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# Hydrogeochemical Assessment of Arsenic and Physicochemical Contaminations in Groundwater Wells in Kabul, Afghanistan


**Faizanulhaq Shams[1], Naweedullah Amin✉[2]**

[1] Department of Research and Laboratory of Water Resources Projects, Water Quality Laboratory Directorate, Ministry of Water and Energy, Kabul, Afghanistan
[2] Department of Zoology, Faculty of Biology, Kabul University, Kabul, Afghanistan
✉E-mail: sodes.amin123@gmail.com (corresponding author)



**ABSTRACT**

Groundwater is a critical source of drinking water in semi-arid regions; however, integrated assessments of arsenic (As) contamination alongside key physicochemical parameters remain limited in the study area. Therefore, this study was conducted to measure the concentration of as, salinity, electrical conductivity (EC), temperature, pH, and total dissolved solids (TDS) in 21 wells across 4 districts of Kabul city. Groundwater samples were collected from selected sites and analyzed for as, salinity, EC, temperature, pH, and TDS, and compared with World Health Organization (WHO) drinking water guidelines to determine suitability for consumption. Arsenic concentrations exhibited pronounced spatial variability, ranging from 0 to 25 mg/L, with all detected values exceeding the World Health Organization (WHO) guideline of 0.01 mg/L by several orders of magnitude. The highest as concentration (25 mg/L) was recorded in the Areba antenna area, indicating a critical contamination hotspot. Salinity values ranged from 0 to 1.9 ppt, while EC ranged from 111 to 3630 µS/cm; 75% of sampled sites exceeded the WHO permissible limit for EC. TDS concentrations ranged from 710.4 to 2323.2 mg/L, with 79% of samples surpassing the recommended drinking water limit. Groundwater pH remained within the WHO guideline range (7.1–8.1), yet these neutral-to-alkaline conditions likely enhanced as mobilization. The combined results indicate widespread mineralization and severe as contamination, rendering much of the groundwater unsuitable for direct consumption without treatment. These findings underscore the urgent need for policy interventions, including systematic groundwater monitoring, arsenic mitigation strategies, and the provision of alternative, safe water supplies to protect local communities.



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## INTRODUCTION

Groundwater represents a critical freshwater resource, particularly in semi-arid regions globally, where surface water scarcity often necessitates its reliance for drinking, irrigation, and aquaculture (Kadiri et al., 2023; Asadi et al., 2015). This dependence, however, renders groundwater highly vulnerable to both natural and anthropogenic contamination, posing significant challenges to human health and ecological integrity (Masood et al., 2023; Renu & Rajani, 2021). Groundwater contamination in semi-arid regions is commonly interpreted within a hydrogeochemical framework that emphasizes the interaction between geogenic sources, physicochemical conditions, and anthropogenic pressures. For instance, neutral to alkaline pH conditions enhance the desorption of arsenic from iron (hydr)oxide surfaces, thereby increasing its mobility and associated health risks (Thakur et al., 2024). The reductive dissolution of Fe(III) oxides, often driven by microbial activity in organic-rich sediments, is a primary mechanism for arsenic release, particularly in reducing environments typical of young alluvial sediments (Kushagra et al., 2015; Thakur et al., 2024). Additionally, physicochemical conditions, such as temperature, salinity, and TDS, further modulate these geochemical interactions, exacerbating contamination under anthropogenic influences, such as agricultural runoff and industrial discharges (Blanchette et al., 2010; Al-Rashidi et al., 2023). Understanding these dynamics is essential for effective groundwater management and for mitigating health risks in affected regions.

Anthropogenic activities exacerbate groundwater quality degradation in urbanizing semi-arid areas. Urbanization, industrial discharges, and agricultural practices contribute to elevated levels of various pollutants (Masood et al., 2023). Parameters such as EC and TDS are key indicators of salinity, which can be influenced by natural hydrogeochemical processes, paleoclimatic environments, and human activities like irrigation (Gopinath et al., 2023; Lei et al., 2023). High salinity and TDS concentrations limit water usability for drinking and irrigation, impacting agricultural yields and compromising aquatic ecosystems essential for aquaculture (Mondal et al., 2024; Tyopine et al., 2024). The pH and temperature of groundwater are also fundamental physicochemical parameters that govern the solubility, speciation, and toxicity of many contaminants, thereby influencing overall water suitability (Ela et al., 2024; Ihunwo et al., 2021). Contaminants of geogenic origin, such as As, naturally occur in certain geological formations and can mobilize into groundwater, leading to severe health consequences including various cancers, cardiovascular diseases, and developmental disorders upon prolonged exposure (Appiah-Opong et al., 2021; Liao et al., 2016). For instance, studies in South Asia, particularly the Indus plain of Pakistan, have identified high arsenic impact zones where dissolved organic matter plays a crucial role in its mobilization (Malik et al., 2020).

