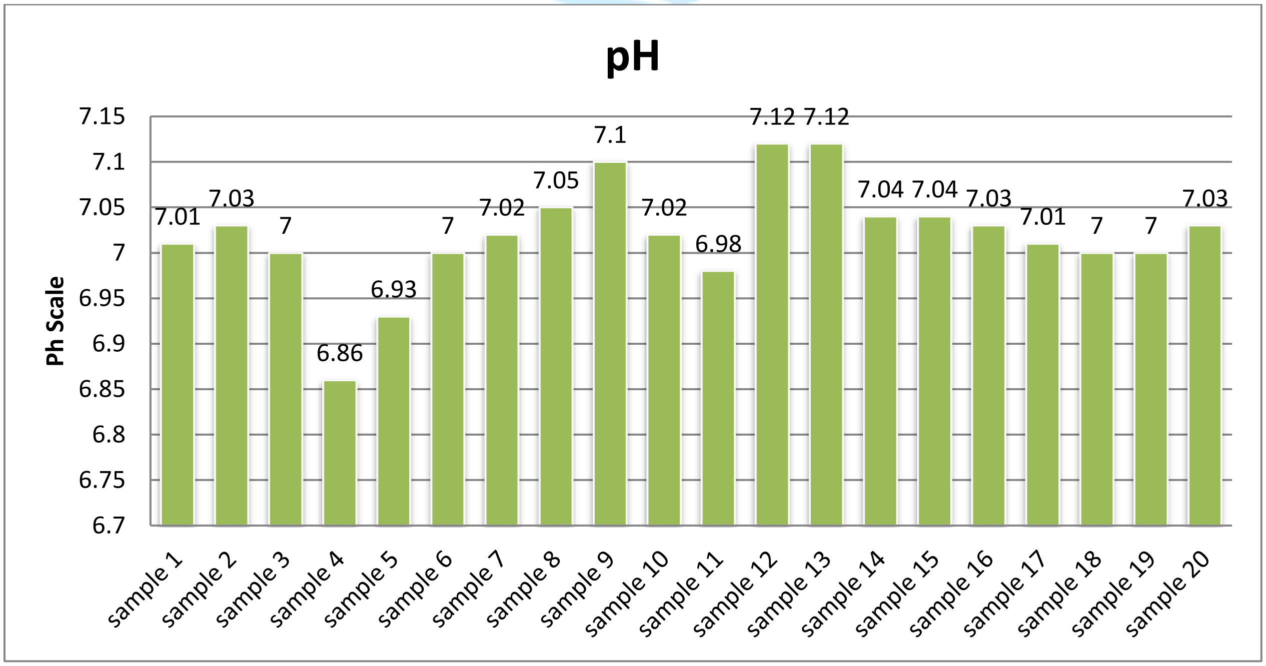

Figure 2. pH levels of the analyzed drinking water samples.

Electrical Conductivity (EC)

Electrical conductivity (EC) values of the analyzed water samples ranged from 662 to 1561 µS cm^{-1}, with most samples exhibiting moderate ionic strength (Figure 2).

Although a few samples showed relatively elevated EC values (>1000 µS cm^{-1}), all samples remained

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within the permissible limits prescribed by the Pakistan National Standards for Drinking Water (NSDW) and the Irrigation Water Quality Guidelines for Pakistan (IWQP). Accordingly, the analyzed water can be considered suitable for both drinking and irrigation purposes with respect to salinity hazard (Figure 4.2.). Electrical conductivity is a key indicator of water salinity and reflects the total concentration of dissolved ionic species, including major cations and anions, present in water (Sultana et al., 2009). The observed EC range suggests moderate mineralization, likely controlled by natural water–rock interactions such as dissolution of carbonate and silicate minerals within the aquifer matrix. Similar EC ranges have been reported for groundwater systems influenced primarily by geogenic processes in northern Pakistan (Rashid et al., 2019; Ullah et al., 2019).

The strong relationship between EC and total dissolved solids (TDS) implies that increases in EC are associated with elevated concentrations of dissolved salts, which may originate from lithological weathering, agricultural return flows, or limited mixing with surface water sources (Daud et al., 2017). However, the absence of extremely high EC values (>2000 µS cm^{-1}) indicates that the aquifer is not significantly impacted by saline intrusion or untreated industrial effluents, unlike groundwater systems reported near industrial estates in Pakistan and India (Hussain et al., 2013; Lokhande et al., 2011).

From an irrigation perspective, EC is a critical parameter because elevated salinity can adversely affect soil structure and crop productivity by restricting water uptake and damaging plant root systems. In the present study, all EC values fall within acceptable limits set by IWQP, suggesting a low to moderate salinity hazard and suitability for agricultural use. Comparable findings were reported by Ibrahim and Sean (1992) and Thankgod and Ruth (2016), who observed that irrigation water with moderate EC does not pose significant risks when proper soil management practices are applied. With respect to drinking water quality, elevated EC can influence taste and indirectly indicate the presence of potentially harmful dissolved constituents (Azizullah et al., 2011; Rasool et al., 2016). The compliance of all samples with NSDW standards suggests that the ionic composition of groundwater does not pose immediate health risks. Moreover, the relatively controlled EC values reflect limited anthropogenic pressure, supporting earlier regional assessments that identified natural geochemical processes as the dominant factor governing groundwater quality (Natasha et al., 2020; Rashid et al., 2019).

