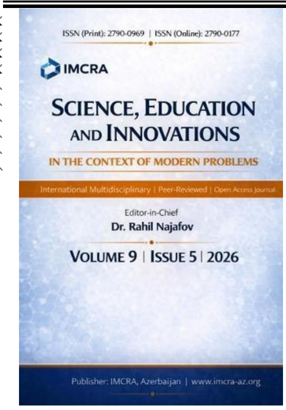

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RESEARCH ARTICLE

The Hydrochemical Composition and Quantitative Determination of Physiologically Active Ions in the Inchkhuri–Patara Inchkhuri Spring System, Martvili Municipality, Georgia

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Keywords spring water; hydrochemical analysis; groundwater quality; physicochemical parameters; trace elements; arsenic; bromide; drinking water; Martvili Municipality; Georgia.

Abstract
Freshwater springs constitute an important source of drinking water and play a vital role in maintaining environmental quality and public health. Continuous monitoring of their physicochemical characteristics is essential for evaluating water quality and ensuring the sustainable management of groundwater resources. This study investigates the hydrochemical composition of spring waters located in the Inchkhuri–Patara Inchkhuri area of Martvili Municipality, Georgia. Water samples were collected from seven representative springs and analyzed using standardized hydrochemical and spectrophotometric methods in the Iason Moseshvili Hydrochemistry Laboratory, Faculty of Exact and Natural Sciences, Akaki Tsereteli State University. The investigated parameters included pH, total hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}), total iron (Fe), copper (Cu^{2+}), chloride (Cl^{-}), bromide (Br^{-}),

bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), total arsenic, dissolved oxygen, biochemical oxygen demand (BOD_5), free carbon dioxide, and permanganate oxidation.

The results indicate that most physicochemical parameters were within the permissible limits established by the Georgian Technical Regulations for Drinking Water. Slightly elevated bromide concentrations were detected in one of the investigated springs, whereas the remaining parameters complied with recommended standards. The study provides the first comprehensive hydrochemical dataset for the Inchkhuri–Patara Inchkhuri spring system and contributes valuable baseline information for future environmental monitoring, groundwater quality assessment, and sustainable management of freshwater resources in western Georgia.

Citation

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Introduction

Freshwater resources are among the most valuable natural assets for sustaining ecosystems, agricultural production, and human health. Groundwater and spring waters constitute major sources of potable water in many regions of the world, particularly in rural and mountainous areas where centralized water supply systems are limited. The quality of these waters is strongly influenced by geological formations, hydrogeological processes, climatic conditions, and anthropogenic activities. Consequently, regular hydrochemical monitoring is essential for assessing water quality, protecting public health, and ensuring the sustainable use of groundwater resources.

Natural waters contain dissolved inorganic ions, gases, and organic compounds whose concentrations vary according to the lithological characteristics of aquifers and the physicochemical processes occurring during groundwater circulation. Among these constituents, calcium, magnesium, bicarbonate, chloride, sulfate, iron, copper, bromide, and trace elements such as arsenic are of particular environmental and biological significance. These components determine water hardness, mineralization, buffering capacity, and overall suitability for drinking, domestic, and agricultural applications. Some trace elements are essential for biological processes at low concentrations, whereas elevated levels may pose ecological and human health risks.

The acid-base status of natural waters, commonly expressed as pH, is one of the most important indicators of water quality because it controls numerous chemical equilibria, oxidation-reduction reactions, metal solubility, and biological activity. Parameters such as dissolved oxygen, biochemical oxygen demand (BOD_5), free carbon dioxide, and permanganate oxidation further provide valuable information regarding the ecological condition of aquatic environments and the presence of organic matter.

Hydrochemical investigations have become an indispensable component of groundwater assessment worldwide. They provide scientific evidence for evaluating water suitability for drinking and irrigation, identifying potential contamination sources, understanding water-rock interactions, and establishing baseline environmental conditions for long-term monitoring programs. Despite the environmental importance of the Martvili Municipality and its abundant spring resources, comprehensive hydrochemical information for the Inchkhuri–Patara Inchkhuri springs remains unavailable.