Previous investigations across various semi-arid regions have highlighted these concerns. For example, research in India has focused on hydrogeochemical investigations to understand groundwater chemistry and identify saltwater intrusion in coastal aquifers (Gopinath et al., 2023). Similarly, studies in Pakistan have addressed the occurrence and risks of antibiotics in groundwater, pointing to anthropogenic sources (Zainab et al., 2021). In the arid inland plains of northwestern China, highly saline groundwater limits freshwater availability, underscoring the need to understand the spatial distribution and controlling factors of salinity (Lei et al., 2023). Despite these efforts, a comprehensive understanding of the spatial variability of critical groundwater quality parameters, specifically arsenic, salinity, EC, temperature, pH, and TDS across multiple urban sites within rapidly urbanizing semi-arid landscapes remains limited. Furthermore, integrated assessments that evaluate groundwater suitability for both human consumption and aquaculture are often lacking.

Previous studies in Kabul have underscored concerns regarding groundwater quality. For example, comprehensive analyses have been conducted to determine hydrogeochemical characteristics, water types, and suitability for drinking, often employing portable digital multiparameter instruments for measuring TDS, pH, and EC, alongside laboratory analyses for other ions like chloride and total hardness (Hamdard et al., 2024; Omary et al., 2024; Singh & Noori, 2022; Jawadi et al., 2020). These investigations have identified areas where groundwater quality is compromised, with some studies focusing on specific pollutants or general water quality indices (WQI) (Jawadi et al., 2020; Omary et al., 2024; Singh & Noori, 2022). Despite these efforts, a comprehensive understanding of groundwater quality dynamics across Kabul province remains challenging. Many existing studies often lack extensive spatial coverage or an integrated multi-parameter approach needed to fully capture the complex interactions between natural and anthropogenic factors influencing groundwater contamination. There is a discernible gap in detailed, spatially explicit assessments that can provide a holistic view of the distribution and sources of key pollutants (Hamidi et al., 2023; Noori & Singh, 2021; Jawadi et al., 2020).

Therefore, this study assesses groundwater quality at 21 sites across 4 districts in Kabul city by analyzing key physicochemical parameters (As, EC, salinity, TDS, pH, and temperature) and evaluating their compliance with WHO drinking water guidelines. Specifically, the study addresses the following question:

what do as and physicochemical parameters vary across 4 districts of Kabul city?

## METHODS AND MATERIALS

This study employed a cross-sectional hydrogeochemical assessment design to evaluate variation in as and physicochemical parameter concentrations across Kabul city. Groundwater sampling sites were selected to provide comprehensive spatial coverage of groundwater resources within Kabul city. A total of 21 groundwater sampling sites were investigated across four administrative districts of Kabul Districts 5, 9, 10, and 15 to capture spatial variability in groundwater quality (Figure 1) below:

**District 5 (Sites 1–6)** included groundwater sources located at Abdul Hai Habibi High School, the adjacent Central Mosque, and nearby commercial areas.

**District 9 (Sites 7–10)** comprised sampling locations in the vicinity of Quba Mosque and Alokhail High School, representing a mixed residential and institutional setting.

**District 10 (Sites 11–15)** included groundwater sources associated with the Osman Car Wash area and surrounding residential zones, reflecting localized commercial and domestic water use.

**District 15 (Sites 16–21)** encompassed sampling sites near the Areeba telecommunication antenna and adjacent residential neighborhoods.