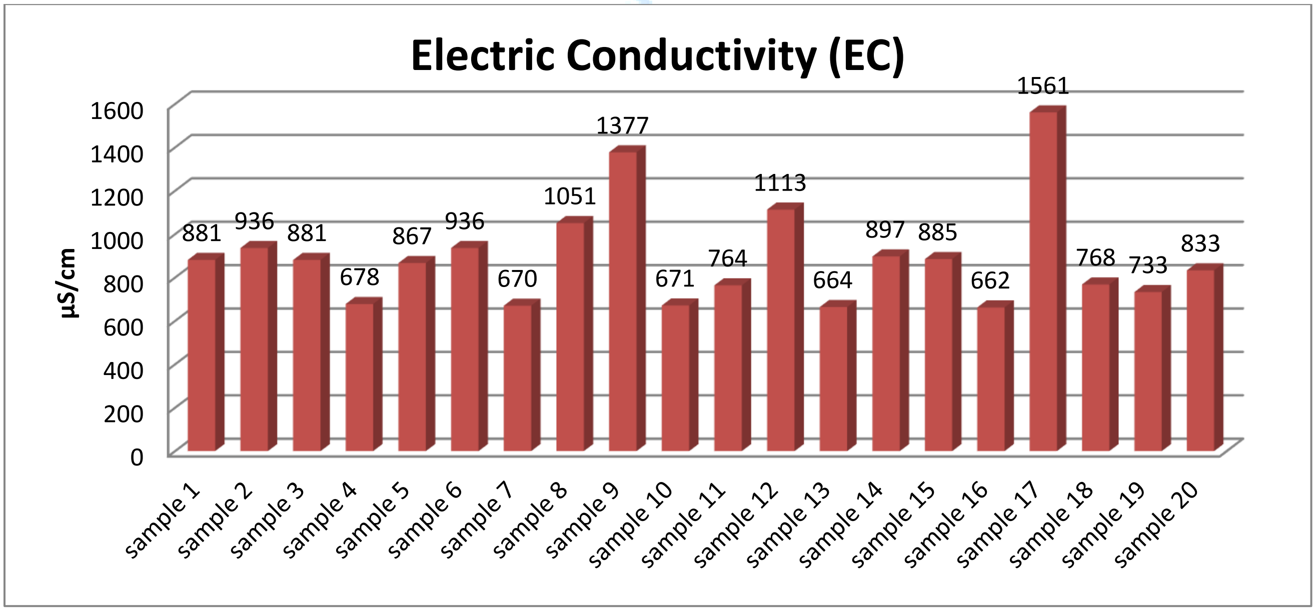

Figure 3. pH levels of the analyzed drinking water samples.

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Total Dissolved Solids (TDS)

Total dissolved solids (TDS) represent the combined concentration of dissolved inorganic salts and minor amounts of organic matter present in water. In the present study, TDS concentrations were evaluated (Figure 4). All analyzed samples were within the permissible limits prescribed by the Pakistan National Standards for Drinking Water (NSDW). Additionally, when compared with the Irrigation Water Quality Guidelines for Pakistan (IWQP), all TDS values were found to be acceptable, indicating suitability for both drinking and agricultural use.

TDS is a critical parameter for assessing overall water quality, as it reflects the cumulative presence of dissolved salts such as bicarbonates, chlorides, sulfates, calcium, magnesium, and sodium, which primarily originate from natural water–rock interactions within the aquifer system (Rashid et al., 2019; Nsabimana et al., 2022). The observed TDS range indicates moderate mineralization, suggesting that groundwater chemistry in the study area is predominantly governed by geogenic processes rather than intensive anthropogenic contamination. The strong correspondence between TDS and electrical conductivity observed in this study further supports the dominance of dissolved ionic species as the principal contributors to groundwater salinity (Sultana et al., 2009; Daud et al., 2017). Similar TDS ranges have been reported for groundwater systems in Pakistan that are influenced by carbonate weathering and limited agricultural return flows (Ullah et al., 2019; Natasha et al., 2020).

Elevated TDS levels can adversely affect water palatability and may indicate the presence of undesirable dissolved constituents when concentrations exceed recommended thresholds (Azizullah et al., 2011; Rasool et al., 2016). However, since all samples in the present study remained within NSDW limits, the groundwater poses no immediate health risk with respect to dissolved solids. From an irrigation perspective, excessive TDS can impair soil permeability and reduce crop yield by increasing osmotic stress on plants. The compliance of all samples with IWQP standards indicates a low to moderate salinity hazard, suggesting that the water is suitable for irrigation under prevailing soil and crop conditions.

Anthropogenic activities such as agricultural runoff, domestic wastewater discharge, and limited industrial effluent input are known to elevate TDS concentrations in surface and groundwater systems (Lokhande et al., 2011; Hussain et al., 2013). The absence of excessively high TDS values (>1000 mg L^{-1}) in the present study suggests minimal influence of such activities near the sampling locations, corroborating findings from regional water quality assessments that highlight natural hydrogeochemical controls as the primary drivers of groundwater composition (Rashid et al., 2019; Daud et al., 2017).

Overall, the TDS results indicate that the groundwater system is moderately mineralized but remains within safe limits for both drinking and irrigation purposes. Continuous monitoring is nonetheless recommended, as increasing agricultural intensification and urban expansion may alter dissolved solids concentrations over time (Murtaza & Zia, 2012; Vinca et al., 2021).

