

Hydrogeochemical Variability and Statistical Assessment of Samukh (Azerbaijan) Artesian Wells

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ABSTRACT

This study evaluated the physicochemical characteristics of artesian groundwater from three settlements (Sarigamış, Garayeri, and Yenibag) in the Samukh district, Azerbaijan. Nine water samples were analyzed for pH, Eh, HCO_3^- , Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , $\text{Na}^+ + \text{K}^+$, and TDS using standard methods. One-way ANOVA and Tukey's HSD test revealed significant differences ($p < 0.001$) among sampling sites for all parameters, indicating spatial hydrogeochemical heterogeneity. Pearson correlation analysis demonstrated strong positive correlations between SO_4^{2-} and Mg^{2+} ($r = 0.999$) and between TDS and Mg^{2+} ($r = 0.963$), suggesting common mineral dissolution sources. While pH, Cl^- , Mg^{2+} , and Ca^{2+} complied with WHO drinking water guidelines, elevated concentrations of SO_4^{2-} (480–701 mg/L), $\text{Na}^+ + \text{K}^+$ (324–381 mg/L), and TDS (943–1203 mg/L) exceeded recommended limits at most sites. The findings show that natural water-rock interactions, especially the dissolution of carbonate and sulphate minerals, are the main factors influencing groundwater chemistry

INTRODUCTION

One of the essential elements supporting human life, economic growth, and ecological balance is water resources. Rapid population growth, urbanisation, climate change, and intensive agricultural practices have all contributed to a sharp increase in the demand for freshwater resources. At the same time, maintaining water quality has become a major global concern (*The United Nations World Water Development Report*, 2024), (Mukherjee et al., 2021). In many parts of the world, groundwater especially artesian water is one of the most significant sources of household and drinking water. Groundwater often has higher physicochemical stability than surface water due to natural filtration through geological strata. However, its chemical makeup is significantly affected by several natural and human-induced elements, such as hydrogeological conditions, water rock interactions, geological structures, and anthropogenic activities. These variables have the potential to significantly change the quality of groundwater and, in turn, its suitability for human consumption. Thus, maintaining safe drinking water supplies, promoting sustainable groundwater resource management, and safeguarding public health all depend on the routine evaluation of the physicochemical properties of artesian water (Abdulshaheed & Halboos, 2024; Al-Turaihi et al., 2023).

Key physicochemical characteristics, including as pH, oxidation reduction potential (Eh), bicarbonate (HCO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), and total dissolved solids (TDS), are the main basis for evaluating the quality of drinking water. In addition to describing the hydrogeochemical characteristics of groundwater, these metrics are crucial markers for assessing its appropriateness for human use. Water's organoleptic qualities may be negatively impacted, its technical uses may be restricted, and human health may be at danger if the required guideline values are deviated from. For an impartial evaluation of drinking water quality, it is therefore essential to compare the observed physicochemical characteristics with the World Health Organization's (WHO) recommended values (Fetrat & Islam, 2024; Yadav et al., 2025).

A comprehensive assessment of water quality is not limited to the determination of individual physicochemical parameters. In contemporary hydrogeochemical studies, statistical methods are widely employed to evaluate spatial variations and identify relationships among water quality indicators. Tukey's Honestly Significant Difference (HSD) post-hoc test pinpoints the precise groups accountable for these differences, while one-way analysis of variance (One-Way ANOVA) is frequently employed to identify statistically significant variations among various water sources. Furthermore, Pearson correlation analysis is used to assess the connections between physicochemical characteristics and to provide light on the hydrogeochemical mechanisms controlling the composition of groundwater. In order to understand the geochemical processes governing groundwater chemistry and water quality, these statistical techniques have been widely used (Ahmed et al., 2024; Choque Quispe et al., 2021; Phan et al., 2023).