Therefore, the present study aims to provide the first detailed hydrochemical characterization of selected spring waters in the Inchkhuri–Patara Inchkhuri area of Martvili Municipality, Georgia. A broad range of physicochemical parameters and major ions was determined using standardized laboratory techniques to evaluate water quality and generate baseline data for future environmental and hydrogeochemical studies. The findings are expected to contribute to regional groundwater management, environmental protection, and the sustainable utilization of freshwater resources.

Objective

The objective of this study was to determine the hydrochemical composition and physicochemical characteristics of the Inchkhuri–Patara Inchkhuri spring waters located in Martvili Municipality, Georgia. For this purpose, the concentrations of pH, total hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}), total iron, copper (Cu^{2+}), bicarbonate (HCO_3^-), bromide (Br^-), chloride (Cl^-), sulfate (SO_4^{2-}), total arsenic, dissolved oxygen, biochemical oxygen demand (BOD_5), free carbon dioxide, and permanganate oxidation were determined using validated analytical methods. This research represents the first comprehensive hydrochemical investigation of these spring waters and establishes a scientific baseline for future environmental monitoring, groundwater quality assessment, and evaluation of their suitability for drinking and agricultural purposes.

Literature Review

Hydrochemical investigations of groundwater and spring water have become increasingly important for evaluating freshwater quality, identifying geochemical processes, and supporting the sustainable management of water resources. The chemical composition of natural waters is controlled by complex interactions among geological formations, groundwater flow paths, climatic conditions, and anthropogenic activities. Consequently, comprehensive hydrochemical characterization has become a fundamental component of environmental monitoring and public health assessment (Freeze & Cherry, 1979; Appelo & Postma, 2005).

Major dissolved ions, including calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), and trace elements such as iron, copper, bromide, and arsenic, are widely recognized as reliable indicators of groundwater quality. Their concentrations provide valuable information regarding mineral dissolution, water-rock interaction, groundwater residence time, and possible natural or anthropogenic contamination. In addition, physicochemical parameters such as pH, dissolved oxygen, biochemical oxygen demand (BOD_5), and permanganate oxidation are commonly used to evaluate the ecological condition and suitability of water for domestic and agricultural purposes (Appelo & Postma, 2005).

The World Health Organization (2022) emphasizes that systematic monitoring of physicochemical and microbiological parameters is essential for protecting drinking water quality and reducing health risks associated with trace elements and other dissolved constituents. International drinking-water guidelines recommend continuous assessment of groundwater resources, particularly in rural areas where spring water serves as the principal source of potable water.

Previous hydrochemical investigations conducted in different regions of Georgia have demonstrated considerable spatial variability in groundwater composition. Chiqovani et al. (2020) investigated the hydrochemical and sanitary characteristics of spring waters in the Nakhunao community of Martvili Municipality and reported that most measured parameters complied with national drinking-water standards while emphasizing the necessity of continuous environmental monitoring. Similarly, Chiqovani et al. (2022) expanded hydrochemical and microbiological assessments of spring waters from the same region and confirmed that local geological conditions strongly influence groundwater quality.

Subsequent studies have extended hydrochemical investigations to numerous municipalities throughout western Georgia. Chiqovani et al. (2023) evaluated the chemical composition of spring waters in Aketi Village, Lanchkhuti Municipality, while another study by Chiqovani et al. (2023) characterized freshwater resources in the villages of Lejokhe, Letane, and Mikava within Tsalenjikha Municipality. Both studies demonstrated variations in major ion concentrations associated with local hydrogeological settings and emphasized the importance of baseline hydrochemical monitoring.

More recent investigations have continued to expand the hydrochemical database for Georgian spring waters. Chiqovani et al. (2024) analyzed springs in Salominao Village (Vani Municipality), whereas Chiqovani et al. (2024) quantified biologically active ions in freshwater sources of Sukhche Village (Khoni Municipality), highlighting the ecological significance of trace elements and their potential contribution to groundwater quality assessment. Additional studies conducted in Khidari Village (Kharagauli Municipality), Akhuti Village (Chkhorotsku Municipality), and the Lasuriashi–Makhashi spring systems of Tsageri Municipality further demonstrated regional differences in hydrochemical characteristics while confirming the suitability of standardized analytical methods for evaluating groundwater quality (Chiqovani et al., 2025a; Chiqovani et al., 2025b; Chiqovani et al., 2025c).