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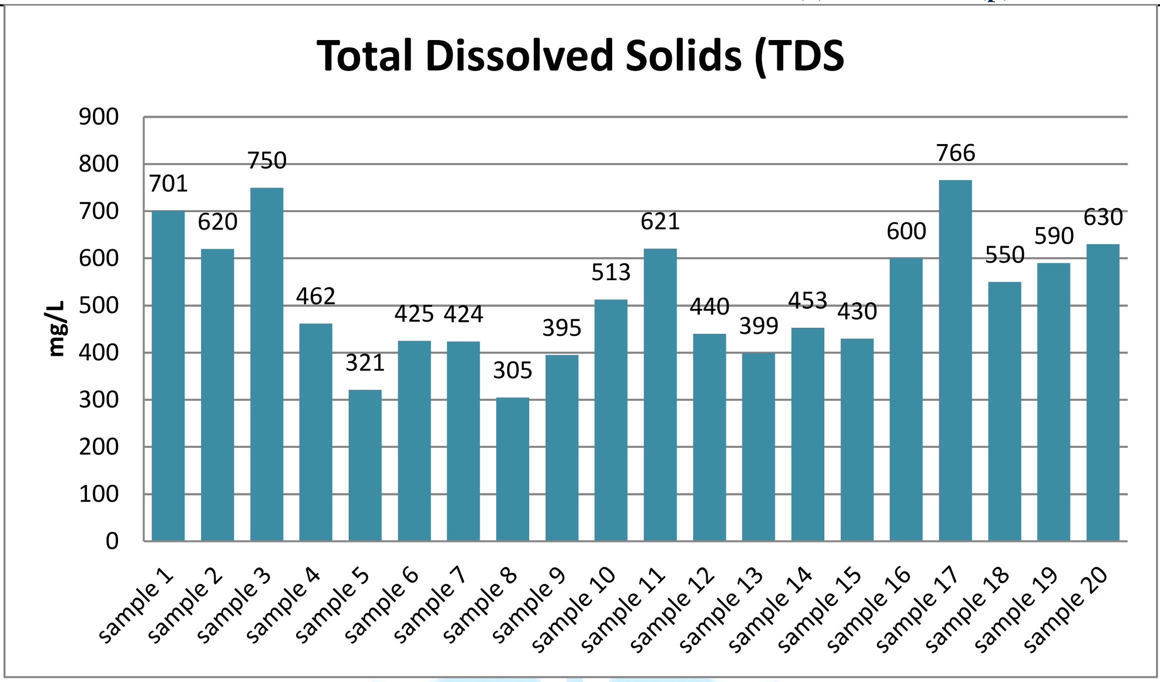

Figure 4. Total dissolved solids (TDS) levels of the analyzed drinking water samples

Turbidity

In the present study, all samples exhibited turbidity values well below the maximum permissible limit of 5 NTU prescribed by the Pakistan National Standards for Drinking Water (NSDW) (Figure 5). Similarly, comparison with the Irrigation Water Quality Guidelines for Pakistan (IWQP) showed full compliance, confirming that the water is suitable for both drinking and irrigation purposes with respect to turbidity. Turbidity is widely used as an indicator of physical water quality and reflects the presence of suspended solids such as clay, silt, organic matter, and microorganisms. Elevated turbidity levels are commonly associated with surface runoff, soil erosion, wastewater intrusion, and anthropogenic disturbances (Cornelius et al., 2017; Thankgod & Ruth, 2016). The consistently low turbidity values recorded in this study indicate minimal suspended particulate matter and suggest that the sampled water is relatively clear and physically stable.

The absence of elevated turbidity further implies limited influence of domestic wastewater discharge, agricultural runoff, or industrial effluents in the vicinity of the sampling sites. Similar low turbidity conditions have been reported in groundwater systems dominated by natural filtration through soil and aquifer materials, where geogenic processes exert greater control over water quality than surface-derived contamination (Rashid et al., 2019; Natasha et al., 2020). This natural attenuation capacity reduces particulate transport and contributes to improved physical water quality. From a public health perspective, low turbidity is particularly important because suspended particles can harbor pathogenic microorganisms and reduce the effectiveness of disinfection processes by shielding microbes from contact with disinfectants (Azizullah et al., 2011). Turbidity values below guideline limits therefore enhance the safety and acceptability of drinking water. In agricultural applications, excessive turbidity may clog irrigation systems and interfere with light penetration in surface water bodies; however, the low values observed in this study pose no such limitations (Pescod, 1992; Thankgod & Ruth, 2016).

Overall, the turbidity results indicate excellent physical water quality and suggest minimal anthropogenic disturbance in the study area. These findings align with regional assessments emphasizing the role of natural hydrogeological conditions in maintaining groundwater clarity and quality (Daud et al., 2017; Vinca et al., 2021). Nevertheless, continued monitoring is

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recommended to detect any future changes associated with land-use modification or increased wastewater generation (Murtaza & Zia, 2012).

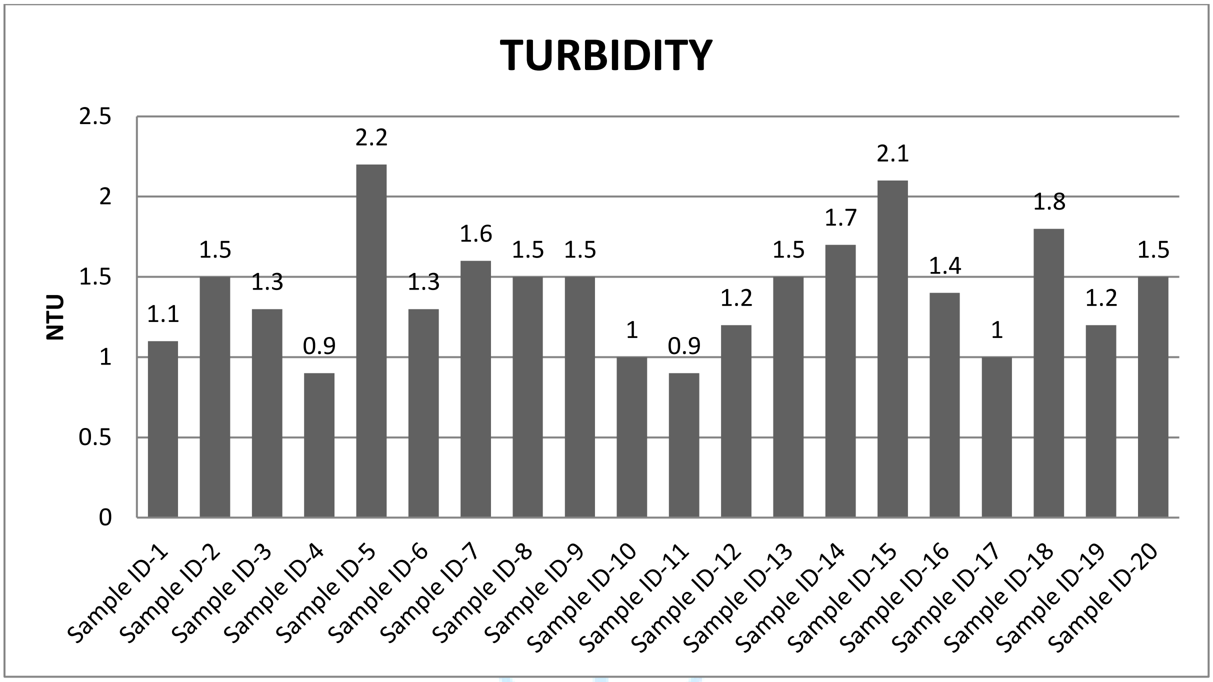

Figure 5. Turbidity levels of the analyzed drinking water samples.