The hydrogeochemical properties of groundwater resources in the Republic of Azerbaijan have been the subject of several investigations. Nevertheless, there are still few thorough evaluations of the physicochemical quality of artesian groundwater in Samukh area using contemporary statistical techniques. The region's heavy agricultural expansion and the widespread use of artesian groundwater for residential water supply and irrigation underscore the need for ongoing groundwater quality monitoring (Mehdiyeva et al., 2026). Therefore, a comparative investigation of the physicochemical characteristics of artesian waters collected from the Sarıgamış, Garayeri, and Yenibag settlements is of considerable scientific and practical importance.

The thorough assessment of the physicochemical properties of the artesian groundwater utilised in the Samukh district, the identification of the main hydrogeochemical factors affecting groundwater quality, and the comparison of the results with globally accepted drinking water standards are what make the current study significant. It is anticipated that the results of this study will offer a scientific foundation for monitoring groundwater quality, safeguarding the environment, and managing water resources sustainably in the area.

The aim of this study was to evaluate the physicochemical characteristics of nine artesian water samples collected from the Sarıgamış, Garayeri, and Yenibag settlements of the Samukh district, Azerbaijan. The study specifically sought to determine whether there were statistically significant differences between the sampling sites using one-way analysis of variance (One-Way ANOVA) and Tukey's Honestly Significant Difference (HSD) post-hoc test, use Pearson correlation analysis to look at the correlations between physicochemical characteristics. Then, compare the results with the World Health Organization's (WHO) suggested guideline values for drinking water quality to see if the artesian waters were safe to consume.

THEORITICAL REVIEW

Previous studies have demonstrated that hydrogeochemical assessment combined with statistical analysis is effective for identifying the factors controlling groundwater quality and spatial variability. Chruszcz-Lipska et al. (2014) reported that the chemical composition of artesian groundwater is strongly influenced by water-rock interactions and the geological characteristics of the aquifer, highlighting the importance of major ions in evaluating groundwater evolution. Similarly, Al-Turaihi et al. (2023) showed that hydrochemical characterization of artesian wells can reveal differences in groundwater composition associated with mineral dissolution and local hydrogeological conditions. More recent studies have applied multivariate statistical approaches to distinguish relationships among physicochemical parameters and identify dominant hydrogeochemical processes (Hamma et al., 2024; Uddin et al., 2023). Yadav et al. (2025) further demonstrated that statistical analysis of groundwater parameters, together with comparison against drinking-water standards, provides a useful framework for determining spatial differences and assessing water-quality suitability. These findings indicate that integrating physicochemical measurements, correlation analysis, variance

testing, and guideline-based assessment can provide a more comprehensive understanding of groundwater quality than evaluating individual parameters independently. However, relatively limited information is available on the spatial hydrogeochemical variability of artesian groundwater in the Samukh district of Azerbaijan, particularly using a combination of ANOVA, Tukey's HSD, and Pearson correlation analysis. Therefore, the present study extends previous hydrogeochemical research by examining the relationships and spatial differences among major physicochemical parameters in artesian wells from Sarigamish, Garayeri, and Yenibag.

METHODOLOGY

Research Materials

The study was conducted using artesian groundwater samples collected from three settlements in the Samukh district of the Republic of Azerbaijan: Sarigamish (40.821731° N, 46.331491° E), Garayeri (40.789240° N, 46.307458° E), and Yenibag (40.843854° N, 46.294117° E). The Samukh district is located in the western part of the Kura-Araz Lowland and is characterized by abundant groundwater resources from a hydrogeological perspective. Groundwater in the region is mainly hosted within alluvial and alluvial-proluvial deposits and is extensively utilized for agricultural irrigation, domestic purposes, and drinking water supply (Kovacevik et al., 2016). Nine groundwater samples were obtained from the selected artesian wells, with three replicate samples collected at each sampling location. The samples were placed in pre-cleaned polyethylene containers, transported to the laboratory under suitable preservation conditions, and subjected to analysis immediately upon arrival.

The objective of the investigation was to evaluate the physicochemical quality of artesian groundwater based on major hydrochemical parameters, identify hydrogeochemical differences among the selected sampling sites, and by comparing the analytical results with the World Health Organization's (WHO) suggested guidelines, determine whether the groundwater is suitable for drinking.