Although these investigations have substantially improved knowledge of the hydrochemical characteristics of Georgian spring waters, no comprehensive study has previously examined the Inchkhuri–Patara Inchkhuri spring system in Martvili Municipality. Consequently, the physicochemical composition of these groundwater resources has remained largely undocumented. The present study addresses this gap by providing the first detailed hydrochemical assessment of selected springs in the study area. Through the determination of major ions, trace elements, and key physicochemical parameters using standardized laboratory methods, this research contributes new baseline data that will support future groundwater monitoring, environmental management, and sustainable utilization of freshwater resources in western Georgia.

Methodology

Study Area

The present study was conducted in the Inchkhuri–Patara Inchkhuri spring system located in the village of Inchkhuri, Martvili Municipality, western Georgia. The study area is characterized by abundant groundwater resources originating from local geological formations and represents an important source of drinking and domestic water for the surrounding population. Seven representative springs were selected for hydrochemical investigation based on their accessibility, continuous water discharge, and local significance.

Sample Collection

Water samples were collected directly from the spring outlets under natural flow conditions to minimize contamination. Prior to sampling, polyethylene bottles were thoroughly rinsed with deionized water and subsequently washed three times with the spring water to be analyzed. The samples were transported immediately to the Iason Moseshvili Hydrochemistry Laboratory of the Faculty of Exact and Natural Sciences, Department of Chemistry, Akaki Tsereteli State University, where all laboratory analyses were performed.

Analytical Methods

The hydrochemical composition of the spring waters was determined using internationally accepted analytical procedures routinely applied in hydrochemical investigations.

The following physicochemical parameters were measured:

- pH
- Total water hardness
- Calcium (Ca^{2+})
- Magnesium (Mg^{2+})
- Total iron (Fe)
- Copper (Cu^{2+})
- Chloride (Cl^-)
- Bromide (Br^-)
- Bicarbonate (HCO_3^-)
- Sulfate (SO_4^{2-})
- Total arsenic
- Dissolved oxygen (DO)
- Biochemical oxygen demand (BOD_5)
- Free carbon dioxide (CO_2)
- Permanganate oxidation

The analytical techniques employed included potentiometric, complexometric, spectrophotometric, acidimetric, alkalimetric, iodometric, permanganatometric, and photometric methods according to standard hydrochemical laboratory procedures.

Laboratory Procedures

The pH of each sample was measured using a calibrated pH meter (pH-673M potentiometer). Total hardness together with calcium and magnesium concentrations was determined by complexometric titration using EDTA (Complexon III). Calcium was quantified using murexide as an indicator in an alkaline medium, whereas magnesium was determined using Eriochrome Black T in an ammonium buffer solution.

Total iron concentration was measured spectrophotometrically following oxidation in an alkaline medium using sulfosalicylic acid as the chromogenic reagent. Copper concentrations were determined by sensitive photometric analysis.

Bicarbonate ions were determined by acidimetric titration using standardized hydrochloric acid with methyl orange as the endpoint indicator. Chloride ions were determined by mercurimetric titration, while bromide concentrations were analyzed using an iodometric method following oxidation to bromate.

Total arsenic was quantified using the iodometric method with standardized iodine solution. Free carbon dioxide was determined by alkalimetric titration with sodium hydroxide in the presence of phenolphthalein. Dissolved oxygen and biochemical oxygen demand (BOD_5) were measured by the modified Winkler iodometric method. Permanganate oxidation was determined using potassium permanganate oxidation under acidic conditions followed by oxalic acid back-titration.

Quality Assurance and Quality Control

All analytical measurements were performed under controlled laboratory conditions using calibrated instruments and analytical-grade reagents. Standardized laboratory protocols were followed throughout the analytical process to ensure measurement accuracy, precision, and reproducibility. Each determination was conducted according to validated hydrochemical analytical procedures routinely applied in environmental water quality assessment.

Data Analysis

The analytical results were compiled and compared among the investigated springs to evaluate spatial variations in groundwater chemistry. The measured concentrations were interpreted in relation to the Georgian Technical Regulation for Drinking Water and the World Health Organization (WHO) Guidelines for Drinking-water Quality (WHO, 2022). The obtained data provide a baseline hydrochemical dataset for evaluating groundwater quality and supporting future environmental monitoring in the Martvili Municipality.