Chemical Parameters

Total Hardness

All analyzed water samples complied with the Pakistan National Standards for Drinking Water (NSDW) maximum permissible limit of 500 mg L^{-1}. However, one sampling location exhibited a value marginally close to the guideline threshold within the study area (Figure 6). When compared with the Irrigation Water Quality Guidelines for Pakistan (IWQP), which recommend a threshold of 300 mg L^{-1}, several samples exceeded this limit, indicating moderate to high hardness for irrigation use.

Water hardness is primarily governed by the presence of calcium and magnesium salts derived from the dissolution of carbonate and silicate minerals within the aquifer system (Rashid et al., 2019). The predominance of moderately hard to very hard water in the study area suggests strong geogenic control, particularly from calcium-rich lithological formations. Similar hardness characteristics have been reported for groundwater systems across northern Pakistan, where carbonate weathering is the dominant hydrogeochemical process (Ullah et al., 2019; Nsabimana et al., 2022).

Although all samples generally complied with drinking water standards, elevated hardness levels can affect domestic water use by causing scale formation in pipes, boilers, and household appliances, thereby reducing system efficiency and increasing maintenance requirements (Ibrahim & Sean, 1992; Zahra & Naseem, 2012). The observed tendency for hardness to exceed irrigation guideline limits in some samples may also influence soil permeability and crop productivity if used continuously without proper management practices (Thankgod & Ruth, 2016).

The results further indicate that hardness in the study area is likely dominated by calcium rather than magnesium, a condition commonly associated with carbonate mineral dissolution. Calcium-rich waters are generally less problematic from a health perspective but are more prone to scaling reactions, which involve the precipitation of insoluble calcium salts under thermal or chemical changes (Liu & Wang, 2019). Such precipitation reactions explain the formation of light, slow-settling flocs

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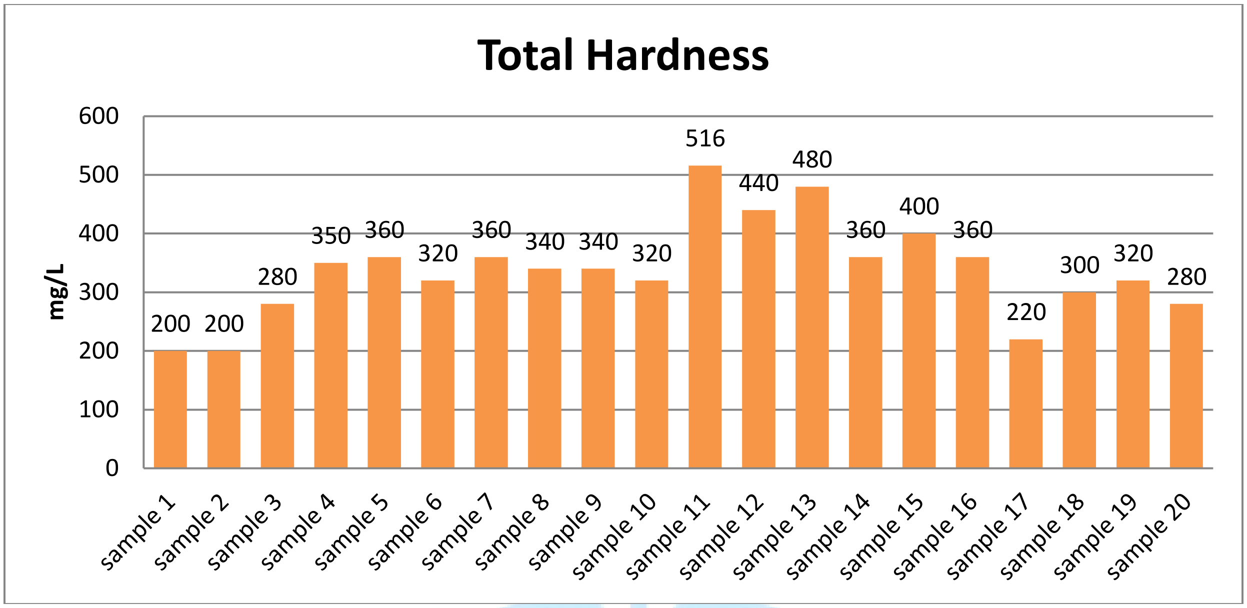
and deposits commonly observed in hard water systems (Murray & Osborne, 2022).



From a public health standpoint, hard water is not considered harmful and may even contribute beneficial dietary minerals; however, very high hardness can reduce consumer acceptability and interfere with soap efficiency (Azizullah et al., 2011; Daud et al., 2017). Overall, the groundwater in the study area can be classified as moderately hard to very hard, remaining suitable for drinking under NSDW guidelines but requiring consideration for scaling control and irrigation management. Continued monitoring is recommended, particularly in areas showing hardness values above IWQP thresholds, as increasing groundwater abstraction and land-use changes may further influence hardness levels Figure 6. Measured total hardness values of the water samples.

Figure 6. Total hardness of the analyzed drinking water samples.