*Spatial Distribution of Groundwater Sampling Sites in Kabul City*

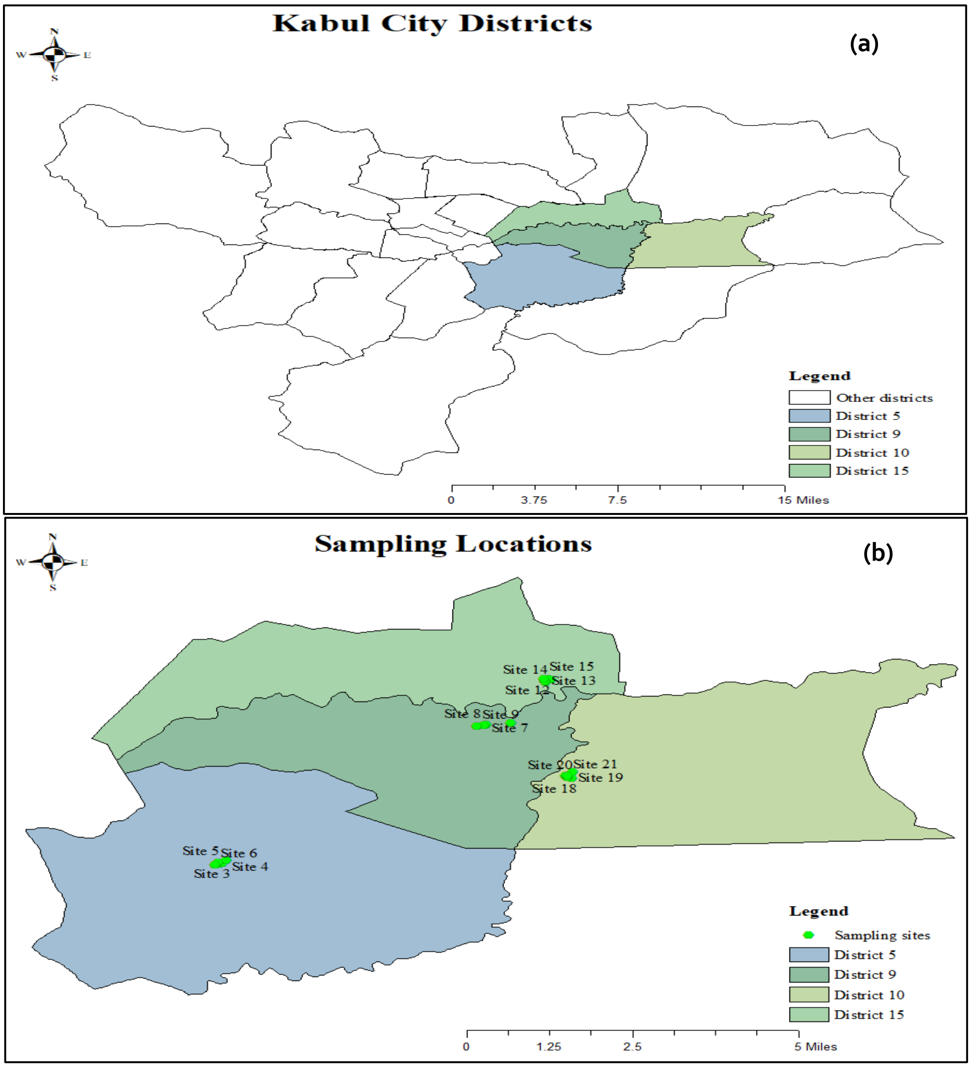


**Figure 1.** *(a) Administrative districts of Kabul Province, highlighting the selected study districts (Districts 5, 9, 10, and 15). (b) Spatial distribution of sampling sites within the selected districts of Kabul Province. Sampling locations are shown as points overlaid on district boundaries.*

### *Water Sampling and Physicochemical Analysis*

Water samples were collected from each of the 21 sites between 3 May 2025 and 6 May 2025. Before sampling, sites and pumps were flushed for 10 minutes to ensure the collection of water representative of the aquifer. At each site, key physicochemical parameters were measured in situ: water temperature, TDS, and EC were determined using a TDS meter (2CA101), while pH was measured using a calibrated pH meter (WTW 3310).

Following these measurements, samples for arsenic analysis were collected in sterile 1-liter polyethylene bottles that were pre-rinsed three times with the source water. All samples were immediately stored in the dark in a cooler maintained at 4°C and transported to the Water Quality Laboratory of the Ministry of Energy and Water.

Arsenic concentration in groundwater samples was determined using a Quick™ Arsenic Test Kit (Part No. 481396). The method is based on generating arsine gas by reacting inorganic arsenic with zinc and acid under controlled conditions. Approximately 100 mL of water sample was transferred into the reaction bottle, and the provided reagents were sequentially added according to the manufacturer's instructions. The bottle was then tightly capped to prevent gas escape, and the reaction was allowed to proceed for the specified time at room temperature (22–28 °C). The arsine gas produced reacted with a mercuric bromide indicator strip placed in the cap, producing a color change from white to varying shades of yellow or brown depending on the arsenic concentration. After the reaction period (about 10 minutes), the developed color on the strip was visually compared with the standard color chart provided in the kit. The corresponding arsenic concentration (mg/L) was recorded.

***Data Analysis***

All statistical analyses and graphical representations were carried out using GraphPad Prism version 10.6.0 (GraphPad Software, San Diego, CA, USA). Descriptive statistics were used to summarize the data, and results are presented as mean ± standard deviation (SD).

## FINDINGS

Groundwater quality is a critical determinant for public health, agricultural sustainability, and ecosystem stability, particularly in semi-arid regions where water resources are often scarce and vulnerable to contamination. An integrated assessment of key physicochemical parameters, including As, salinity, EC, temperature, pH, and TDS, reveals significant concerns for water safety and usability when compared against international water quality guidelines.

Arsenic concentrations in groundwater samples varied considerably across the surveyed sites (Figure 2). In the vicinity of Abdul Hai Habibi High School sites, concentrations ranged from 0 to 20 mg/L. Higher levels were detected at Site 1 and Site 6 (20 mg/L each), while intermediate values were recorded at Sites 3, 4, and 5 (5–10 mg/L) (Figure 2a). In the Quba Mosque area sites, arsenic concentrations were comparatively low. Site 7 showed 5 mg/L, whereas Sites 8, 9, and 10 contained no detectable arsenic (0 mg/L) (Figure 2b). Groundwater from the Osman Car Wash area showed moderate contamination, with values ranging from 5 to 15 mg/L. The highest level was found at Site 11 (15 mg/L), while Sites 12, 14, and 15 consistently showed 10 mg/L, and Site 13 contained 5 mg/L (Figure 2c). At the Areba antenna area sites, concentrations demonstrated wider variability, ranging from 0 to 25 mg/L. The highest recorded concentration in the entire dataset occurred at Site 18 (25 mg/L). Other sites in this area ranged from 0 to 15 mg/L, with 0 mg/L at Site 21 (Figure 2d).