Water Sampling

Groundwater samples were collected from artesian wells located in the Sarigamish, Garayeri, and Yenibag settlements of the Samukh district, Azerbaijan, during the summer of 2026. Three independent replicate samples were collected from each sampling site, yielding a total of nine groundwater samples for analysis. Water samples were collected in sterile 1-L polyethylene bottles. Before sampling, each well was purged by allowing groundwater to flow continuously for 3–5 min to remove stagnant water from the outlet and obtain representative groundwater samples. Following collection, the samples were stored at 4 ± 1 °C and transported to the laboratory for physicochemical analyses as soon as possible to prevent changes in water quality during storage and transportation.

The physicochemical characteristics of the groundwater samples were determined using standard analytical procedures. The analyzed parameters included pH and oxidation–reduction potential (Eh), bicarbonate (HCO_3^-),

chloride (Cl^-), sulfate (SO_4^{2-}), magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium plus potassium (Na^+/K^+), and total dissolved solids (TDS).

The pH and oxidation-reduction potential (Eh) were measured using a calibrated multiparameter pH meter (S220- KIT SevenCompact pH/ion meter, Mettler Toledo). Bicarbonate (HCO_3^-) was determined by the alkalinity titration method in accordance with Standard Method 2320 B (Chruszcz-Lipska et al., 2014; Verma, 2004). Chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were determined according to the corresponding Standard Methods for the Examination of Water and Wastewater (APHA, AWWA & WEF, 2017) (*Standard Methods for the Examination of Water and Wastewater*, 1926). The combined concentration of sodium and potassium ions (Na^+/K^+) was calculated using the difference method ('Chapter 52 Sodium and Potassium', 1996). Total dissolved solids (TDS) were calculated using the Summation of Constituents (SOC) method by summing the concentrations of the major dissolved. Statistical

processing of the data was conducted with OriginPro 8.0 (OriginLab Corporation, Northampton, MA, USA) and Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA). Variations in the physicochemical characteristics of groundwater among the investigated artesian well sites were assessed by one-way analysis of variance (ANOVA). In cases where the ANOVA indicated a statistically significant difference, Tukey's Honestly Significant Difference (HSD) multiple-comparison procedure was subsequently used to determine which sampling sites differed significantly from one another.

Pearson's correlation coefficient (r) was calculated to examine the linear relationships between the measured physicochemical parameters. The coefficient provides information on both the magnitude and direction of the association between two variables, with values ranging from -1 to +1. Positive values approaching +1 represent strong positive associations, whereas coefficients approaching -1 reflect strong inverse relationships. Values near zero suggest that the variables have little or no linear association. For all statistical tests, results were considered statistically significant when the p-value was below 0.05 (Hamma et al., 2024; Uddin et al., 2023).

Water Quality Assessment

The physicochemical characteristics of the groundwater samples were evaluated by comparison with the guideline values for drinking water quality established by the World Health Organization (WHO). The assessed parameters included pH, bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium plus potassium (Na^+/K^+), and total dissolved solids (TDS). The comparison was conducted to determine the suitability of the artesian groundwater for drinking purposes, identify parameters exceeding the recommended guideline values, and interpret the hydrogeochemical characteristics of the investigated groundwater. The WHO Guidelines for Drinking-water Quality (WHO, 2022) served as the reference standard for evaluating the analytical results (*Guidelines for Drinking-Water Quality*, 2026).

RESEARCH RESULTS AND DISCUSSION

The physicochemical properties of groundwater obtained from the Sarigamish, Garayeri, and Yenibag artesian wells were statistically compared by means of one-way analysis of variance (ANOVA), with Tukey's Honestly Significant Difference (HSD) test subsequently applied for post-hoc comparisons (Table 1). The results demonstrated statistically significant differences in the majority of the examined physicochemical parameters among the three sampling locations ($p < 0.001$). The observed differences point to pronounced spatial variability in groundwater chemistry and may reflect the effects of contrasting geological settings, water-rock interactions, and site-specific hydrogeological conditions on the chemical characteristics of the artesian aquifers.