Calcium (Ca^{2+})

All tested water samples remained within the Pakistan National Standards for Drinking Water (NSDW) maximum allowable limit of 200 mg L^{-1}, reflecting satisfactory calcium concentrations across the study area. No sampling point recorded values above the recommended guideline level (Figure 7). The calcium concentrations observed in this study reflect the influence of natural geochemical processes, particularly the dissolution of calcium-bearing minerals such as calcite and dolomite within the aquifer matrix (Rashid et al., 2019). The predominance of calcium within acceptable limits suggests balanced water–rock interactions and supports the classification of groundwater as moderately mineralized. Calcium plays a dual role in water quality. From a domestic perspective, elevated calcium contributes to hardness, which may lead to scale formation in pipes, boilers, and household appliances, reducing system efficiency over time (Ibrahim & Sean, 1992; Zahra & Naseem, 2012). However, the calcium concentrations recorded in this study, being within NSDW limits, are unlikely to pose significant operational problems or reduce water acceptability. From a public health standpoint, calcium is an essential dietary mineral, and its presence in drinking water can contribute positively to daily intake requirements (Azizullah et al., 2011; Daud et al., 2017). The observed calcium levels therefore do not represent a health risk and may instead offer nutritional benefits, consistent with findings from groundwater studies in Pakistan and comparable hydrogeological settings (Ullah et al., 2019; Nsabimana et al., 2022).

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The strong association between calcium concentration and total hardness observed in the study area further indicates that calcium is the dominant hardness-causing ion, rather than magnesium. This pattern is typical of carbonate-rich aquifers and aligns with regional hydrochemical investigations conducted in northern Pakistan (Rashid et al., 2019).

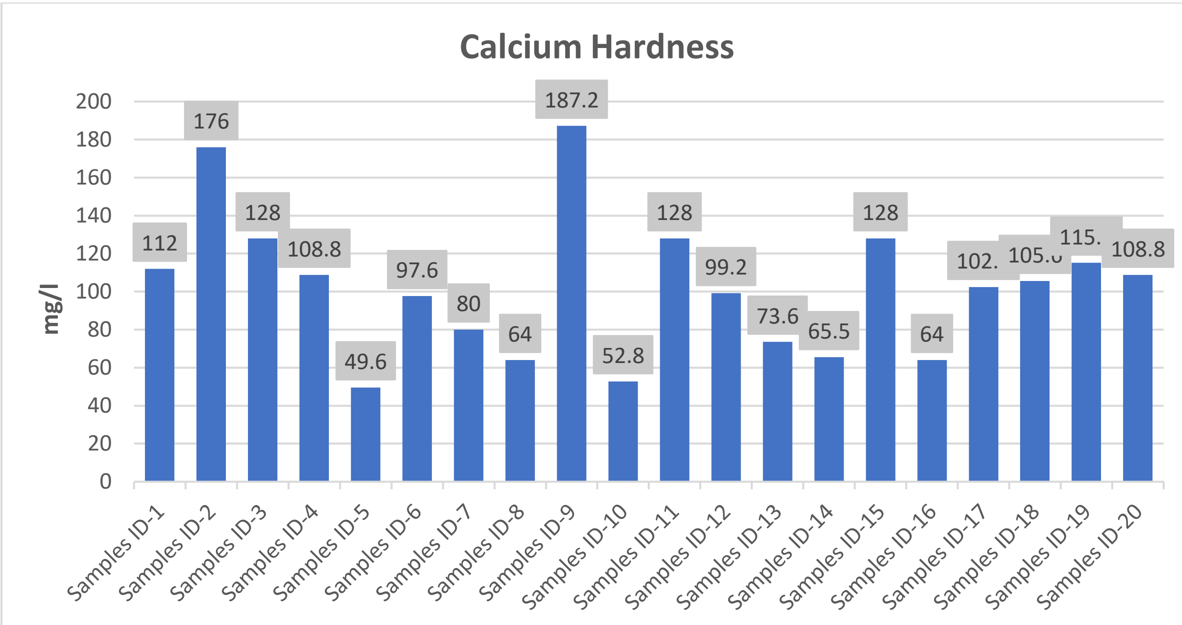

Figure 7. Calcium concentrations of the analyzed drinking water samples.

Magnesium

The magnesium concentrations measured in the drinking water samples from the study area showed considerable variation. According to the Pakistan National Standards for Drinking Water (NSDW), the permissible limit for magnesium is 100 mg L^{-1}; however, the majority of samples substantially exceeded this guideline value. Only two samples, with concentrations of 24 and 88 mg L^{-1}, were found to be within the acceptable range. As illustrated in Figure 8, the observed concentrations clearly demonstrate pronounced exceedances relative to the standard, indicating elevated magnesium levels across most sampling locations (Figure 8). The results indicate that the majority of the samples exceed the permissible limit for magnesium, representing a significant water quality concern (Daud et al., 2017; Liu & Wang, 2019). Elevated magnesium concentrations, while essential for human nutrition in small amounts, may pose health risks if consumed in excess, including gastrointestinal issues and complications for individuals with kidney disorders (Mebrahtu & Samuel, 2011).

The highest recorded concentration (406.4 mg L^{-1}) is particularly alarming, exceeding the standard by more than fourfold, suggesting a need for intervention to prevent potential long-term health impacts (Khan et al., 2020; Rashid et al., 2019). The observed high magnesium levels may be attributed to geological factors, such as the dissolution of magnesium-bearing minerals (dolomite, magnesite) in the aquifer matrix, as well as anthropogenic contributions including industrial effluents, wastewater discharge, and agricultural runoff (Hussain et al., 2013; Arti et al., 2011). Similar patterns of elevated magnesium in groundwater have been reported in other regions due to both natural and human-induced sources (Nsabimana et al., 2022; Ullah et al., 2019). Regular monitoring and effective water treatment strategies are therefore critical to mitigate the risks associated with high magnesium levels and ensure safe drinking water supply for the local population.