Discussion

The hydrochemical characteristics of the Inchkhuri–Patara Inchkhuri spring waters demonstrate that groundwater quality in the study area is primarily controlled by natural geological processes rather than anthropogenic contamination. The observed variations in the concentrations of major ions and physicochemical parameters are consistent with groundwater–rock interactions that occur during the movement of water through carbonate- and silicate-bearing formations. Such hydrogeochemical processes have been widely reported as the principal factors controlling groundwater chemistry in natural spring systems (Freeze & Cherry, 1979; Appelo & Postma, 2005).

The measured pH values (7.2–8.2) indicate neutral to slightly alkaline water conditions, suggesting good buffering capacity and favorable geochemical equilibrium. Similar pH ranges have been reported for spring waters in other regions of western Georgia, where carbonate minerals contribute to the stabilization of groundwater acidity (Chiqovani et al., 2020; Chiqovani et al., 2022). Neutral and slightly alkaline groundwater generally promotes the stability of dissolved ions while reducing the mobility of several potentially toxic metals.

Calcium and magnesium were the dominant cations detected in the investigated springs, reflecting the dissolution of carbonate minerals within the local geological formations. Differences in calcium and magnesium concentrations among sampling sites likely result from variations in lithological composition, groundwater residence time, and the intensity of mineral weathering. Comparable hydrochemical patterns have been reported in previous investigations conducted in the municipalities of Tsalenjikha, Vani, Khoni, Chkhorotsku, and Kharagauli (Chiqovani et al., 2023a; Chiqovani et al., 2023b; Chiqovani et al., 2024a; Chiqovani et al., 2024b; Chiqovani et al., 2025a).

Iron concentrations varied considerably among the investigated springs, with the highest concentration recorded in the Igor spring. Elevated iron concentrations are commonly associated with the dissolution of iron-bearing minerals under reducing groundwater conditions and are frequently observed in natural aquifers. In contrast, copper concentrations remained below or near the analytical detection limit in most sampling locations, indicating the absence of significant anthropogenic contamination from industrial or agricultural sources.

The concentrations of chloride, bicarbonate, sulfate, and bromide ions also exhibited spatial variability. Bicarbonate is the dominant anion in most natural groundwater systems and reflects carbonate dissolution during groundwater circulation. Chloride concentrations remained relatively low, suggesting minimal influence from domestic wastewater or other external pollution sources. Bromide concentrations were generally low; however, a relatively elevated value was observed in the Kau spring. Although this concentration slightly exceeded the recommended level, it appears to represent a localized hydrogeochemical characteristic rather than widespread contamination. Additional seasonal monitoring would be useful to determine whether this enrichment is persistent or temporary.

The concentrations of dissolved oxygen, free carbon dioxide, biochemical oxygen demand (BOD_5), and permanganate oxidation indicate that the investigated springs contain relatively low levels of organic matter. These parameters suggest favorable ecological conditions and limited organic pollution within the groundwater system. Similar observations have been reported in previous hydrochemical studies of Georgian spring waters, where groundwater quality was largely controlled by natural hydrogeological conditions rather than anthropogenic influences (Chiqovani et al., 2020; Chiqovani et al., 2025b).

Total arsenic concentrations remained low in most investigated springs, although relatively higher values were detected in the Igor spring. Because arsenic is a naturally occurring trace element that may originate from geological formations, continuous monitoring is recommended to ensure that concentrations remain within acceptable drinking-water standards established by the World Health Organization (WHO, 2022). Long-term surveillance is particularly important because seasonal hydrological conditions may influence trace element mobility.

Comparison with previous investigations conducted in western Georgia demonstrates that the Inchkhuri–Patara Inchkhuri spring waters exhibit hydrochemical characteristics similar to those reported from neighboring municipalities. However, differences in individual ion concentrations confirm that local geological structure, groundwater flow conditions, and mineral composition significantly influence water chemistry. Therefore, each spring system should be evaluated individually rather than assuming regional hydrochemical uniformity.