The observed variations in physicochemical parameters may also reflect differences in groundwater residence time, mineral dissolution processes, and the geochemical composition of the aquifer materials. Similar spatial heterogeneity in groundwater quality has been reported in previous hydrogeochemical studies, where geological setting and aquifer lithology were identified as the primary factors controlling groundwater composition (Hansani et al., 2026).

Table 1. One-way ANOVA and Tukey HSD comparison of physicochemical parameters of artesian waters collected from three locations in Samukh district

Parameters	F	p	Sarigamish	Garayeri	Yenibag
pH	32.23	<0.001	7.21 ± 0.02 ^a	7.36 ± 0.02 ^b	7.32 ± 0.03 ^b
Eh	58492.98	<0.001	32.70 ± 0.02 ^a	39.56 ± 0.04 ^c	34.59 ± 0.01 ^b
HCO ₃ (mg\l)	2368.63	<0.001	51.43 ± 0.32 ^a	58.53 ± 0.04 ^b	61.96 ± 0.07 ^c
Total Cl ⁻ (mg/l)	1816.73	<0.001	51.14 ± 0.08 ^a	53.51 ± 0.12 ^c	57.74 ± 0.19 ^b
SO ₄ ⁻ (mg/l)	667407.24	<0.0001	700.71 ± 0.12 ^a	480.23 ± 0.29 ^c	560.36 ± 0.26 ^b
Mg ⁺⁺ (mg/l)	3674.68	<0.001	14.68± 0.18 ^a	4.77± 0.16 ^c	8.61± 0.26 ^b
Ca ⁺⁺ (mg/l)	146.33	<0.001	24.20 ± 0.20 ^a	23.98 ± 0.04 ^a	22.61 ± 0.06 ^b
Na ⁺ /K ⁺ (mg/l)	60413.3	<0.001	360.39 ± 0.31 ^a	324.41 ± 0.15 ^c	381.28 ± 0.07 ^b
TDS (mg/l)	6399.52	<0.001	1202.56 ± 0.90 ^a	942.77 ± 4.78 ^c	1092.55 ± 0.52 ^b

Note: Data are presented as mean ± standard error (SE) based on three replicates (n = 3). Within each row, means bearing different superscript letters (a, b, c) are significantly different according to Tukey's HSD multiple-comparison test ($p < 0.05$). F denotes the F-statistic obtained from the one-way ANOVA, while p represents the corresponding significance level.

The measured pH values varied between 7.21 and 7.36, demonstrating a slightly alkaline character across all groundwater samples. The observed range was within the World Health Organization (WHO) guideline interval of 6.5–8.5 for drinking water. One-way ANOVA showed a statistically significant variation in pH among the three sampling locations ($F = 32.23$, $p < 0.001$). Tukey's HSD multiple-comparison analysis indicated that the Sarigamish site differed significantly from both Garayeri and Yenibag, while the difference between the

latter two sites was not statistically significant. The observed alkaline conditions may be associated with buffering by the carbonate-bicarbonate system, suggesting relatively stable acid-base conditions within the investigated groundwater system.

The oxidation-reduction potential (Eh) also showed highly significant differences among the sampling sites ($F = 58,492.98$, $p < 0.001$). The highest Eh value was recorded in Garayeri (39.56 ± 0.04 mV), whereas the lowest was observed in Sarıgamış (32.70 ± 0.02 mV). Tukey's HSD test demonstrated significant differences among all three groundwater samples. Such spatial differences may reflect variations in groundwater oxygenation, residence time, and the extent of water-rock interactions.

The concentration of bicarbonate (HCO_3^-) differed significantly among the sampling sites ($F = 2,368.63$, $p < 0.001$), ranging from 51.43 ± 0.32 mg/L in Sarıgamış to 61.96 ± 0.07 mg/L in Yenibag. Significant differences were observed among all three locations. The relatively high bicarbonate levels may result primarily from the dissolution of carbonate-bearing minerals and are consistent with the natural geochemical evolution of groundwater.