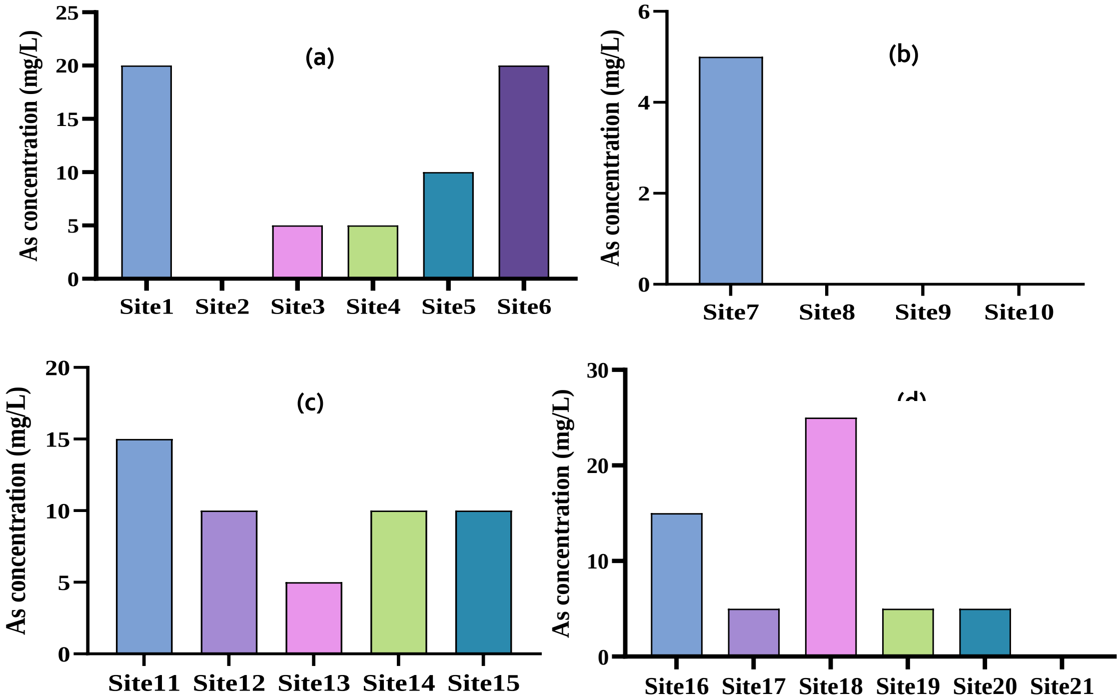


**Figure 2.** *Arsenic concentration across different sampling sites: (a) Abdul Hai Habibi High School sites, (b) Quba Mosque area sites, (c) Osman Car Wash area, and (d) Areba antenna area sites*

Notably, all measured arsenic concentrations exceeded the WHO provisional guideline value of 0.01 mg/L for drinking water (Karim, 2000) by several orders of magnitude. This degree of contamination aligns with the severe arsenic crises documented in other South Asian aquifers. For instance, the levels we observed are comparable to, and in some cases exceed, the range of 13.10 to 292 µg/L reported in Bangladesh (Rahman et al., 2022) and the range of <10 to 206 µg/L reported in Punjab, Pakistan (Shakoor et al., 2015). Earlier studies in Bangladesh revealed that, on average, 51% of 2508 water samples in 10 districts contained arsenic levels between 0.05 and 2.50 mg/L (50 to 2500 µg/L), far surpassing both the WHO limit and Bangladesh's maximum permissible limit of 0.05 mg/L (Anawar et al., 2002; Karim, 2000). Similarly, in Pakistan, groundwater arsenic concentrations also frequently exceed the WHO standard. Studies in the Vehari and Lodhran districts of Punjab, Pakistan, found an average arsenic concentration of 7.7 µg/L, with a maximum concentration reaching 41.6 µg/L (Khalid et al., 2024). While the geological and hydrogeological drivers in Afghanistan may differ, the resulting human health impacts are likely analogous, underscoring a regional geogenic challenge. The stark spatial variability, with pronounced hotspots such as the Areba antenna area, suggests a complex interplay of subsurface geology and potential anthropogenic influences that future work must focus on (Loodin, 2024).

Salinity levels across the sampled sites showed spatial variation, ranging from 0 to 1.9 ppt (Figure 3). At the Abdul Hai Habibi High School sites, salinity values ranged from 0.6 to 1.2 ppt. The highest salinity was observed at Site 1 (1.2 ppt), while the lowest values were measured at Sites 4 and 5 (0.6 ppt) (Figure 3a). The Quba Mosque area sites exhibited comparatively higher salinity levels, ranging from 1.5 to 1.9 ppt. The maximum value was detected at Site 8 (1.9 ppt), whereas Sites 9 and 10 recorded 1.5 ppt each (Figure 3b). Groundwater from the Osman Car Wash area showed salinity values between 0.9 and 1.2 ppt. Sites 11 and 13 contained 1.1 ppt, Sites 12 and 15 recorded 0.9 ppt, and Site 14 showed the highest value within this area (1.2 ppt) (Figure 3c). The Areba antenna area sites displayed the widest variation, ranging from 0 to 1.3 ppt. Site 17 had the highest salinity (1.3 ppt), while Site 21 contained no detectable salinity (0 ppt). Other sites in this area had values between 0.9 and 1.2 ppt (Figure 3d). When assessing drinking water acceptability, salinity levels below 500 mg/L (approximately 0.5 ppt) are typically considered safe by international standards such as those of the WHO (Alrowais et al., 2023). The observed range of 0–1.9 ppt indicates that water quality in this regard is largely acceptable. However, the upper end may warrant further assessment for potential palatability or health implications over the long term, especially if it approaches the upper limits of aesthetic guidelines (Rosinger et al., 2021).