Overall, the present investigation provides the first comprehensive hydrochemical characterization of the Inchkhuri–Patara Inchkhuri spring system. The generated baseline dataset contributes valuable scientific information for groundwater resource management, environmental monitoring, and future hydrogeochemical research in Georgia. Further studies incorporating seasonal sampling, multivariate statistical analysis, hydrochemical facies classification, and water quality indices would provide a more comprehensive understanding of groundwater evolution and long-term environmental sustainability.

Figure 1. Location of Inchkhuri Village in Martvili Municipality, Samegrelo–Zemo Svaneti Region, Western Georgia. **Source:** Prepared by the authors using data from OpenStreetMap and Google Earth (2026).

Figure 2. Waterfall near Inchkhuri Village and the Abasha River, Martvili Municipality, Western Georgia.

Source: Photograph by the authors (2026).

Study Area

The present investigation was carried out in the Inchkhuri–Patara Inchkhuri spring system, located in the village of Inchkhuri, Martvili Municipality, Samegrelo–Zemo Svaneti Region, western Georgia. The municipality occupies a transitional geomorphological zone extending from the Odishi Plain in the south to the foothills and southern slopes of the Egrisi Mountain Range in the north. It is bordered by Lentekhi Municipality to the north, Khoni and Tsageri municipalities to the east, Abasha Municipality to the south, and Senaki and Chkhorotsku municipalities to the west. This geographical setting creates highly diverse geological, hydrological, and climatic conditions that strongly influence groundwater recharge, circulation, and hydrochemical evolution (Freeze & Cherry, 1979; Appelo & Postma, 2005).

The elevation within Martvili Municipality ranges from approximately 60 m above sea level in the southern lowlands to 3,003 m in the mountainous northern region. Such pronounced topographic variability promotes the development of multiple groundwater flow systems, abundant perennial springs, and complex interactions between surface water and groundwater. Mountainous recharge zones receive substantial precipitation, allowing groundwater to infiltrate fractured bedrock and carbonate formations before emerging naturally as springs in lower elevations (Freeze & Cherry, 1979; Appelo & Postma, 2005).

The regional geology is dominated by carbonate and sedimentary formations together with fractured rock aquifers that facilitate groundwater storage, natural filtration, and prolonged water–rock interaction. The southwestern part of Martvili Municipality is influenced by the Askhi Mountain Range, which is characterized by extensive karst landscapes, caves, waterfalls, and mineral deposits. Karstified carbonate rocks enhance groundwater permeability and contribute significantly to the hydrochemical characteristics of spring waters through the dissolution of carbonate minerals and prolonged geochemical exchange processes (Freeze & Cherry, 1979; Appelo & Postma, 2005).

Hydrologically, the municipality belongs to the Tekhuri and Abasha River basins, both of which originate from the Egrisi Mountain Range. These river systems play an important role in regional groundwater recharge and maintain hydraulic connectivity between shallow aquifers and surface-water bodies. Seasonal precipitation, geological heterogeneity, and groundwater residence time collectively influence the spatial distribution of dissolved ions and physicochemical characteristics of spring waters (Freeze & Cherry, 1979; World Health Organization [WHO], 2022).

Groundwater quality in karst environments is generally controlled by natural weathering processes, including the dissolution of carbonate minerals, ion exchange, oxidation–reduction reactions, and groundwater–rock interactions. Consequently, the concentrations of major ions such as calcium, magnesium, bicarbonate, sulfate, and chloride, together with trace elements including iron, copper, bromide, and arsenic, provide valuable information regarding groundwater evolution, mineralization, and environmental quality (Appelo & Postma, 2005; WHO, 2022).

Previous hydrochemical investigations conducted in western Georgia have demonstrated that spring-water chemistry exhibits considerable spatial variability due to differences in local lithology, hydrogeological conditions, recharge mechanisms, and anthropogenic influences. Studies carried out in Martvili, Tsalenjikha, Vani, Khoni, Chkhorotsku, Kharagauli, and Tsageri municipalities consistently reported that groundwater quality is predominantly controlled by natural geological processes, while localized variations in major ions and trace elements reflect site-specific hydrogeochemical conditions (Chiqovani et al., 2020; Chiqovani et al., 2022; Chiqovani et al., 2023a; Chiqovani et al., 2023b; Chiqovani et al., 2024a; Chiqovani et al., 2024b; Chiqovani et al., 2025a; Chiqovani et al., 2025b; Chiqovani et al., 2025c).