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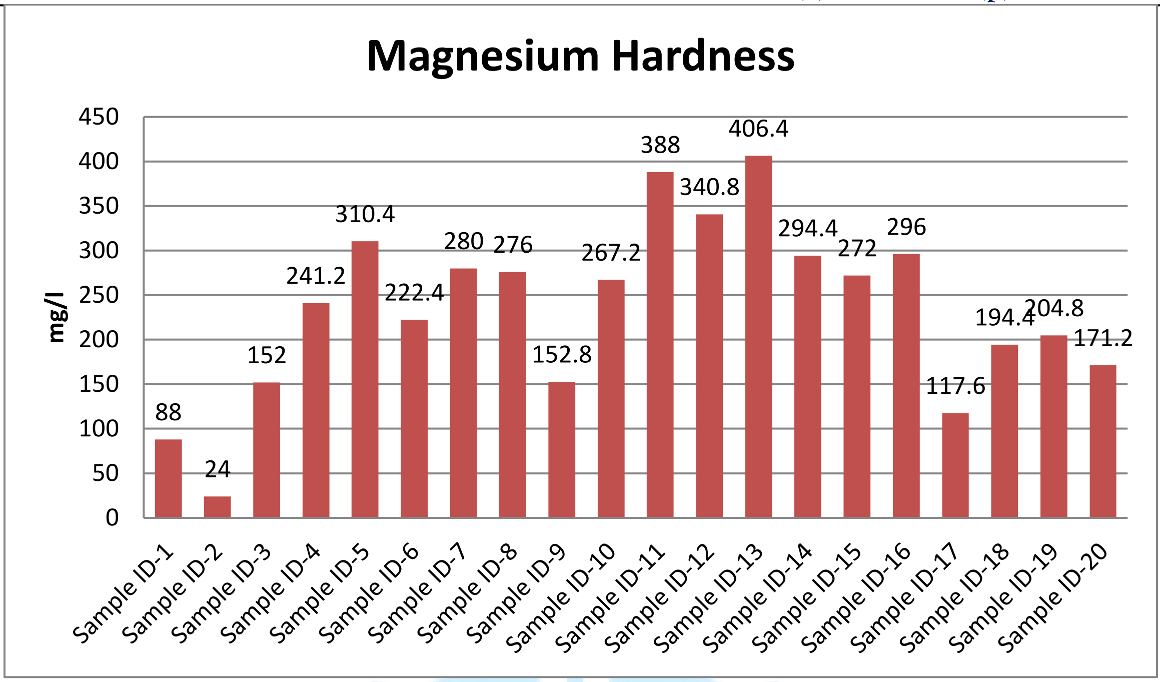

Figure 8. Magnesium concentrations of the analyzed drinking water samples.

Total Alkalinity

The total alkalinity of the analyzed water samples ranged from 208 to 644 mg L^{-1}. The majority of samples exceeded the National Standards for Drinking Water (NSDW) permissible limit of 250 mg L^{-1}, (Figure 9). These findings indicate a widespread elevation in alkalinity across the sampled drinking water sources within the study area. The observed excessive alkalinity in the sampled water highlights significant deviations from both drinking water and irrigation standards. Elevated total alkalinity primarily arises from the abundance of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, which can originate from geogenic processes, such as the dissolution of carbonate-rich minerals (limestone, dolomite) in the aquifer matrix, or anthropogenic inputs from industrial effluents, domestic wastewater, and agricultural runoff (Azizullah et al., 2011).Effect on water quality and usability: High alkalinity directly increases the buffering capacity of water, which can reduce its effectiveness for domestic and industrial use. Specifically, water with alkalinity above the recommended limits tends to have a bitter taste and can form scale deposits in pipes, boilers, and irrigation equipment, ultimately affecting both human consumption and infrastructure longevity (Ali & Nabeel, 2023; Mebrahtu & Samuel, 2011). Effect on irrigation and soil quality: Excessive bicarbonate levels induce soil sodicity when applied for irrigation. High bicarbonate water reacts with calcium and magnesium in the soil, reducing soil permeability and aggregate stability, which can decrease crop yield and long-term soil fertility (Ahmadzai et al., 2018).

Therefore, the use of these waters without treatment could adversely impact agricultural productivity. Environmental and health implications: Prolonged discharge of high-alkalinity water into natural water bodies can disrupt local aquatic ecosystems, promoting mineral precipitation and altering pH-dependent chemical equilibria. For humans, chronic exposure to high alkalinity may exacerbate gastrointestinal issues in sensitive populations, especially in combination with elevated hardness and other ions (Daud et al., 2017; Natasha et al., 2020). The extreme values observed, such as 644 mg L^{-1}, indicate severe deviation from permissible limits, suggesting that both natural geochemical processes and anthropogenic influences are simultaneously contributing to the high alkalinity. For instance, upstream industrial discharges may increase bicarbonate concentrations, while aquifer lithology

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amplifies the effect through mineral dissolution, creating a compound effect on total alkalinity.
Techniques such as lime softening, ion exchange, or controlled dilution can mitigate risks associated with high bicarbonate levels, thereby improving water suitability for both drinking and irrigation purposes (Rashid et al., 2019).