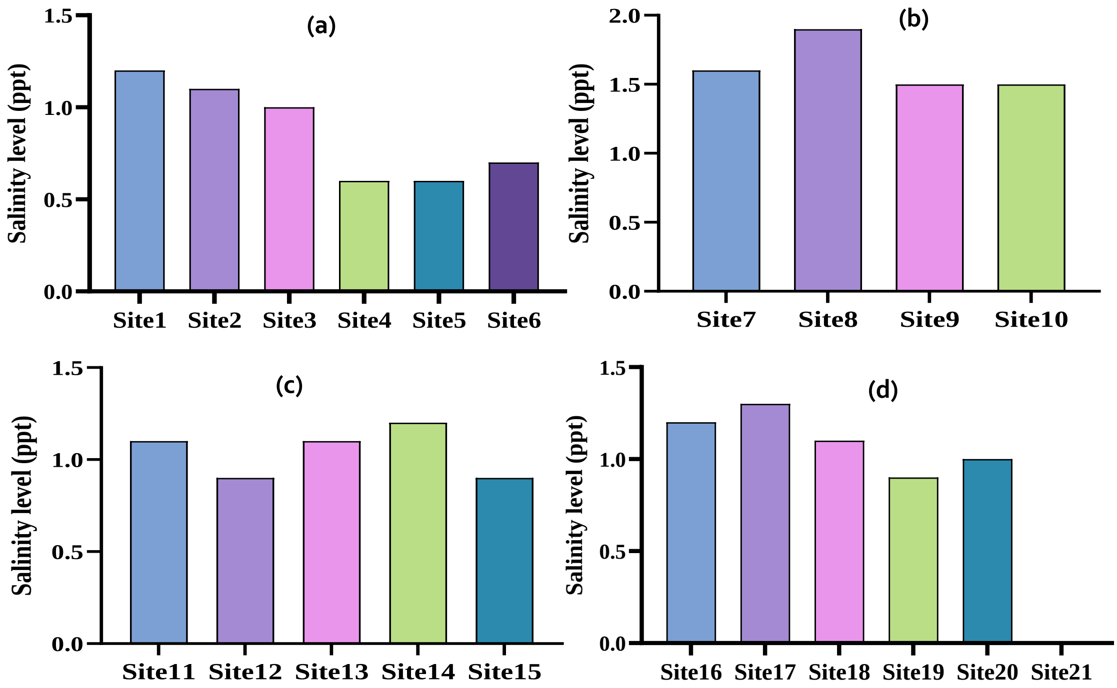


**Figure 3.** *Salinity level (ppt) across different sampling sites: (a) Abdul Hai Habibi High School sites, (b) Quba Mosque area sites, (c) Osman Car Wash area, and (d) Areba antenna area sites*

The EC of groundwater, a proxy for total ion content, showed substantial variation, mirroring the spatial heterogeneity observed in arsenic and salinity. Values ranged from 111 µS/cm to a maximum of 3630 µS/cm across the study area (Figure 4). A clear spatial pattern emerged, with the Quba Mosque area sites exhibiting the highest EC levels (2860–3630 µS/cm). This aligns with our salinity data and further confirms that this zone has the highest total dissolved solids. Notably, 75% of the sampled sites (18 out of 24) exceeded the WHO permissible limit of 1500 µS/cm for drinking water (Walton, 1989), indicating widespread inorganic contamination. The pervasive exceedance of EC guidelines, coupled with the severe arsenic contamination, paints a comprehensive picture of critically compromised groundwater quality. The strong correlation between elevated EC and high salinity in the Quba Mosque area suggests a common source of ionic enrichment, likely the dissolution of native minerals in the local geology (Ali et al., 2024; Bahir & Ouhamdouch, 2020). However, the inverse relationship between this high-EC zone and the primary arsenic hotspots suggests complex, spatially distinct hydrogeochemical controls. While geogenic origins are probable for the general ion load, anthropogenic activities such as agricultural runoff or wastewater infiltration cannot be ruled out as contributing factors, a phenomenon documented in other semi-arid regions (Rehman et al., 2020). Consequently, the groundwater in this aquifer is largely unsuitable for drinking without treatment, with EC being a dominant parameter in this classification, often accounting for a significant portion of the overall water quality assessment (Vaiphei et al., 2020).