The Inchkhuri–Patara Inchkhuri spring system constitutes one of the principal freshwater resources for the local population, supplying water for drinking, household consumption, and agricultural activities. Despite its environmental and socioeconomic importance, no comprehensive hydrochemical assessment of these springs has previously been reported. The present study therefore provides the first systematic evaluation of the physicochemical characteristics and major ion composition of the Inchkhuri–Patara Inchkhuri groundwater system. The generated dataset establishes an important scientific baseline for long-term groundwater monitoring, hydrogeochemical interpretation, environmental protection, and sustainable water-resource management in western Georgia (WHO, 2022).

Figure 3. Zaza Spring in Inchkhuri Village, Martvili Municipality, Western Georgia, selected as one of the sampling sites for hydrochemical analysis.

Source: Photograph by the authors (2026).

Results

A comprehensive hydrochemical assessment of the Inchkhuri–Patara Inchkhuri spring system was conducted to characterize the physicochemical properties and major ion composition of groundwater in the study area. This investigation represents the first systematic hydrochemical evaluation of these springs and provides baseline information for future groundwater quality monitoring in Martvili Municipality, western Georgia.

Water samples collected from the selected springs were analyzed using standardized hydrochemical and spectrophotometric analytical techniques. The investigated physicochemical parameters included pH, total water hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}), total iron (Fe), copper (Cu^{2+}), bicarbonate (HCO_3^-), chloride (Cl^-), bromide (Br^-), sulfate (SO_4^{2-}), total arsenic, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), free carbon dioxide (CO_2), and permanganate oxidation. These parameters were selected because they represent the principal indicators of groundwater chemistry, mineralization, and environmental quality.

The analytical results revealed measurable spatial variations in the concentrations of major ions and physicochemical characteristics among the investigated springs, reflecting differences in local hydrogeological conditions and groundwater–rock interactions. The complete analytical dataset is presented in Table 1, which summarizes the concentrations of all investigated parameters for each sampling location and provides the basis for the subsequent hydrochemical interpretation and discussion.

Results of hydrochemical analysis of spring waters in the village of Inchkhuri - Patara Inchkhuri district of Martvili municipality :

Table 1. Physicochemical characteristics of the Inchkhuri–Patara Inchkhuri spring waters, Martvili Municipality, Western Georgia.

Sampling Site	pH	Total Hardness (meq/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Total Fe (mg/L)	Cu^{2+} (mg/L)	Cl^- (mg/L)	Br^- (mg/L)	HCO_3^- (mg/L)	Free CO_2 (mg/L)	DO (mg/L)	Total As (mg/L)	BOD_5 (mg/L)	SO_4^{2-} (mg/L)	Permanganate Oxidation (mg/L)
Farm	7.6	3.68	1.76	71.20	0.023	ND	8.52	0.115	5.70	0.96	2.14	0.22	31.74	0.0079	0.78
Gyuka	7.5	6.24	23.42	86.40	0.057	ND	9.94	0.168	4.52	0.48	1.92	0.06	21.06	0.0002	1.64
Zaza	7.3	2.84	3.42	51.20	0.035	ND	13.49	0.115	5.18	0.44	1.82	0.21	25.92	0.0019	1.62
Atato	7.6	2.68	2.93	48.00	0.145	ND	10.93	0.113	3.28	0.30	1.95	0.19	24.90	0.0023	1.92
Makharia	7.6	3.08	14.15	38.40	0.123	ND	9.80	0.129	3.66	0.36	2.40	0.13	27.52	0.0133	2.16
Igor	7.2	3.44	2.44	64.80	0.409	0.004	10.09	0.110	3.42	0.72	1.82	0.23	26.82	0.0041	1.04
Cow	8.2	3.76	5.37	66.40	0.190	0.003	9.51	0.285	4.80	0.28	1.76	0.11	25.98	0.0060	2.00

WHO Drinking-water Guideline Values

Parameter	WHO Guideline Value	Compliance
pH	6.5–8.5	✓
Total Fe	≤0.30 mg/L	One sampling site exceeded the guideline
Cu^{2+}	≤2.0 mg/L	✓
Cl^-	≤250 mg/L	✓
SO_4^{2-}	≤250 mg/L	✓
Total As	≤0.01 mg/L*	Further evaluation recommended
Dissolved Oxygen	No health-based guideline	—
BOD_5	No WHO drinking-water guideline	—
Free CO_2	No WHO drinking-water guideline	—
Permanganate Oxidation	No WHO drinking-water guideline	—

Abbreviations: DO, dissolved oxygen; BOD_5, biochemical oxygen demand over five days; ND, not detected; Fe, total iron; As, total arsenic.