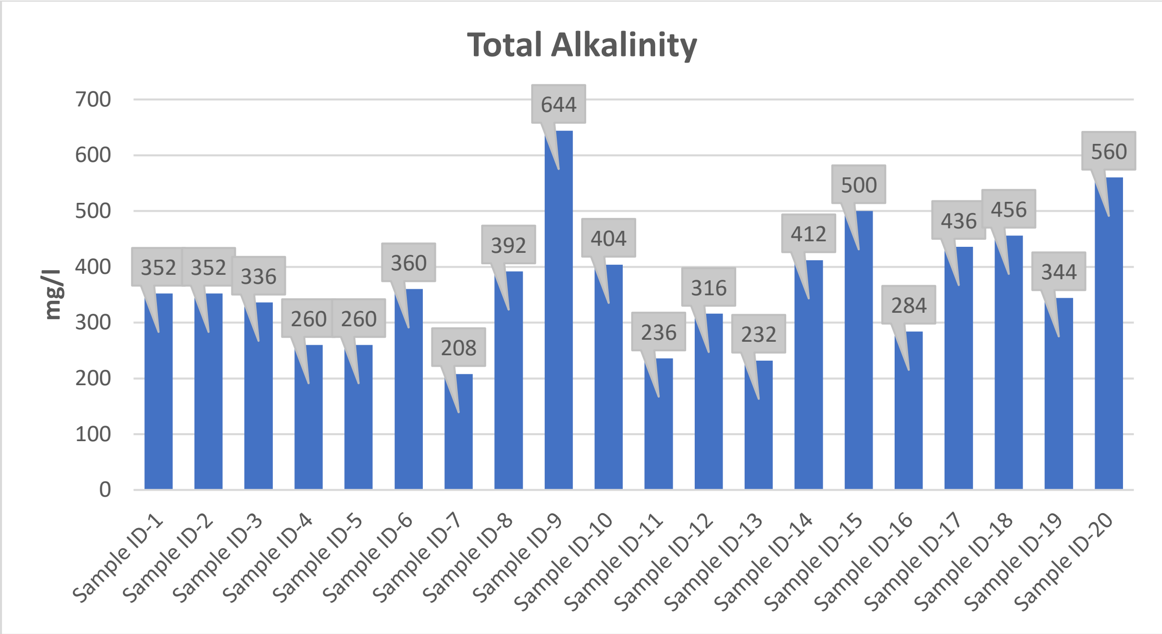

Figure 9. Total alkalinity of the analyzed drinking water samples.

Chloride

The chloride concentrations in the analyzed water samples ranged from 38.04 to 220.24 mg L^{-1}. All recorded concentrations remained below the National Standards for Drinking Water (NSDW) permissible limit of 250 mg L^{-1}, indicating acceptable chloride levels across the study area. Similarly, when compared with the Irrigation Water Quality Guidelines for Pakistan (IWQP), all measured chloride concentrations were within permissible limits (Figure10). Chloride is an important indicator of salinity and anthropogenic influence in water systems. Elevated chloride levels can affect both plant growth and soil structure, as excessive chloride can accumulate in soils, leading to osmotic stress and reduced crop productivity (Ibrahim & Sean, 1992). In the context of irrigation, chloride is primarily introduced through municipal wastewater and industrial effluents, which can carry salts from domestic or industrial activities into the drainage network.

In the current study, while the absolute chloride levels remain within permissible limits, it is noteworthy that certain locations, particularly the Haidara drain, approach the upper threshold suggested by FAO guidelines for irrigation (>10 me/L). At these levels, prolonged irrigation with water containing elevated chloride may cause chloride toxicity in sensitive crops, resulting in leaf burn, reduced growth, and decreased yield. This emphasizes that even within permissible limits, the cumulative effects of chloride on soil and crops should not be ignored. Natural and anthropogenic sources: The observed chloride concentrations likely reflect a combination of natural geogenic contributions (mineral dissolution) and human activities, including sewage discharge and agricultural return flows. This interplay determines the spatial variability in chloride levels across sampling sites. Agricultural implications: Although within NSDW and IWQP limits, continuous application of water with moderately high chloride can gradually increase soil salinity, reduce nutrient uptake by plants, and alter soil microbial activity, potentially affecting long-term soil fertility (Ahmadzai et al., 2018). Water quality

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management: Regular monitoring of chloride, particularly at sensitive drains like Haidara, is necessary to prevent gradual soil degradation and ensure sustainable irrigation practices. Blending or treatment strategies may be considered if chloride concentrations show an increasing trend over time.

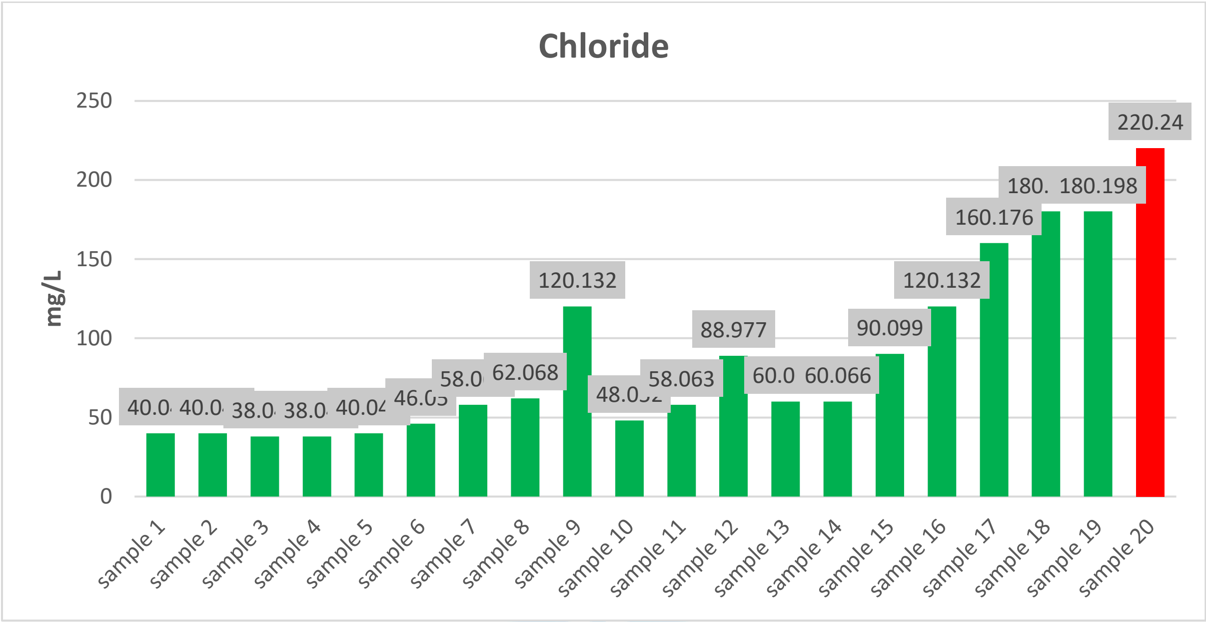

Figure 10. Chloride concentrations of the analyzed drinking water samples.