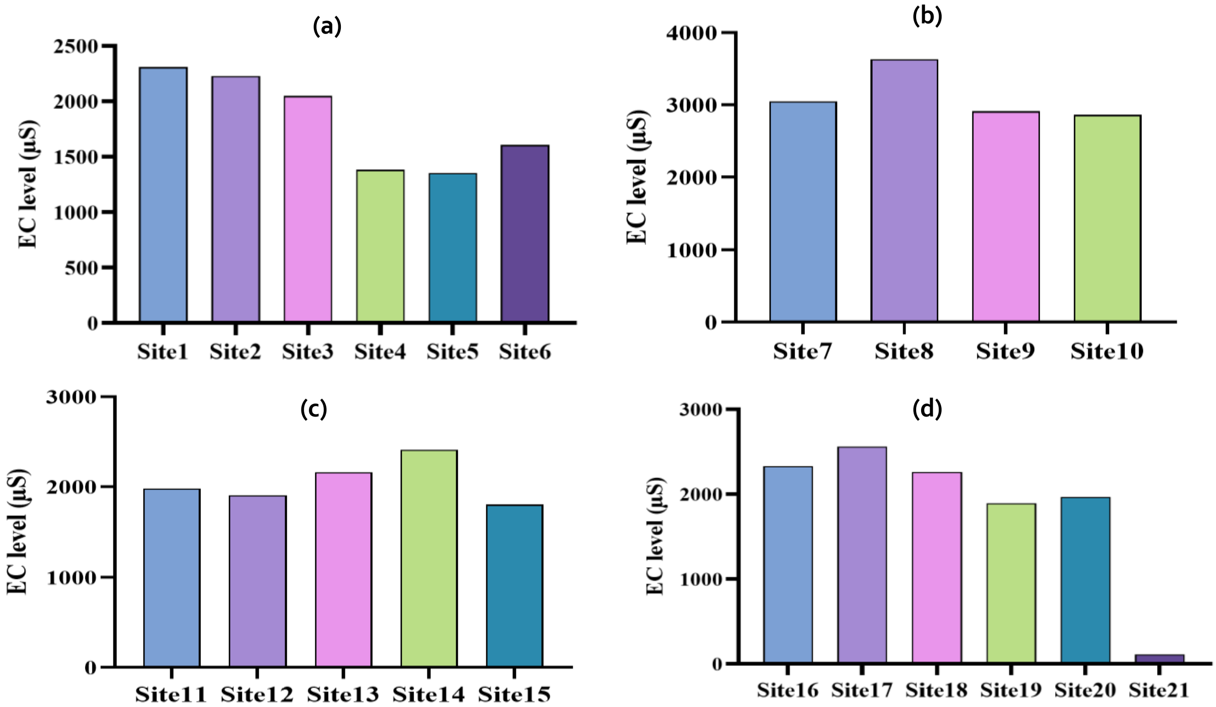


**Figure 4**. *Electron conductivity level (ppt) across different sampling sites: (a) Abdul Hai Habibi High School sites, (b) Quba Mosque area sites, (c) Osman Car Wash area, and (d) Areba antenna area sites*

Groundwater temperature displayed a discernible spatial pattern, ranging from 18.5 °C to 26.0 °C across the study area (Figure 5). The Osman Car Wash area consistently exhibited the warmest groundwater, with a peak of 26.0 °C at Site 13. In contrast, the Areba antenna area was the coolest, with temperatures as low as 18.5 °C at Site 16. The Abdul Hai Habibi High School and Quba Mosque areas displayed intermediate values. The observed temperature gradient is significant, as it may influence biogeochemical processes that control groundwater quality. The elevated temperatures in the Osman Car Wash area (24.1–26.0 °C) are strongly indicative of anthropogenic thermal pollution, likely exacerbated by the Urban Heat Island (UHI) effect (Riedel, 2019; Taylor & Stefan, 2009). Warmer temperatures can accelerate microbial metabolism and mineral dissolution rates, potentially exacerbating the mobilization of contaminants like arsenic. This provides a plausible, secondary control on the spatial distribution of our geochemical results. Consequently, the thermal regime should not be viewed in isolation but as an integral component of the aquifer's hydrogeochemical system, with implications for both water quality and the potential for geothermal energy exploitation in urban areas (Farr et al., 2017).