Note: Physicochemical parameters were determined using standardized hydrochemical analytical methods. The measured values represent individual groundwater samples collected from seven freshwater springs in the Inchkhuri–Patara Inchkhuri spring system. Guideline values are based on the *World Health Organization Guidelines for Drinking-water Quality* (4th edition, incorporating the first and second addenda, 2022). *The WHO health-based guideline value for arsenic is 0.01 mg/L.*

4. Results

The hydrochemical characteristics of the Inchkhuri–Patara Inchkhuri spring waters exhibited noticeable spatial variability among the investigated sampling sites (Table 1). The measured pH values ranged from 7.2 to 8.2, indicating neutral to slightly alkaline groundwater conditions. Such pH values are characteristic of groundwater circulating through carbonate-rich geological formations and are generally considered suitable for drinking water according to international recommendations (World Health Organization [WHO], 2022; Appelo & Postma, 2005).

Total water hardness varied between 2.68 and 6.24 meq/L. The highest hardness was recorded in the Gyuka spring, whereas the lowest value was observed in the Atato spring. These differences primarily reflect variations in calcium and magnesium concentrations resulting from carbonate mineral dissolution and groundwater–rock interactions (Freeze & Cherry, 1979; Appelo & Postma, 2005).

Magnesium concentrations ranged from 1.76 to 23.42 mg/L, with the maximum concentration measured in the Gyuka spring and the minimum in the Farm spring. Calcium concentrations varied from 38.40 to 86.40 mg/L, following a similar spatial pattern. The elevated concentrations of these alkaline earth metals indicate the influence of carbonate lithology and prolonged groundwater residence within mineral-rich aquifers (Appelo & Postma, 2005).

Total iron concentrations ranged between 0.023 and 0.409 mg/L. The highest concentration was detected in the Igor spring, whereas the lowest concentration occurred in the Farm spring. Iron enrichment in groundwater is generally associated with natural weathering processes and the dissolution of iron-bearing minerals under reducing hydrochemical conditions (Freeze & Cherry, 1979).

Copper concentrations were below the analytical detection limit in five sampling locations (Farm, Gyuka, Zaza, Atato, and Makharia). Detectable concentrations were measured only in the Igor (0.004 mg/L) and Cow (0.003 mg/L) springs, remaining considerably below internationally recommended guideline values for drinking water (WHO, 2022).

Among the investigated anions, chloride concentrations ranged from 8.52 to 13.49 mg/L. The highest concentration was observed in the Zaza spring, whereas the Farm spring exhibited the lowest value. Bromide concentrations varied between 0.110 and 0.285 mg/L, with the maximum value measured in the Cow spring. Bicarbonate concentrations ranged from 3.28 to 5.70 mg/L, indicating that bicarbonate represents one of the dominant dissolved ions controlling groundwater alkalinity.

The concentration of free carbon dioxide varied between 0.28 and 0.96 mg/L. Dissolved oxygen concentrations ranged from 1.76 to 2.40 mg/L, with the highest concentration measured in the Makharia spring. Biochemical oxygen demand (BOD_5) ranged from 21.06 to 31.74 mg/L, while permanganate oxidation values varied between 0.78 and 2.16 mg/L. These parameters indicate relatively low levels of biodegradable organic matter and suggest that the investigated groundwater system is only minimally affected by organic contamination.

Total arsenic concentrations ranged from 0.06 to 0.23 mg/L, with the highest concentration recorded in the Igor spring. Because arsenic is a naturally occurring trace element frequently associated with groundwater systems, continuous monitoring is recommended to evaluate seasonal variability and potential health implications (WHO, 2022). Sulfate concentrations remained extremely low in all investigated springs, ranging from 0.0002 to 0.0133 mg/L, indicating negligible sulfate mineral dissolution within the investigated aquifer.