The concentration of chloride (Cl^-) also varied significantly ($F = 1,816.73$, $p < 0.001$). The highest chloride concentration was measured in Yenibag (57.74 ± 0.19 mg/L), whereas the lowest was observed in Sarıgamış (51.14 ± 0.08 mg/L). Nevertheless, the chloride concentrations recorded in all groundwater samples remained well below the WHO guideline limit of 250 mg/L, suggesting that the observed chloride levels are primarily associated with natural geological processes rather than anthropogenic inputs.

Among all investigated parameters, sulfate (SO_4^{2-}) exhibited the greatest variability ($F = 667,407.24$, $p < 0.001$). Sulfate concentrations were 700.71 ± 0.12 mg/L in Sarıgamış, 560.36 ± 0.26 mg/L in Yenibag, and 480.23 ± 0.29 mg/L in Garayeri. Tukey's HSD test confirmed significant differences among all sampling sites. The elevated sulfate concentrations are likely related to the dissolution of gypsum, anhydrite, and other sulfate-bearing minerals. Importantly, sulfate concentrations in all groundwater samples exceeded the WHO recommended guideline value of 250 mg/L, suggesting that sulfate enrichment represents one of the major hydrogeochemical characteristics of the investigated aquifer system.

The concentration of magnesium (Mg^{2+}) also differed significantly among the sampling sites ($F = 3,674.68$, $p < 0.001$). The highest concentration was recorded in Sarıgamış (14.68 ± 0.18 mg/L), whereas the lowest occurred in Garayeri (4.77 ± 0.16 mg/L). These differences may be attributed to variable dissolution of dolomite and other magnesium-bearing minerals. However, all measured concentrations remained well below the WHO guideline value of 50 mg/L.

For calcium (Ca^{2+}), significant differences were detected by ANOVA ($F = 146.33$, $p < 0.001$). However, Tukey's HSD test indicated no significant difference between Sarıgamış and Garayeri, whereas Yenibag differed significantly from both locations. This finding suggests similar carbonate mineralization in the Sarıgamış and Garayeri aquifers. The measured calcium concentrations (22.61 –

24.20 mg/L) were considerably lower than the WHO recommended limit of 75 mg/L.

The combined concentration of sodium and potassium (Na^+/K^+) also differed significantly among the sampling sites ($F = 60,413.30$, $p < 0.001$). The highest concentration was recorded in Yenibag (381.28 ± 0.07 mg/L) and the lowest in Garayeri (324.41 ± 0.15 mg/L). Higher levels of these alkali metals are generally attributed to silicate mineral weathering and cation-exchange reactions occurring within the aquifer system. In the analyzed groundwater samples, sodium concentrations were above the WHO guideline value of 200 mg/L for aesthetic acceptability.

The concentration of total dissolved solids (TDS) ranged from 942.77 to 1202.56 mg/L and showed statistically significant differences among the sampling sites ($F = 6,399.52$, $p < 0.001$). The highest TDS value was observed in Sarigamish, whereas the lowest occurred in Garayeri. Although the Garayeri groundwater remained below the WHO guideline value of 1000 mg/L, the TDS concentrations in both Sarigamish and Yenibag exceeded this threshold, indicating a relatively high degree of groundwater mineralization. This elevated mineralization is likely associated with prolonged groundwater residence time and intensified water-rock interaction.

Overall, the results indicate that most physicochemical parameters of the investigated artesian groundwater comply with WHO drinking water guidelines. However, the elevated concentrations of SO_4^{2-} , Na^+/K^+ , and, in some cases, TDS suggest that continuous hydrogeochemical monitoring and, where necessary, appropriate water treatment should be considered before long-term domestic consumption. These results provide further evidence that groundwater chemistry in the Samukh district is largely governed by natural geological and hydrogeochemical processes.