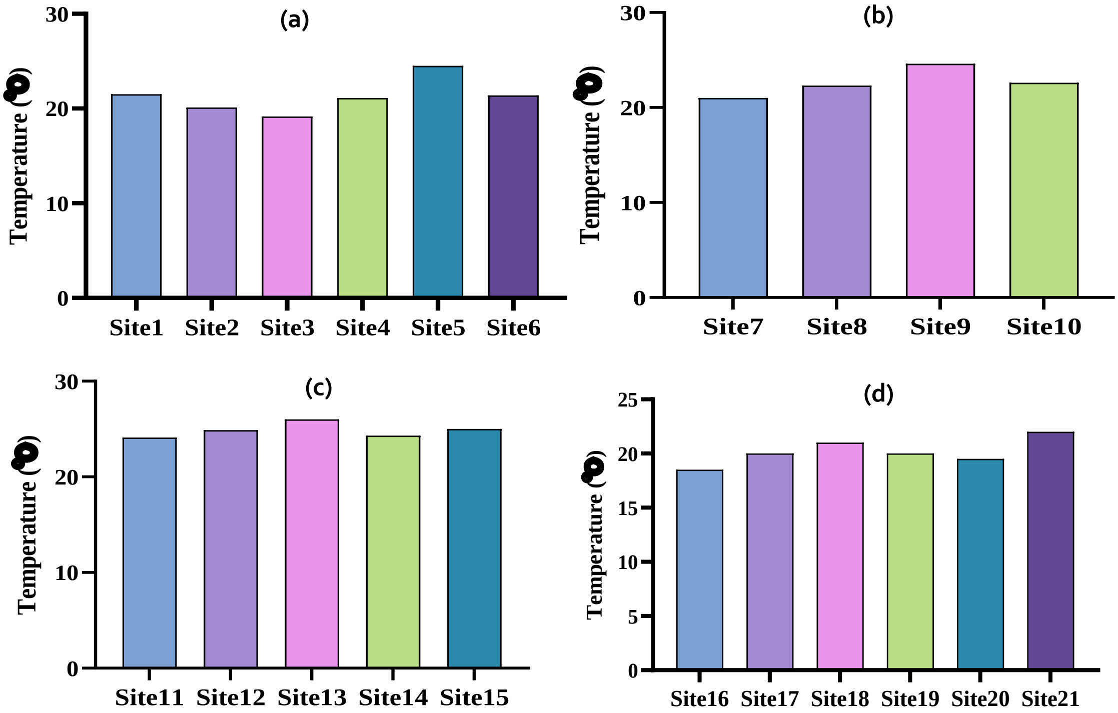


**Figure 5.** *Temperature (°C) across different sampling sites: (a) Abdul Hai Habibi High School sites, (b) Quba Mosque area sites, (c) Osman Car Wash area, and (d) Areba antenna area sites*.

pH levels across the study area ranged from neutral to slightly alkaline (7.1 to 8.1), consistently within the WHO-recommended range of 6.5 to 8.5 for drinking water (Figure 6). The Osman Car Wash area exhibited the most alkaline conditions, with a maximum pH of 8.1, while the Quba Mosque area showed the widest variability, including the most neutral value of 7.1. The consistently neutral to alkaline pH conditions (7.1–8.1) are a critical control on the aquifer's geochemistry. While this range is ideal for preventing pipe corrosion and ensuring water palatability, it has a more nuanced implication for arsenic. In this pH range, particularly as conditions become more alkaline, arsenic mobilization is often enhanced by the desorption of arsenate species from metal (hydr)oxide surfaces in the aquifer matrix (Kanel et al., 2023). This suggests that the widespread alkaline conditions are a key environmental factor facilitating the high arsenic concentrations observed, even in the absence of extreme pH values. Therefore, the ostensibly "safe" pH range paradoxically contributes to the severity of the arsenic contamination crisis in the region (Jeelani et al., 2020).

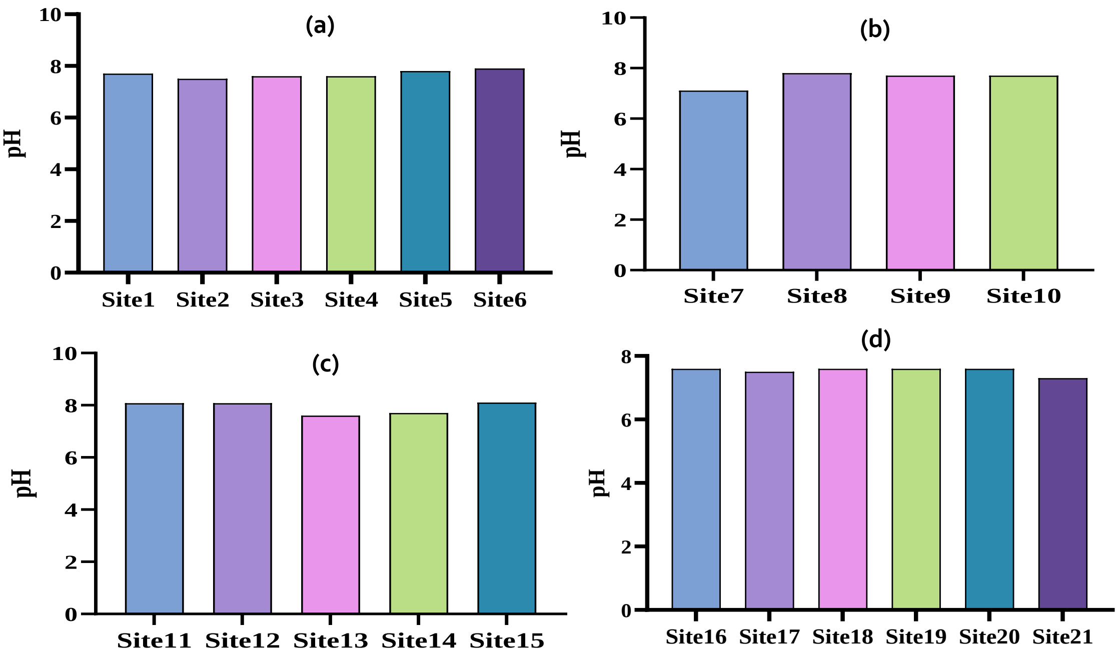


**Figure 6.** *pH across different sampling sites: (a) Abdul Hai Habibi High School sites, (b) Quba Mosque area sites, (c) Osman Car Wash area, and (d) Areba antenna area sites*