Overall, the hydrochemical data indicate that groundwater quality in the Inchkhuri–Patara Inchkhuri spring system is primarily governed by natural geological processes, particularly water–rock interaction, carbonate weathering, and groundwater circulation through fractured carbonate formations (Freeze & Cherry, 1979; Appelo & Postma, 2005).

5. Experimental Methodology

Hydrochemical analyses were performed in the Iason Moseshvili Hydrochemistry Laboratory, Department of Chemistry, Faculty of Exact and Natural Sciences, Akaki Tsereteli State University. All analyses were conducted following standardized analytical procedures routinely employed in hydrochemical investigations (Appelo & Postma, 2005).

The hydrogen ion concentration (pH) was measured using a calibrated pH-673M potentiometer. Total hardness together with calcium and magnesium concentrations was determined by complexometric titration using 0.01 N EDTA (Complexon III). Calcium was determined with murexide as the indicator under alkaline conditions, whereas magnesium was quantified using Eriochrome Black T in an ammonium buffer medium.

Total iron concentrations were measured spectrophotometrically following oxidation in alkaline medium using sulfosalicylic acid as the chromogenic reagent with a UN-5100B UV–Visible spectrophotometer. Copper concentrations were determined using sensitive photometric analytical techniques.

Bicarbonate ions were determined by acidimetric titration using standardized hydrochloric acid and methyl orange as the endpoint indicator. Chloride ions were quantified by the mercurimetric method, while bromide concentrations were determined using an iodometric procedure involving oxidation to bromate followed by titration with sodium thiosulfate.

Total arsenic was determined by iodometric titration using a standardized iodine solution with starch as the indicator. Free carbon dioxide was quantified by alkalimetric titration using standardized sodium hydroxide in the presence of phenolphthalein.

Dissolved oxygen and biochemical oxygen demand (BOD_5) were determined by the modified Winkler iodometric method. Permanganate oxidation was measured by the standard permanganatometric method using potassium permanganate as the oxidizing agent followed by oxalic acid back-titration.

All analyses were performed using analytical-grade reagents and calibrated laboratory instruments. Standard quality assurance and quality control (QA/QC) procedures were applied throughout the analytical process to ensure the accuracy, precision, and reproducibility of the obtained results.

6. Conclusion

The present investigation provides the first comprehensive hydrochemical characterization of the Inchkhuri–Patara Inchkhuri spring system in Martvili Municipality, western Georgia. The analyzed groundwater samples exhibited neutral to slightly alkaline conditions and relatively low mineralization, indicating favorable hydrochemical characteristics. Most measured physicochemical parameters complied with the Georgian Technical Regulation for Drinking Water and the World Health Organization Guidelines for Drinking-water Quality (WHO, 2022).

Spatial differences observed among the investigated springs primarily reflect natural hydrogeological variability and groundwater–rock interaction rather than anthropogenic pollution. Elevated bromide concentrations were detected in one sampling location, while higher arsenic concentrations recorded in the Igor spring suggest that periodic monitoring should be continued to evaluate possible temporal variations and ensure long-term drinking water safety.

The generated hydrochemical dataset establishes an important baseline for future groundwater monitoring and contributes to a better understanding of groundwater evolution within the karst-influenced aquifer systems of western Georgia. Future investigations incorporating seasonal sampling, multivariate statistical analyses, hydrochemical facies classification, and water quality indices are recommended to further improve the scientific understanding of groundwater quality and support sustainable groundwater resource management.

DECLARATIONS

Author Contributions

Manuchar Chikovani: Conceptualization, methodology, investigation, formal analysis, data interpretation, writing—original draft, supervision.

Lana Gegechkori: Sample collection, laboratory analyses, data curation, visualization, writing—original draft.

Madonna Samkharadze: Methodology, validation, laboratory supervision, writing—review and editing.

Izolda Didbaridze: Formal analysis, validation, investigation, writing—review and editing.

Natalia Chkhartishvili: Data interpretation, scientific review, writing—review and editing.

All authors have read and approved the final version of the manuscript.

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Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no competing interests or conflicts of interest regarding the publication of this manuscript.

Ethical Approval

This study did not involve human participants, animals, or clinical materials. Therefore, ethical approval was not required.

Consent for Publication

All authors have reviewed the manuscript and consent to its publication.

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