Pearson Correlation Analysis

Pearson's correlation analysis was used to investigate the associations among the measured physicochemical parameters of the artesian groundwater samples (Table 2). The analysis identified both pronounced positive and negative correlations, suggesting that the observed groundwater chemistry is influenced by interconnected hydrogeochemical processes, such as mineral dissolution, water-rock interactions, and ion-exchange reactions.

Table 2. Pearson correlation matrix among the physicochemical parameters of artesian groundwater samples

	pH	Eh	HCO ₃ ⁻ (mg\ L)	Cl ⁻ (mg/l)	SO ₄ ⁻ (mg/l)	Mg ⁺⁺ (mg/l)	Ca ⁺⁺ (mg/l)	Na ⁺ /K ⁺ (mg/l)	TDS (mg/l)
pH	1								
Eh	0.826663 5	1							
HCO ₃ ⁻ (mg\ L)	0.798861 9	0.44960 99	1						
Cl ⁻ (mg/l)	-0.1087 242	-0.44939 21	0.07230729 3	1					
SO ₄ ⁻ (mg/l)	-0.9505 465	-0.91621 72	-0.76949022	0.29019 401	1				
Mg ⁺⁺ (mg/l)	-0.9497 985	-0.92624 49	-0.75090643	0.29404 307	0.999199 04	1			
Ca ⁺⁺ (mg/l)	-0.3627 503	-0.12238 415	-0.82170763	-0.35805 476	0.281157 15	0.254688 05	1		
Na ⁺ /K ⁺ (mg/l)	-0.3783 78	-0.80247 91	0.17197200 1	0.54132 549	0.496226 62	0.519442 06	-0.68426	1	
TDS (mg/l)	-0.8659 547	-0.98302 37	-0.56844788	0.49556 739	0.957758 78	0.963053 26	0.01879 4	0.70388	1

A very strong positive association was found between SO₄²⁻ and Mg²⁺ ($r = 0.999$), which may indicate a common geological origin or a shared control by the dissolution of sulfate- and magnesium-bearing minerals. In addition, TDS showed strong positive relationships with Mg²⁺ ($r = 0.963$) and SO₄²⁻ ($r = 0.958$), suggesting that these ions contribute substantially to the overall mineral content and mineralization of the groundwater.

Significant positive relationships were likewise observed between pH and Eh ($r = 0.827$) and between pH and HCO₃⁻ ($r = 0.799$). These associations indicate the important contribution of the carbonate-bicarbonate buffering system to the regulation of groundwater acid-base conditions and may also be indicative of the role of carbonate mineral dissolution in shaping the observed groundwater chemistry.

Conversely, several parameters showed strong negative correlations. The strongest negative correlation was observed between Eh and TDS ($r = -0.983$), indicating that increasing groundwater mineralization is associated with lower oxidation-reduction potential. Similarly, pH was strongly negatively correlated with SO₄²⁻ ($r = -0.951$), Mg²⁺ ($r = -0.950$), and TDS ($r = -0.866$), suggesting that increasing concentrations of dissolved ions are associated with slight decreases in pH values.

The concentration of HCO₃⁻ exhibited a strong negative correlation with Ca²⁺ ($r = -0.822$) and moderate negative correlations with SO₄²⁻ ($r = -0.769$) and Mg²⁺ ($r = -0.751$). These relationships may reflect differences in the dominant geochemical processes controlling carbonate dissolution and sulfate mineral weathering within the aquifer.

In contrast, chloride (Cl^-) showed weak to moderate correlations with most physicochemical parameters, indicating that chloride is relatively conservative in the studied groundwater system and is less influenced by the hydrogeochemical processes affecting the major ions.

Overall, the Pearson correlation analysis demonstrates that the hydrogeochemistry of the investigated artesian groundwater is primarily governed by water-rock interactions, particularly the dissolution of carbonate and sulfate minerals. The close association between SO_4^{2-} , Mg^{2+} , and TDS further indicates that these constituents are the principal contributors to groundwater mineralization in the study area. These findings are consistent with the results of the ANOVA and Tukey HSD analyses, which revealed significant spatial differences among the three sampling sites, confirming the influence of local geological conditions on groundwater quality.