Total Dissolved Solids concentrations, which are directly correlated with EC, confirmed the prevalence of high mineral content in the aquifer. Values ranged from 710.4 mg/L to 2323.2 mg/L, with the Quba Mosque area again exhibiting the highest levels, consistent with the EC and salinity data (Figure 7). A significant majority of sites (79%) exceeded the WHO-recommended limit of 1000 mg/L for drinking water, underscoring the pervasive nature of inorganic contamination (Rizk, 2009). The coherent picture emerging from TDS, EC, and salinity data unequivocally classifies the groundwater in this aquifer as mineralized and largely unsuitable for drinking without treatment. This extensive mineralization, while influenced by the natural geology, is likely exacerbated by anthropogenic pressures such as urbanization and agricultural practices, as documented in similar semi-arid environments (Ojo et al., 2024; Khan et al., 2020). The high ionic strength from this dissolved load, occurring in tandem with a neutral to alkaline pH, creates a geochemical environment that favors the desorption and mobilization of arsenic, thereby unifying the observed water quality issues into a single, complex contamination crisis (Gallagher & Dietrich, 2010).

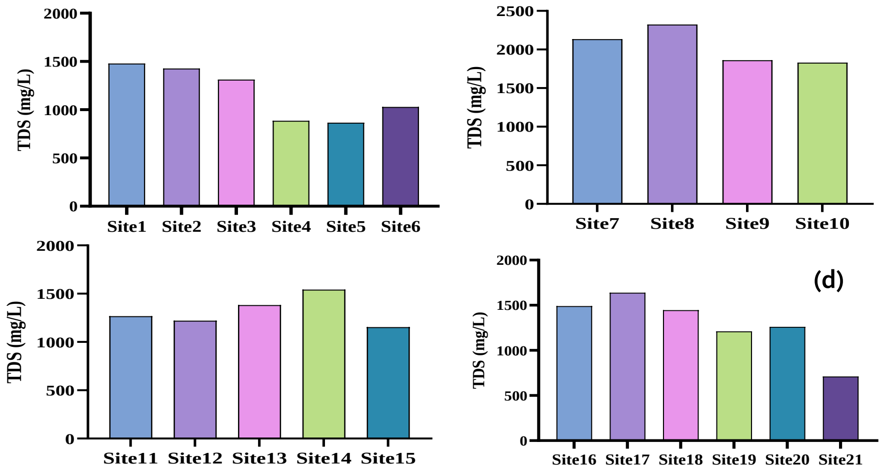


**Figure 7.** Total dissolved solids (mg/L) across different sampling sites: (a) Abdul Hai Habibi High School sites, (b) Quba Mosque area sites, (c) Osman Car Wash area, and (d) Areba antenna area sites.

## CONCLUSION

This study provides an integrated hydrogeochemical interpretation of groundwater quality across selected districts of Kabul, highlighting the combined influence of physicochemical conditions and mineralization processes on groundwater contamination. A key theoretical contribution of this work is the demonstration that neutral to alkaline groundwater conditions (pH 7.1–8.1), while typically regarded as favorable for water infrastructure and palatability, can play a critical role in enhancing arsenic mobilization through desorption from metal (hydr)oxide surfaces. This finding reinforces the hydrogeochemical theory that contaminant risk is governed not only by concentration thresholds but also by geochemical conditions that control contaminant mobility. The coexistence of elevated As, EC, and TDS indicates that large portions of the groundwater system are unsuitable for direct consumption without treatment, posing persistent public health risks for groundwater-dependent communities in Kabul. These results can directly inform groundwater management strategies by identifying priority areas for monitoring and intervention and by emphasizing the need to incorporate geochemical controls into water quality assessments rather than relying solely on single-parameter standards. The findings underscore the necessity of routine groundwater quality monitoring, the development of As-specific mitigation and treatment strategies, regulation of anthropogenic discharges, and the provision of alternative safe water sources in high-risk areas. A key limitation of this study is its cross-sectional design, which provides a spatial snapshot of groundwater quality but does not capture seasonal variability or long-term temporal trends that may influence As mobilization and groundwater chemistry. Future research should incorporate multi-seasonal and longitudinal monitoring to evaluate temporal dynamics in groundwater quality and to better the processes governing arsenic variability under changing hydrological and environmental conditions.

## AUTHORS CONTRIBUTIONS

**Faizanulhaq Shams:** Conceptualization, methodology development, field investigation, data collection, formal analysis, visualization, and original draft preparation. **Naweedullah Amin:** Study supervision, research design refinement, data interpretation, critical review and editing of the manuscript, and overall project oversight. Both authors reviewed and approved the final version of the manuscript.

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## CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest

## DATA AVAILABILITY STATEMENT

All data generated or analysed during this study are included in this publication.

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