Comparison of Water Quality Parameters with National Standards for Drinking Water (NSDW) and Irrigation Guidelines

The physicochemical characteristics of ten water samples were analyzed and compared against the Pakistan National Standards for Drinking Water (NSDW) and irrigation guidelines (Table 1). The pH values ranged from 6.86 to 7.10, indicating neutral to slightly alkaline conditions, within the permissible NSDW limits of 6.5–8.5. Such pH levels suggest minimal corrosive potential, suitable for domestic and agricultural use (Azizullah et al., 2011; Daud et al., 2017).

The total dissolved solids (TDS) varied from 321 to 750 mg/L, below the NSDW threshold of 1000 mg/L, indicating moderate mineralization consistent with previous reports in the region (Hussain et al., 2013; Khan et al., 2020). The electrical conductivity (EC) ranged between 670 and 1377 µS/cm, reflecting the ionic strength of water, with higher EC values corresponding to elevated TDS (Ahmadzai et al., 2018; Pan et al., 2022). Elevated TDS and EC may affect soil salinity and crop growth during irrigation, necessitating periodic monitoring (Ali & Nabeel, 2023).

Turbidity levels were low, ranging from 0.9 to 2.2 NTU, significantly below the NSDW limit of 5 NTU. This indicates minimal suspended particulate matter and good water clarity, reducing the risk of microbial contamination and improving palatability (Mullins et al., 2018; Murray & Osborne, 2022).

The water samples were classified as moderately hard to hard, with total hardness ranging from 200 to 360 mg/L (NSDW limit: 500 mg/L). Hardness was primarily due to calcium and magnesium ions, consistent with regional groundwater characteristics (Liu & Wang, 2019). While high hardness may lead to scaling in pipes, it is generally not harmful to human health (Nsabimana et al., 2022). Notably, magnesium hardness in several samples (IDs 4, 5, 7, 8) exceeded the NSDW limit of 100 mg/L, which may have mild laxative effects if consumed over prolonged periods (Zahra & Naseem, 2012). Calcium hardness remained largely within limits except for sample ID-9.

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Total alkalinity ranged from 208 to 644 mg/L, with sample ID-9 exceeding the NSDW limit of 500 mg/L. Elevated alkalinity reflects higher bicarbonate or carbonate content, which can influence water taste and reduce domestic soap efficiency (Arti et al., 2011; Hussain et al., 2013). Chloride concentrations varied from 58 to 180 mg/L, below the permissible limit of 250 mg/L, indicating minimal corrosivity and suitability for irrigation of most crops (Daud et al., 2017).

Generally, the water samples are generally suitable for drinking and irrigation, with most parameters within NSDW guidelines. Exceptions include localized elevated magnesium hardness and total alkalinity, suggesting the need for targeted water treatment or blending for sensitive applications. The observed variability likely reflects geological formations, anthropogenic inputs, and seasonal factors (Azizullah et al., 2011; Vinca et al., 2021). Regular monitoring is recommended to ensure sustained water quality compliance and manage potential scaling or salinity effects in distribution systems and irrigated soils (Natasha et al., 2020; Ullah et al., 2019).

Table 1. Water quality parameters of ten samples compared with NSDW and irrigation guidelines.

Parameter	*Unit*	*S 1*	*S 2*	*S 3*	*S 4*	*S 5*	*S 6*	*S 7*	*S 8*	*S 9*	*S 10*	*NSDW / Irrigation Limit*
pH	–	7.01	7.03	7.00	6.86	7.00	7.02	7.05	7.10	7.02	7.05	6.5–8.5
Total Dissolved Solids	mg/L	321	395	424	425	462	513	620	621	701	750	1000
Electrical Conductivity	µS/cm	881	936	881	678	867	936	936	670	1051	1377	1500
Turbidity	NTU	1.1	1.5	1.3	0.9	2.2	1.3	1.6	1.5	1.5	1.0	5
Total Hardness	mg/L	200	200	280	350	350	320	360	340	340	320	500
Total Alkalinity	mg/L	352	352	336	260	260	360	208	392	644	404	500
Calcium Hardness	mg/L	112	176	128	108.8	49.6	97.6	80	64	187.2	52.8	200
Magnesium Hardness	mg/L	88	24	152	241.2	310.4	222.4	280	276	152.8	180	100
Chloride	mg/L	58	88	60	60	90	120	160	180	180	220	250

Conclusion

The comprehensive physicochemical evaluation of water samples from Tehkal Bala, Peshawar, revealed that most water quality parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, total hardness, calcium, and chloride generally comply with the National Standard for Drinking Water (NSDW). These findings indicate that the water in this region is largely suitable for drinking, domestic use, and irrigation purposes. The pH values (6.86–7.12) were within the neutral range, while EC (670–1377 µS/cm) and TDS (321–750 mg/L) reflected moderate ionic strength and mineral content compatible with human consumption and agricultural applications. Low turbidity levels further indicate water clarity and minimal suspended particulate matter, thereby reducing the risk of microbial contamination. Total hardness remained below the NSDW threshold of 500 mg/L; however, certain samples exhibited moderately elevated hardness primarily due to calcium, which could influence specific domestic and industrial applications.

Despite overall compliance, magnesium concentrations consistently exceeded permissible

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limits in multiple samples, highlighting a potential health risk associated with prolonged consumption. Elevated magnesium levels likely originate from natural geological formations and/or anthropogenic activities, underscoring the importance of continuous monitoring and potential remedial measures.

In conclusion, while the water quality in Tehkal Bala is generally safe for domestic, drinking, and irrigation purposes, systematic monitoring and targeted treatment interventions are recommended to mitigate elevated magnesium and localized high calcium concentrations, ensuring sustained compliance with NSDW standards and safeguarding public health.

Declaration of competing interest

The authors declare that they have no conflict of interest

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