Comparison with WHO Drinking Water Guidelines

The measured physicochemical properties of the artesian groundwater samples were evaluated against the World Health Organization (WHO) guideline values established for drinking-water quality (Table 3). The results showed that pH, bicarbonate (HCO_3^-), chloride (Cl^-), magnesium (Mg^{2+}), and calcium (Ca^{2+}) concentrations remained within the corresponding recommended limits at all sampling locations. This finding suggests that, with respect to these parameters, the groundwater does not present a major limitation for its potential use as drinking water.

In contrast, sulfate (SO_4^{2-}) concentrations exceeded the WHO recommended guideline value of 250 mg/L in all investigated groundwater samples. The highest sulfate concentration was recorded in the Sarıgarnış artesian well (700.71 ± 0.12 mg/L), followed by Yenibag (560.36 ± 0.26 mg/L) and Garayeri (480.23 ± 0.29 mg/L). Elevated sulfate concentrations are commonly associated with the dissolution of sulfate-bearing minerals, such as gypsum and anhydrite, within the aquifer. High sulfate levels may adversely affect the taste of drinking water and, in sensitive individuals, may produce laxative effects.

Similarly, the combined concentration of sodium and potassium (Na^+/K^+) exceeded the recommended WHO guideline value at all sampling sites. The highest concentration was observed in Yenibag (381.28 ± 0.07 mg/L), whereas the lowest was measured in Garayeri (324.41 ± 0.15 mg/L). These elevated concentrations are likely associated with silicate weathering and cation exchange processes occurring within the groundwater system.

The concentration of total dissolved solids (TDS) exceeded the WHO recommended guideline value of 1000 mg/L in the Sarıgarnış (1202.56 ± 0.90 mg/L) and Yenibag (1092.55 ± 0.52 mg/L) groundwater samples, while the Garayeri sample (942.77 ± 4.78 mg/L) remained within the recommended limit. Elevated TDS values indicate increased groundwater mineralization resulting from prolonged water-rock interactions and the dissolution of soluble minerals within the aquifer (Jiang et al., 2024).

Overall, the findings indicate that natural hydrogeochemical processes, such as geological structure, mineral weathering, and water-rock interactions, largely regulate the chemical composition of the examined artesian groundwater.

The statistically significant differences observed for most physicochemical parameters demonstrate that each sampling site possesses distinct hydrogeochemical characteristics. Although the majority of the investigated parameters complied with the WHO drinking water guidelines, the elevated concentrations of SO_4^{2-} , Na^+/K^+ , and TDS at some sampling locations show that ongoing monitoring of groundwater quality and recurring evaluation are required to guarantee the long-term suitability of these groundwater resources for drinking.

CONCLUSIONS AND RECOMMENDATIONS

This comprehensive investigation of artesian groundwater quality in the Samukh district demonstrated that the physicochemical characteristics of the three sampling sites exhibit significant spatial variability. The elevated concentrations of sulfate (SO_4^{2-}), sodium+potassium (Na^+/K^+), and total dissolved solids (TDS) at most sites exceed WHO drinking water guidelines, primarily due to natural geological processes including mineral dissolution and water-rock interactions. Nonetheless, elements like pH, calcium, magnesium, and chloride stayed within permissible bounds for ingestion by humans. For irrigation purposes, the moderately elevated TDS (942–1203 mg/L) and sulfate concentrations may pose slight salinity risks, though magnesium and calcium levels are within suitable ranges for agricultural use. The sodium adsorption ratio and salinity hazard should be carefully evaluated before extensive irrigation application. Overall, while the artesian groundwater is partially suitable for drinking purposes with treatment for sulfate and sodium reduction, its use for irrigation requires periodic monitoring and salinity management. This study offers a scientific foundation for the region's sustainable water resource management, environmental preservation, and groundwater quality monitoring.

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